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Policy choices can help keep 4G and 5G universal broadband affordable

Edward J. Oughton [a,c,*], Niccolò Comini [b], Vivien Foster [b], Jim W. Hall [c]

[a] George Mason University, Fairfax, VA, United States
[b] World Bank, Washington DC, United States
[c] University of Oxford, Oxford, United Kingdom

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ABSTRACT

The UN Broadband Commission has committed to universal broadband by 2030. But can this objective really be affordably delivered? The aim of this paper is to assess universal broadband viability in the developing world, quantifying the relationship between demand-side revenue and supply-side cost. A comprehensive scenario-based simulation model is developed open-source, capable of evaluating the global cost-effectiveness of different 4G and 5G infrastructure strategies. Utilizing remote sensing and demand forecasting, least-cost network designs are developed for eight representative Low and Middle-Income Countries (Malawi, Uganda, Kenya, Senegal, Pakistan, Albania, Peru and Mexico), the results from which form the basis for global aggregation via a new assessment framework. The cost of meeting a minimum ~10 Mbps per user is estimated at USD 2 trillion using 5G Non-Standalone, approximately 0.67% of annual GDP for the developing world over the next decade. However, by creating a favorable regulatory environment, governments can bring down these costs by almost half – to USD 1.2 trillion (approximately 0.41% of annual GDP) – and avoid the need for public subsidy. Providing governments make judicious choices, adopting fiscal and regulatory regimes conducive to lowering costs, universal broadband may be within reach of most developing countries over the next decade.

1. Introduction

Internet access is increasingly seen as a cornerstone for sustainable development (Bali Swain and Ranganathan, 2021; Hackl, 2018). However, many Low and Middle Income Countries (LMICs) have yet to achieve near-comprehensive population coverage of 3G cellular infrastructure, leading to a growing divide between countries (Montenegro and Araral, 2020). While some 4G deployments have taken place (offering maximum speeds of ~100 Mbps), it can be challenging to deliver significant infrastructure upgrades with substantially lower Average Revenue Per User (ARPU) compared to markets in high income countries (Hilbert, 2010). Meanwhile, 5G is now being deployed bringing substantial performance improvements, such as speeds of 1 Gbps, as well as a new range of use cases (Cave, 2018; Oughton et al., 2021). Various technologies are being evaluated for universal broadband deployment strategies, including terrestrial 4G/5G cellular, drone-assisted architectures (Matracia et al., 2021) and Low Earth Orbit (LEO) satellite constellations (Osoro and Oughton, 2021).

The United Nations (UN) Broadband Commission has called on the international community to work towards an interim milestone of 75 percent global coverage of broadband by 2025, with the aspiration of full global coverage by 2030. Many countries are now examining how to best encourage the deployment of universal broadband infrastructure to support the delivery of the Sustainable Development Goals (SDGs), but confront the fact that technological and policy decisions involve difficult trade-offs (Forge and Vu, 2020). For example, can the UN goal of universal broadband really be delivered or is it too much of a financial burden for countries?

Thus, the aim of this paper is to assess the viability of reaching universal broadband in the developing world, quantifying the relationship between demand-side revenue and supply-side cost. Using this approach, a key goal is to estimate how viability can as far as possible be achieved through judicious decisions on technology choice, infrastructure sharing, spectrum pricing and taxation (hence, focusing mainly on exploring supply-side decisions). As the network investments required could indeed be substantial, it is important to undertake independent and transparent assessment of different universal broadband strategies, to evaluate the impact on viability. This has already been identified as an important area of research (Ioannou et al., 2020) with the results providing necessary insight for setting national policies for enhancing

* Corresponding author at: George Mason University, 4400 University Drive, Fairfax, VA 22030, United States.
E-mail addresses: eoughton@gmu.edu (E.J. Oughton), ncomini@worldbank.org (N. Comini), vfoster@worldbank.org (V. Foster), jim.hall@eci.ox.ac.uk (J.W. Hall).

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digital connectivity. Such an exercise may not necessarily predict the future dynamics of deployment but can contribute to our understanding of the general trade-offs in universal broadband decisions. Given this aim, the following research question is articulated:

1.1. Is universal broadband both (commercially) viable and (financially) affordable in the developing world?

Answering this question raises difficult methodological challenges. Much of the past research in this area has been isolated to individual country assessments, each using a bespoke model which reflects the unique specificities of the market being evaluated (Benseny et al., 2019; Boik et al., 2019; Ioannou et al., 2020; Lee et al., 2021; Liu and Wang, 2021; Macher et al., 2017; Ovando et al., 2015). While such an approach serves an important purpose, there is also a need for a forecasting-based model which is more adaptable to application in many different countries. This enables global comparison of different broadband strategies, particularly for supporting decisions across LMICs (Prado and Bauer, 2021), reflecting technological and geographic heterogeneity in broadband markets (Dasgupta et al., 2021; Oughton and Lehr, 2021). The method developed in this paper contributes to this important area of academic research.

Governments must consider the range of technologies Mobile Network Operators (MNOs) could utilize to meet universal broadband. Although policies are generally technology neutral, governments must consider all options, such as 4G or 5G, to choose feasible targets reflecting the level of capacity to be provided, speed of deployment and cost. Second, governments must decide on the desired balance between competition and consolidation in infrastructure deployment. While competition is generally desirable to create a dynamic and efficient market, in more remote geographic areas, demand may not be high enough to support more than one infrastructure provider, and infrastructure sharing facilitated by supportive government regulations may allow network expansion at significantly lower cost. Finally, government design of the fiscal regime for broadband infrastructure will affect the viability of deployment for new technologies. Particularly important is government policy for pricing access to radio spectrum, which may constitute a significant part of the cost of providing broadband services. This gives rise to trade-offs between government revenues and population coverage, leading to tensions between maximizing fiscal revenues from the sector and minimizing the need for public subsidy to reach universal broadband.

The paper is organized as follows. Section 2 provides an overview of the relevant literature and situates the contribution of this research. Section 3 describes the geospatial simulation methodology used to quantify the performance of universal broadband strategies. Section 4 presents the main findings, and Section 5 undertakes a discussion and provides relevant conclusions.

2. The benefits and challenges of broadband connectivity

A growing number of studies identify the economic benefits of broadband. For example, firms which embrace digital connectivity are more productive (Bertschek and Niebel, 2016; Hjort and Poulsen, 2019), more innovative (Paunov and Rollo, 2016) and better at expanding into new markets (Gnangnon and Iyer, 2018; Muto and Yamano, 2009). Thus, areas with better broadband have lower unemployment rates (Lobo et al., 2020), better regional economic productivity (Jung and López-Bazo, 2020) and higher levels of social welfare (Björkegren, 2019a).

Equally, there are many consumer benefits, which make policies stimulating the adoption of digital technologies attractive for governments. Mobile phone use is positively associated with increased food access (Wantchekon and Riaz, 2019), financial inclusion (Batista and Vicente, 2020; Hasbi and Dubus, 2020), public health care access (Haenssgen et al., 2021; Haenssgen and Ariana, 2017), and poverty reduction (Medeiros et al., 2021; Tadesse and Bahiigwa, 2015). Citizens and governments also gain benefits as cell phones are powerful tools to help reduce corruption (Elbahnasawy, 2014; Kanyam et al., 2017) and improve governance (Asongu and Nwachukwu, 2016).

At the macroeconomic level, better broadband infrastructure is associated positively with a range of macroeconomic indicators, particularly GDP (Briglauer and Gugler, 2019; Czernich et al., 2011; Koutroumpis, 2009). Countries with higher 3G penetration tend to enjoy greater GDP per capita growth than those with comparable total mobile penetration (Williams et al., 2013). Recent estimation suggests that a 10% increase in mobile penetration is associated with an average increase in GDP per capita between 0.59 to 0.76% depending on the model specification (Bahia and Castells, 2019). In the United States, every 10-percentage point gain in penetration annually (from 3G to 4G) has been estimated to generate more than 231,000 jobs (Shapiro and Hassett, 2012). However, broadband deployment can exhibit diminishing returns to scale, and connection speed is a moderator of this effect, whereby beyond a threshold further quality increases are deemed unproductive (Koutroumpis, 2019). Hence, while broadband contributes to economic growth, its contribution is far from straightforward (Tranos, 2012).

Most digital infrastructure globally is deployed by private operators via market methods (Cave, 2017; Cave et al., 2019; Gruber, 2005; Jeon et al., 2020; Moshi and Mwakatumbula, 2017; Oughton et al., 2015; Wallsten, 2001; Yoo, 2017). A common challenge in the deployment of broadband occurs from the cost of supply exceeding the price users are willing (or capable) to pay, notably in remote areas (Gerli et al., 2018; Oughton et al., 2018a; Rosston and Wallsten, 2020). Providing access in areas where it may not be commercially viable can be assisted through government policies aimed at reducing the cost of digital infrastructure, and/or provision of government subsidy to make-up the viability gap. Universal access policies often mandate private operators to finance deployment of infrastructure in unviable locations via cross-user subsidization (Curien, 1991), with capital being reallocated from highly profitable areas (Glass and Tardiff, 2021).

One way that governments can improve the viability of investments to reduce the digital divide is by allowing infrastructure and resource sharing (Afraz et al., 2019; Hou et al., 2019; Koutroumpis et al., 2021; Maksymyuk et al., 2019; Meddour et al., 2011; Rebato et al., 2016; Samdanis et al., 2016; Sanguanpuak et al., 2019; Strover et al., 2021). The standard approach that each MNO in the market builds their own dedicated network is increasingly looking unviable, given declining revenues and the costs of delivery in rural areas. These considerations become even more relevant with the advent of 5G, which is expected to require a large increase in cellular sites to provide greater capacity ('network densification') (Rendón Schneir et al., 2018). Hence, the idea of greater infrastructure sharing for different parts of the network is looking more realistic (Meddour et al., 2011) as MNOs become open to the idea of market co-operation with competitors (Oughton, 2021; Sanguanpuak et al., 2018; Yrjola, 2020), consolidating infrastructure duplication, while producing savings on capital and operational costs (Oladejo and Falowo, 2020). Much of this debate focuses on the concept of static versus dynamic efficiency in industrial organization (Grajek et al., 2019), with a static approach focusing on squeezing out market efficiencies for a single point in time, contrasting with a dynamic approach which aims to gain long-term benefits from infrastructure-based market competition (Cave, 2006; Cave et al., 2019).

Governments have a large influence over the efficient allocation of radio spectrum to maximize aggregate societal value (Cave and Pratt, 2016) and limit market power (Peha, 2017). A key challenge of spectrum management is responding to new technologies (e.g. 5G), and the potential institutional changes that may be required (Gomez et al., 2019; Lehr, 2020; Oughton and Jha, 2021; Vuojala et al., 2019; Weiss et al., 2019). Spectrum auctions are the common tool for allocating resources while maximizing efficiency and equity objectives (Goetzendorff et al., 2018). However, higher spectrum prices are often correlated with negative consumer outcomes, including lower coverage levels and slower data speed (Bahia and Castells, 2019). Equity issues are often addressed by imposing coverage obligations via the auction design, lowering spectrum revenues, but leading to higher net social welfare (Cave and Nicholls, 2017). Governments may decide to provide subsidies to encourage availability in highly unviable locations (Bourreau et al., 2020), as has been common for many telecom technologies (Kenny and Kenny, 2011; Prieger, 2013; Rajabiun and Middleton, 2014). However, there is a trade-off between taxing operators and simultaneously providing universal broadband subsidies. Indeed, the network externalities of mobile networks mean the social welfare cost of taxing the mobile sector may be as much as three times the fiscal revenue raised (Björkegren, 2019b).

3. Method

A comprehensive simulation model is developed open-source, to assess the viability of different strategic universal broadband policy choices, relating to 4G and 5G network deployment. The method subjects this model to a set of heterogenous scenarios, which enable 'what-if' questions to be tested (Chen et al., 2020; Jefferson, 2020; Kayser and Shala, 2020; Kishita et al., 2020; Meadows and O'Brien, 2020). Scenario analysis is a common approach to explore technology futures (where historical experience is not a dependable guide to the future) and provides useful insight into the comparative performance of different decision options, especially for policy (Crawford, 2019; Frith and Tapinos, 2020; Gordon, 2020; Hutajulu et al., 2020; Metz and Hartley, 2020; Wright et al., 2020).

The method consists of three steps. First, countries with similar demand-side and supply-side broadband characteristics are clustered. Second, an assessment model capable of simulating 4G and 5G deployment strategies is developed to test the implications of different decisions in each cluster of countries. Finally, the cost per capita for the specific countries modeled is generalized to all other nations in each cluster, based on their population.

3.1. Country clustering

Detailed modeling of all 135 emerging economies would be extremely challenging. Therefore, the motivation for clustering countries is to enable a representative subset to be assessed. Grouping by cluster then enables the cost per capita from the assessed countries to be generalized to others within that cluster, reducing estimation uncertainty.

Countries are clustered based on a combination of factors which affect digital infrastructure viability. Using a theoretical understanding of broadband adoption and infrastructure deployment from the literature, three main factors are selected (Gallardo et al., 2020; Koutroumpis, 2009; Preissl and Howell, 2021; Reddick et al., 2020; Rhinesmith et al., 2019). The demand-side is captured by Gross Domestic Product (GDP) per capita, as an indicator of the ability to pay for broadband services, and population density, representing the mean number of users available. The supply-side is represented by existing 4G network coverage, which reflects the current level of infrastructure provision and therefore future incremental cost.

High income countries are excluded from the clustering process, as are outliers with very extreme values (such as The Maldives) to avoid outliers skewing the clustering results. This allows the analysis to focus on developing countries where the challenges of broadband deployment are driven by the need for wide-area coverage in areas of low population density and/or low take-up. Using K-means clustering, a popular classical unsupervised machine learning method, six clusters are exogenously specified. This quantity significantly reduces the group-level variation via the Within-Group Sum of Squares (Hothorn and Everitt, 2014), while making the results easy to obtain and report. The default R *stats* algorithm defined by Hartigan and Wong (Hartigan and Wong, 1979) is applied. Data on GDP per capita and population density (World Bank, 2020), as well as 4G coverage (GSMA, 2020), enable Fig. 1 to report the summary cluster statistics, along with a global map indicating the country clusters. A detailed description of the clustering process is provided in Section 1 of the Supplementary Materials.

Only these three clustering variables are used to ensure the outcome of this statistical exercise remains explainable. For example, Cluster 1 (C1) has mainly low-income countries with below average population density and 4G coverage. Cluster 2 (C2) also has mainly low-income countries with below average population density, but above average 4G coverage. Cluster 3 (C3) includes very densely populated countries, with low GDP per capita and 4G coverage only marginally above average. Cluster 4 (C4) includes middle income countries with mean population density, but above average 4G coverage. Cluster 5 (C5) also comprises middle-income countries with above average 4G coverage, but below average population density. Finally, Cluster 6 (C6) includes mainly upper middle-income countries, with above average 4G coverage, and mean population density.

Representative countries are then selected from each cluster ensuring a reasonable geographic spread and the practicalities of data availability. These include Uganda and Malawi from Cluster 1, Kenya and Senegal from Cluster 2, Pakistan from Cluster 3, Albania from Cluster 4, Peru from Cluster 5, and Mexico from Cluster 6. The key characteristics of these countries are shown in Table 1, using metrics sourced from the World Bank (World Bank, 2020), GSMA (GSMA, 2020) and where available crowdsourced mobile broadband results (Speedtest, 2020). Generally, these countries differ from left to right in terms of development, so Malawi has the lowest income per capita, whereas Mexico has the highest. This effect subsequently has an impact on 3G and 4G coverage, which generally increases from left to right, as the cluster numbers increase.

3.2. Python telecommunication assessment library (pytal)

While there have been analyses of these selected countries focusing on various parts of the digital ecosystem (Ahmad et al., 2019; Avilés, 2020; Cave and Mariscal, 2020; Hameed et al., 2018; Ignacio et al., 2020; Mir and Dangerfield, 2013; Ovando, 2020), few examples develop a scientifically reproducible open-source codebase which can be used to test real world decisions. Many country-specific 5G assessments have been carried out in OECD markets, such as the UK (Oughton et al., 2018b; Oughton and Frias, 2018, 2016; Oughton and Russell, 2020) and the Netherlands (Oughton et al., 2019a). However, they fail to scale to other countries because of their dependence on country-specific methods and data. Therefore, the Python Telecommunications Assessment Library (pytal) has been developed to provide a new globally-scalable simulation model using remote sensing, which can be applied to undertake cross-country comparative analytics for 4G and 5G universal broadband. Fig. 2 visualizes the universal broadband assessment method.

3.2.1. Demand module

The demand module follows a standard infrastructure forecasting method (Thoung et al., 2016). The density of cell phones ($Users\_on\_network_{it}$) for a hypothetical MNO in the ith local statistical area (per km^2) for time period t is calculated using the local population density ($Population_i$), the national percentage of unique cell phone users ($Penetration_t$) and the number of cellular networks ($Networks_i$), as illustrated in Eq. (1):

$$Users\_on\_network_{it} = \frac{Population_i \cdot (Penetration_t \;/\; 100)}{Networks_i} \tag{1}$$

Population estimates for local statistical areas are obtained by aggregating from a global 1 km^2 gridded dataset (Tatem, 2017; WorldPop, 2019). Penetration data for unique cellular subscribers is taken

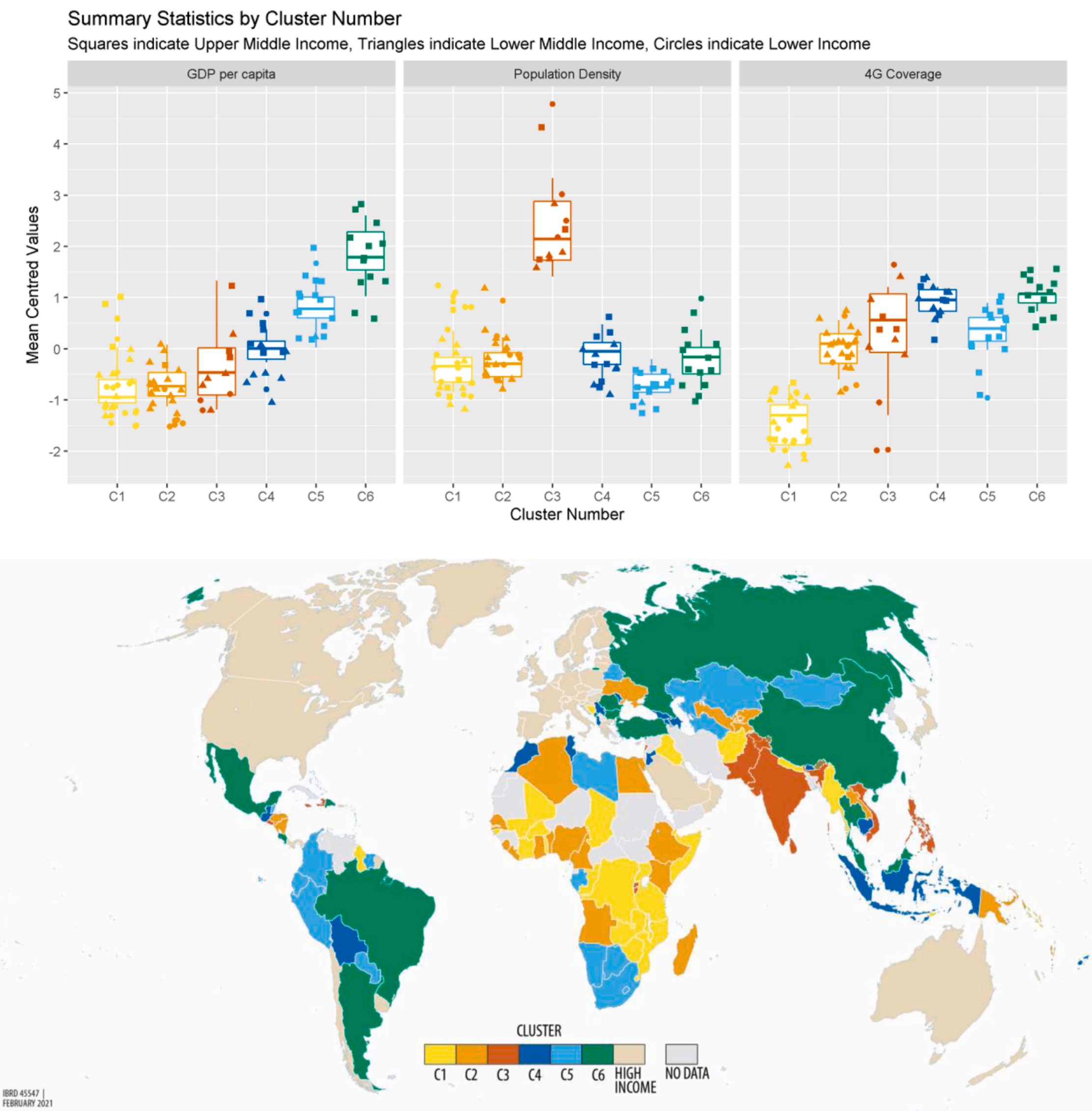

Fig. 1. Clustering summary statistics and global mapping.

Table 1
Selected countries for analysis.

Cluster	C1	C1	C2	C2	C3	C4	C5	C6
Country	Malawi	Uganda	Senegal	Kenya	Pakistan	Albania	Peru	Mexico
Region	SSA	SSA	SSA	SSA	SA&SE	E&CA	LAC	LAC
Income group	Low	Low	Lower-middle	Lower-middle	Lower-middle	Upper-middle	Upper-middle	Upper-middle
4G Population Coverage	16%	31%	50%	61%	67%	96%	84%	85%
3G Population Coverage	27%	88%	95%	96%	85%	97%	95%	97%
Population Density (per km2)	192	213	82	90	275	105	25	65
Population (m)	18.1	42.7	15.9	51.4	212.2	2.9	32.0	126.2
GDP Per Capita	USD 389	USD 643	USD 1522	USD 1711	USD 1473	USD 5254	USD 6947	USD 9698
Rural Population	83%	76%	53%	73%	63%	40%	22%	20%
Area (km2)	94,280	200,520	192,530	569,140	770,880	27,400	1280,000	1943,950
Mean Mobile Broadband Speedtest (Mbps)	–	11	22	22	17	51	–	30

from the GSMA for 2010–2020 (GSMA, 2020) as illustrated in Fig. 3(A). The number of networks in the user calculation is exogenously set depending on the present number of national networks in each market, yielding a representative market share for a hypothetical operator.

The data demand ($Demand_{it}$) in the ith local statistical area (km^2) needing to be met from the number of users on the network ($Users\_on\_network_{it}$) in time period t can be obtained by taking the national smartphone penetration rate ($SPPenetration_{st}$) for the s urban or rural settlement type, the desired per user capacity (*Scenario*) and an overbooking factor (*OBF*) as not all users will access the network at the same time, as illustrated in Eq. (2):

$$Demand_{it} = \frac{Users\_on\_network_{it} \cdot SPPenetration_{st} \cdot Scenario}{OBF} \tag{2}$$

Historical data are used up to 2020, with future years forecast at a compound rate coherent with the historical adoption trajectory

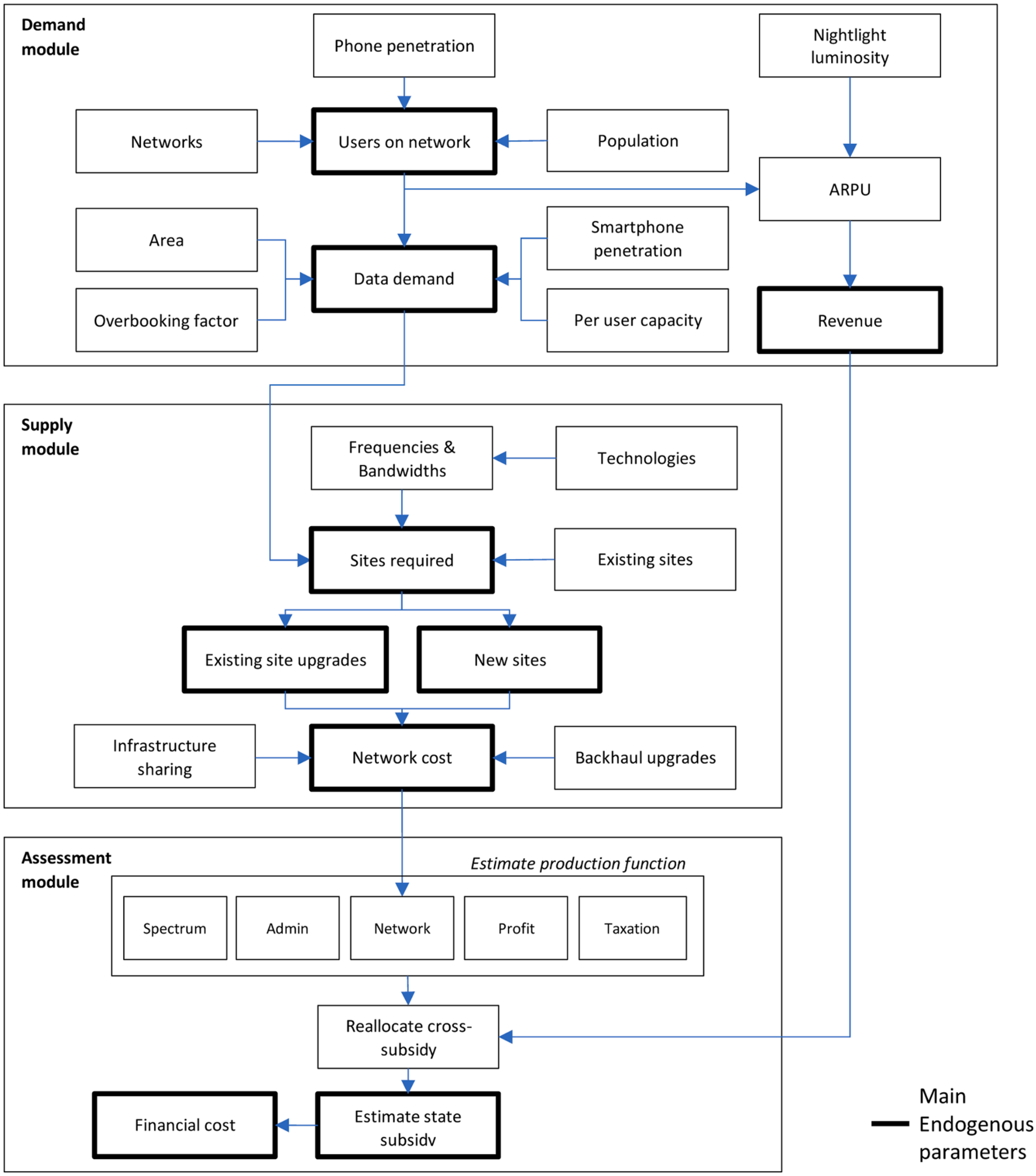

Fig. 2. Universal broadband assessment method in *pytal*.

(Malawi: 3.5%, Uganda: 2%: Senegal: 1.5%, Kenya: 1.5%, Pakistan: 2.5%, Albania: 0.3%, Peru: 0.5%, Mexico: 1.2%).

Fig. 3(B) contains the smartphone adoption rates for urban and rural users, based on survey data (Research ICT Africa, 2018) forecast forward over the study period annually (equating to national smartphone growth as follows: Malawi: 5%, Uganda: 5%: Senegal: 2%, Kenya: 2%, Pakistan: 4%, Albania: 1.5%, Peru: 1%, Mexico: 1%). With cellular networks being designed for either capacity, coverage, or a mixture of the two, the scenarios tested here take this into account. To ensure viability, high capacity is targeted at users in urban and suburban areas as cities form only a small proportion of total land mass, with lower capacity targeted at rural areas. In Scenario 1 (S1), users are targeted with ~25 Mbps in urban, ~10 Mbps in suburban and ~2 Mbps in rural. In Scenario 2 (S2), users are targeted with ~200 Mbps in urban, ~50 Mbps in suburban and ~5 Mbps in rural. In Scenario 3 (S3), users are targeted with ~400 Mbps in urban, ~100 Mbps in suburban and ~10 Mbps in rural. It should be noted that S3 is the only scenario that fully meets the goal of the UN Broadband Commission, which suggests a minimum capacity of ~10 Mbps for the entire population. As all possible users do not try to access the network simultaneously, an overbooking factor of 20 is used ($OBF = 20$) as identified in the GSMA 5G guide (GSMA, 2019), given the potential values in the literature range from 20 to 50 depending on desired Quality of Service (Oughton et al., 2019a; Oughton and Frias, 2018, 2016). This is similar to exogenously specifying the number of active users in other studies (Souza et al., 2021), but which is less suitable here due to the temporal change in adoption rates.

The sum of the expected revenue ($Revenue_{it}$) in the ith area per km^2 can be estimated given the Average Revenue Per User ($ARPU_i$) per month and the density of cell phone users ($Users_{it}$) for each time period t, as illustrated in Eq. (3):

$$Revenue_i = \sum ARPU_i \cdot Users_{it} \cdot 12 \tag{3}$$

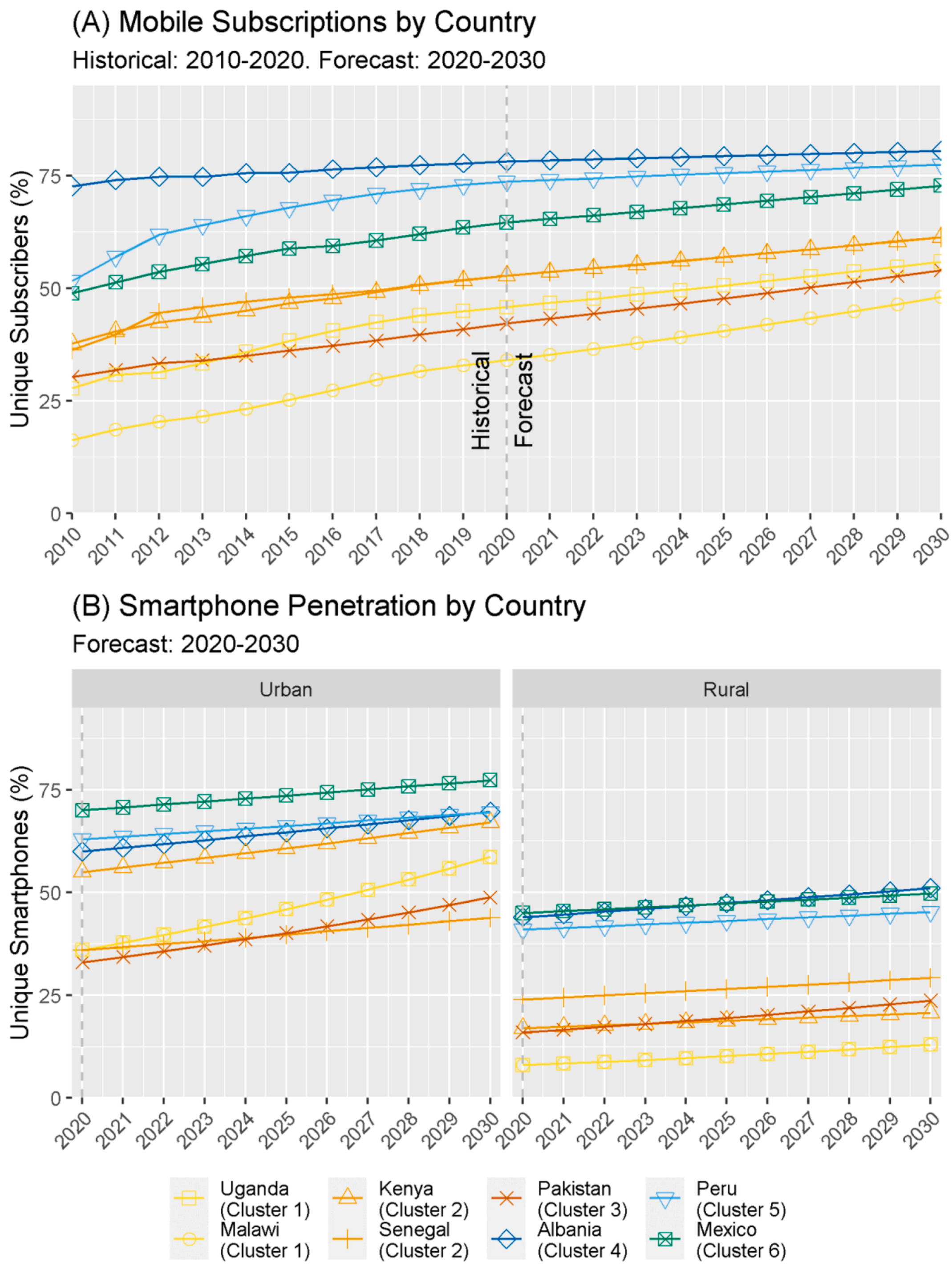

Fig. 3. Demand forecasts by country.

The revenue is discounted over the ten-year assessment period using a discount rate of 5%, with the ARPU estimated based on extracted nighttime luminosity values averaged over each region. This is an established way to estimate mobile ARPU, given the ability to pay for electricity is highly correlated with the ability to pay for broadband services (Oughton and Mathur, 2021). Luminosity data are available in Digital Number (DN) units and averaged for each local statistical area, whereby high luminosity is treated as being >20 DN km^2, medium

Table 2
Monthly ARPU by country.

Type	Monthly ARPU ($)							
	Malawi	Uganda	Senegal	Kenya	Pakistan	Albania	Peru	Mexico
High	3.5	3.5	8	8	4	8	11	11
Medium	2.5	2.5	5	5	2	7	10	10
Low	1	1	2	2	1	4	5	5

luminosity as >15 DN km^2, and low luminosity as being <15 DN km^2. The monthly ARPU amounts allocated to each of these bands by country are listed in Table 2, based off the average 2020 ARPU (GSMA, 2020).

3.2.2. Supply module

The supply module is based on a geospatial system model which can estimate the number of additionally required sites to meet required demand. The area capacity is estimated by obtaining the mean Network Spectral Efficiency ($\overline{\eta}^f_{area}$) (bps/Hz/km^2) given the average number of cells per site ($\overline{\eta}_{cells}$) and density of co-channel sites (ρ_{sites}) using the same spectrum frequency (f), as detailed in Eq. (4).

$$\overline{\eta}^f_{area} = \overline{\eta}^f_{cells} \cdot \rho_{sites} \tag{4}$$

The total capacity for an area ($Capacity_{area}$) can then be estimated for all frequencies by multiplying the Network Spectral Efficiency ($\overline{\eta}^f_{area}$) by the available spectrum bandwidth (BW^f), as in Eq. (5).

$$Capacity_{area} = \sum_f \overline{\eta}^f_{area}\, BW^f \tag{5}$$

The full technical engineering method which underpins the supply module can be found in Section 2 in the Supplementary Materials. This includes comprehensive detail on the estimation of the baseline infrastructure (Collins Bartholomew, 2019, TowerXchange, 2017, TowerXchange, 2018a, TowerXchange, 2018b, TowerXchange, 2019a, TowerXchange, 2019b), least-cost network designs (3GPP, 2019, GSMA, 2019; Oughton et al., 2019a; Oughton, 2019), upgrade strategies (De Andrade et al., 2015; Shehata et al., 2017; Sutton, 2018, 2019), costs, and spectrum prices (NERA Economic Consulting, 2017a, NERA Economic Consulting, 2017b). For example, as part of this method, the least-cost fiber network designs estimate the required quantity of new fiber links that need building, as illustrated in Fig. 4, where black connections represent existing fiber, red connections represent new fiber and yellow nodes represent are new fiber access points.

3.2.3. Cost estimation

The cost module first calculates the total discounted cost of capital and operating expenditures over the 10-year horizon, to obtain the Net Present Value in the first year of the assessment period (2020). Based on a highly detailed cost assessment reported in Section 2.6 of the Supplementary Materials, a typical three-sector macro cell requiring three remote radio units has a greenfield cost of $31.5k for equipment, $20k for the site build, $5k for installation, which is broadly similar with the stated costs in the literature (Frias and Pérez, 2012; Johansson et al., 2004; Markendahl and Mäkitalo, 2010; Nikolikj and Janevski, 2014; Oughton and Frias, 2018; Paolini and Fili, 2012; Smail and Weijia, 2017; Yunas et al., 2014; 5G. NORMA, 2016; Ofcom 2018). As administration is added later, these costs are lower than other studies that may use site costs between $100–200k each. The cost of electricity for each macro cell annually varies but is treated as $5k per year for 4G and $10k for 5G, which is much higher than European-centric estimates (METIS, 2017) but accounts for higher local energy prices, whilst also reflecting the fact that 5G consumes far more power than 4G. Other operating costs for maintenance and servicing are treated as being 10% of the investment capex of all active electronic components (METIS, 2017), similar to other estimates of 5–10% (Markendahl and Mäkitalo, 2010). In terms of other annual operating costs, rental would be between $1–9.6k for the site depending on the settlement type (urban, suburban, or rural) and maintenance costs would be $3.15k, producing an annual cost of ~$8.8k excluding the backhaul. The backhaul, regional and core fiber network is built and operated by the MNO and is dependent on the geographic area it needs to cover, given the least-cost network structure. Hence, rural costs are generally higher as links need to traverse longer distances.

An administration cost is also used, which can be as high as 30% in OECD nations (Rendon Schneir et al., 2019), but this value is adapted for countries with significantly lower labor prices, hence 20% of the network cost is applied annually. A Weighted Average Cost of Capital (WACC) is applied at 15% (WACC Expert, 2020), which is substantially higher than OECD nations, but this value is set by money markets and reflects the relative risk of lending (which can be higher in some countries due to political stability, poorer legal transparency, corruption etc.).

3.2.4. Spectrum costs

Spectrum costs consist of an upfront reserve price, a competitive premium and any associated annual fees over the license duration. Identifying spectrum costs for all countries globally can be challenging as not all information is made public. A sensible approach for the baseline is to use past spectrum prices to guide approximate values, after controlling for bandwidth, population and other major factors that make international comparison challenging. Based on statistical distribution for historical auction prices paid for different spectrum categories based on the six cluster groupings identified, Section 2.7 of the Supplementary Materials presents the dollar cost per MHz per capita, adjusting for bandwidth and market potential. The results for each cluster are shown in Table 3, indicating a factor of 10 in the variation of spectrum costs across countries, illustrating the sensitivity of these costs to market conditions and government policy. Coverage spectrum below 1 GHz is more desirable (due to better propagation characteristics) and therefore more expensive relative to capacity spectrum over 1 GHz.

3.3. Assessment of government policy choices

The simulation model is used to estimate the cost of reaching universal broadband in the selected countries for alternative government policy choices regarding the mobile technology, extent of infrastructure sharing, and pricing of spectrum.

When it comes to mobile technology choice, three technologies are included in the upgrade strategies tested, each of which deliver different use cases. Upgrading to 4G provides Mobile Broadband. On the other hand, upgrading to 5G non-standalone (NSA) delivers both Enhanced Mobile Broadband and Massive Machine Type Communications (also known as the ‘Internet of Things’). Finally, 5G standalone (SA) provides all use cases, including Ultra-Reliable and Low-Latency Communications. Additionally, two backhaul technologies are tested for both 4G and 5G, including fixed fiber optic versus wireless (microwave/millimeter wave) options.

In terms of the regulatory environment for infrastructure sharing, several options are considered. Under the baseline scenario, each MNO builds its own dedicated network. In passive site sharing, MNOs share physical facilities, such as the site compound and tower, but not any electrical components. With a Multi Operator Radio Access Network (MORAN), known as active sharing, MNOs share all passive and active components, including the radio heads and backhaul. In contrast, a Shared Rural Network (SRN) allows MNOs to share all passive and active equipment via a MORAN but only in rural areas.

As far as spectrum pricing is concerned, changes from the baseline spectrum prices reported above are explored via a −75% and +100% change in cost to provide low and high scenarios respectively. Corporate taxation is also included in the model at an illustrative rate of 30%. Although simulations were also conducted for low (10%) and high (40%) variations of taxes, results are not reported due to limited sensitivity.

For each scenario, the model reports the percentage of the population that can be covered on a commercially viable basis for a single hypothetical network, after accounting for excess profits (>20%) being reallocated via user cross-subsidization to unviable locations. The total financial cost of meeting 100% coverage is also reported, including the public subsidy that may be required to close any remaining viability gap.

Although there are many potential externalities, in this assessment we focus exclusively on the financial costs to the two main parties

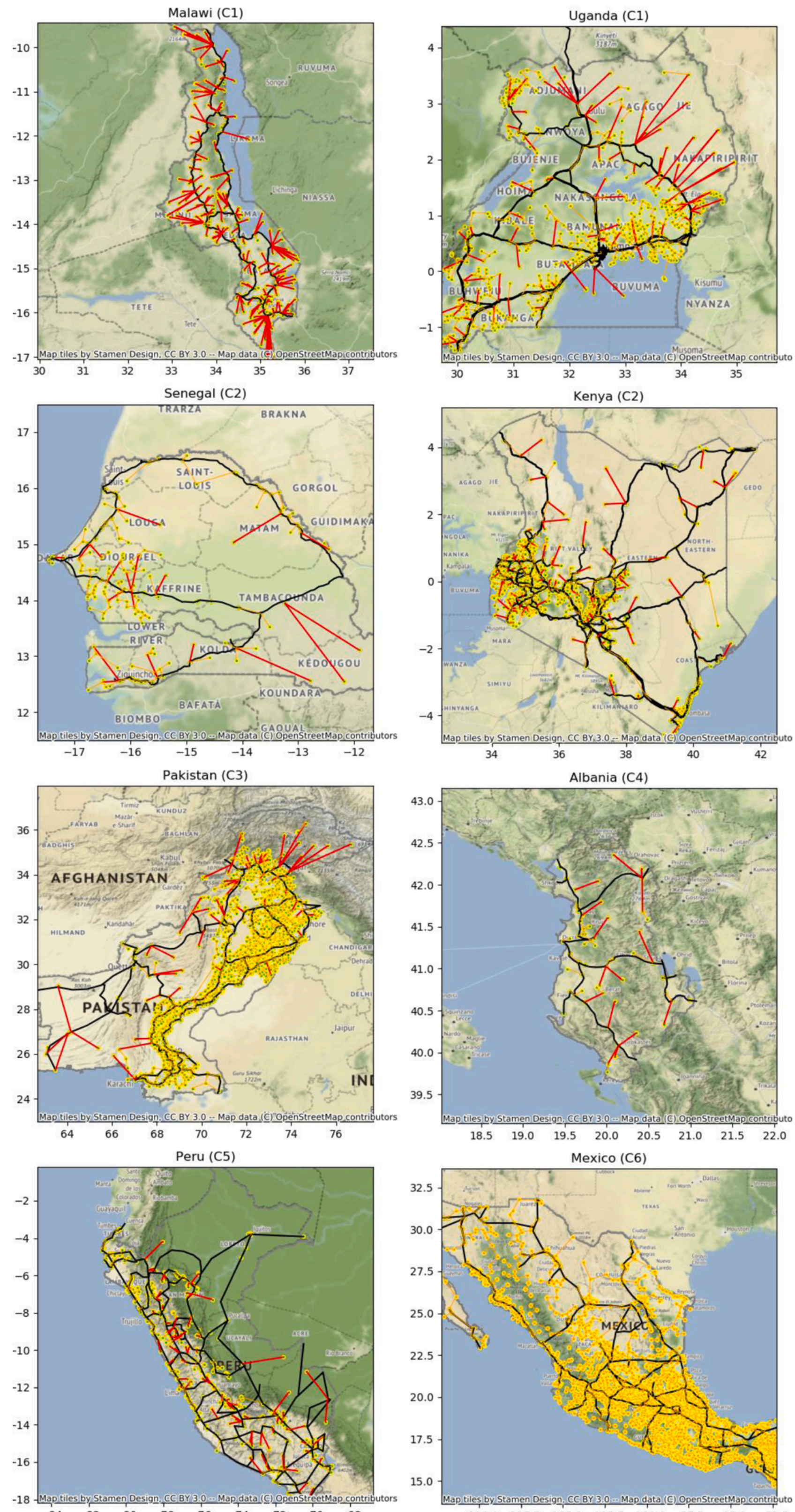

Fig. 4. Least-cost fiber network designs for existing and planned connections
Black: Existing network, Red: required network build-out, Yellow: Regional fiber edges and nodes.

Table 3
Baseline spectrum prices by country.

Type	Spectrum cost ($/MHz/Pop)							
	Malawi	Uganda	Senegal	Kenya	Pakistan	Albania	Peru	Mexico
Coverage (<1 GHz)	0.02	0.02	0.15	0.15	0.05	0.40	0.20	0.20
Capacity (>1 GHz)	0.01	0.01	0.08	0.08	0.03	0.10	0.10	0.10

(operators and governments). Thus, a simplified form of the financial cost ($Financial\_Cost_i$) can then be obtained by the summation of the financial cost to the network operator ($Private\_Cost_i$) and government ($Government\_Cost_i$) in each local statistical area i, as detailed in Eq. (6).

$$Financial\_Cost_i = Private\_Cost_i + Government\_Cost_i \tag{6}$$

The operator cost ($Private\_Cost_i$) for the ith local statistical area can be obtain by taking the summation of the costs for the network ($Network_i$), administration ($Administration_i$), spectrum ($Spectrum_i$), tax (Tax_i), plus the profit margin ($Profit_i$), as illustrated below in Eq. (7):

$$Private\_Cost_i = Network_i + Administration_i + Spectrum_i + Tax_i + Profit_i \tag{7}$$

The government cost ($Government\_Cost_i$) can be calculated based on any subsidies required to deploy infrastructure in unviable locations ($Subsidy_i$), minus any additional fiscal revenue obtained from private operators, via spectrum license fees ($Spectrum_i$) and taxation (Tax_i) as detailed in Eq. (8).

$$Government\_Cost_i = Subsidy_i - (Spectrum_i + Tax_i) \tag{8}$$

Metrics calculated for local statistical areas can then be aggregated to desired spatial levels, such as the national level. When aggregate estimates are produced, if only the cost of the hypothetical operator is considered, just a proportion of the market would be represented. Therefore, aggregate estimates for the whole market cost are produced, to provide universal broadband costs for all operators in a market to reach full coverage (in the baseline case). It is possible to also calculate these metrics on a per capita basis, which when multiplied by the population for other countries within each cluster, provide global insight.

Having completed the description of the method, a discussion of model uncertainties and other limitations is now undertaken.

3.4. Model uncertainty and limitations

The model developed here is based on a standard Long Run Incremental Cost (LRIC) method which is frequently used for decision-support analytics in telecom regulatory modeling. The basis of this approach is to develop a 'hypothetical Mobile Network Operator' which has an average endowment of existing sites, spectrum, and other sunk assets. This approach does lead to generalizations, compared to modeling an actual operator, which produces a limitation.

Moreover, by adopting a cost-minimization approach, the model does not extend to include full behavioral dynamics of economic agents, which is beyond the scope of this analysis and an area for future research. For example, on the supply-side agents may respond to changes in relative prices depending on different market structure and electricity access scenarios, whereas on the demand-side various education levels and demographic groups could affect take-up. Increasing model complexity is always a trade-off when being used for policy topics, as transparency and explain-ability is highly important, justifying exclusion from the model developed here (as demonstrated by substantial supplementary evidence). Future research should consider the implications of different market structures on the heterogenous responses of market agents.

Whilst great care is taken to obtain accurate estimates of model inputs, there are several inevitable sources of uncertainty. Uncertainty is introduced by not having explicit geospatial information on (i) cellular sites or regional fiber, (ii) ARPU, phone penetration or smartphone ownership, and (iii) backhaul technology. The methods used to derive these estimated data layers ensure that the aggregate quantity of supply-side infrastructure or demand-side users is accurate (e.g. total towers, total users etc.), but uncertainty is introduced in the regional spatial allocation of assets and users in the assessment.

Additionally, in the absence of other evidence, the modeling assumes that spectrum prices for 5G, which are a major cost driver, will be like those applied for previous generation technologies. For example, higher capacity 5G services depend on larger spectrum bandwidth. However, historical spectrum prices relate to much smaller bandwidths (e.g. 10 MHz bandwidth at 800 MHz for 4G) than the larger spectrum bandwidth needed to support much higher capacity 5G services. In that sense, historic prices may not be a reliable guide to what would emerge in future 5G auctions.

Finally, the simulations assume that MNOs can take a fair profit margin based on the capital employed to build the network (e.g. 20%). This is in addition to the WACC risk premium and reflects the risk involved with infrastructure investment. Higher revenues in areas with high demand are reallocated to unviable locations, essentially forcing some degree of geographic cross-subsidization, and thereby reducing the viability gap relative to the outcome of a pure profit-maximizing strategy.

4. Results

This section presents the results of the simulation exercise described above for the study period from 2020 to 2030. As the policy objective of providing universal broadband has already been identified, the analysis focuses on how this can be reached in the most cost-effective way. In making these judgments, the total financial cost is used as the primary performance metric, which is to say the industry's production cost net of taxation but inclusive of any government subsidies. The analysis also explores the net fiscal impact of achieving universal broadband, considering both government revenues from spectrum pricing and corporate taxations, as well as government subsidies to the sector where these are warranted to cover remaining viability gaps. The discussion of the results also considers how these can be used to inform government policy choices on technology, the design of the regulatory framework for infrastructure sharing, and the pricing of spectrum.

4.1. Financial cost of universal access

The cost of reaching universal broadband varies dramatically according to the technology selected and the desired level of capacity (see Table 4).

For any level of capacity demanded per user, the differential between the most expensive technology choice compared to the most cost-effective one is several multiples. The magnitude of the cost differential between technologies generally increases with the baseline level of 4G coverage. Countries like Malawi and Uganda (with 4G coverage of 15–30%) face cost differentials of 200–400% between technology choices, whereas countries like Albania and Mexico (with 4G coverage of 85–95%) can face cost differentials as high as 1000% between different technologies, driven by the existing level of 4G investment. For 4G technology, the consequence of choosing fiber backhaul is to almost double the cost of meeting universal access, although this differential drops at higher levels of user capacity demand. In the case of 5G technology, the choice of fiber backhaul at least doubles the cost of reaching

Table 4
Financial cost results for all technologies, scenarios, and strategies (NPV 2020–2030).

Technology Results reported by Country

			C1		C2		C3	C4	C5	C6
Scenario	Strategy	Metric	Malawi	Uganda	Senegal	Kenya	Pakistan	Albania	Peru	Mexico
S1 (<25 Mbps)	4G (W)	Financial Cost ($Bn)	1.6	1.7	1.3	4.4	27	0.023	4.9	6.9
S1 (<25 Mbps)	4G (F)	Financial Cost ($Bn)	2.5	5	2.6	9.3	70	0.038	12	13
S1 (<25 Mbps)	5G NSA (W)	Financial Cost ($Bn)	1.6	1.5	0.98	3.5	13	0.19	8.2	40
S1 (<25 Mbps)	5G SA (F)	Financial Cost ($Bn)	4.1	8.8	2.2	9	58	0.54	15	71
S2 (<200 Mbps)	4G (W)	Financial Cost ($Bn)	3.9	5.1	2.3	9.1	110	0.047	8.1	18
S2 (<200 Mbps)	4G (F)	Financial Cost ($Bn)	4.9	10	5.7	20	220	0.085	20	28
S2 (<200 Mbps)	5G NSA (W)	Financial Cost ($Bn)	2.4	3.6	1.9	5.9	67	0.25	11	57
S2 (<200 Mbps)	5G SA (F)	Financial Cost ($Bn)	5	14	4.5	14	310	0.61	34	130
S3 (<400 Mbps)	4G (W)	Financial Cost ($Bn)	6.7	10	4.7	20	220	0.26	13	24
S3 (<400 Mbps)	4G (F)	Financial Cost ($Bn)	7.9	16	9.4	33	360	0.4	39	36
S3 (<400 Mbps)	5G NSA (W)	Financial Cost ($Bn)	3.3	4.9	2.2	7.8	100	0.32	14	64
S3 (<400 Mbps)	5G SA (F)	Financial Cost ($Bn)	5.9	15	5.2	18	560	0.71	67	150

[1] Infrastructure Sharing Strategy: Baseline.
[2] Spectrum Pricing Strategy: Baseline.
[3] Taxation Strategy: Baseline.
[4] Results rounded to 2 s.f.

universal coverage in most cases.

The desired capacity per user also has a significant impact on the total cost of universal broadband, although unit costs decline dramatically. Considering 5G (NSA) technology, the cost of providing the higher capacity represented by S3 (<~400 Mbps) is in most cases approximately double the cost associated with providing capacity of S1 (<~25 Mbps). However, the capacity provided to users under S3 is up to 16 times higher than S1, indicating the magnitude of scale economies in the provision of capacity. These results suggest the importance of having a clear understanding of likely growth in capacity demanded by users when designing a broadband network.

4.2. Impact of technology choice

To minimize the cost of meeting universal broadband, governments must identify the most relevant technology for any specific country setting. Table 5 presents the lowest financial cost technology in each country across all scenarios for capacity per user and encompassing

Table 5
Identifying the cheapest technology for achieving universal service.

Least (Financial) Cost Technology for Universal Coverage

			Infrastructure Sharing			Spectrum Pricing		Taxation		Hybrid
Country	Scenario	Baseline	Passive	Active	SRN	Low P.	High P.	Low T.	High T.	Lowest
Malawi	S1 (<25 Mbps)	5G NSA (W)	4G (W)	4G (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Malawi	S2 (<200 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Malawi	S3 (<400 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Uganda	S1 (<25 Mbps)	5G NSA (W)	5G NSA (W)	4G (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Uganda	S2 (<200 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Uganda	S3 (<400 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Senegal	S1 (<25 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Senegal	S2 (<200 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	4G (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	4G (W)
Senegal	S3 (<400 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Kenya	S1 (<25 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Kenya	S2 (<200 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Kenya	S3 (<400 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Pakistan	S1 (<25 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Pakistan	S2 (<200 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Pakistan	S3 (<400 Mbps)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)	5G NSA (W)
Albania	S1 (<25 Mbps)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)
Albania	S2 (<200 Mbps)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)
Albania	S3 (<400 Mbps)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)
Peru	S1 (<25 Mbps)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)
Peru	S2 (<200 Mbps)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)
Peru	S3 (<400 Mbps)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)
Mexico	S1 (<25 Mbps)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)
Mexico	S2 (<200 Mbps)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)
Mexico	S3 (<400 Mbps)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)	4G (W)

policy choices on infrastructure sharing and spectrum pricing. Several striking findings emerge.

First, for all but three countries (Malawi, Uganda and Senegal), the same technology is always the least cost, irrespective of the demand scenario or the adoption of different policies to reduce costs. This suggests that underlying country characteristics, such as economic geography and the existing legacy infrastructure, are critical determinants of technology choice. For example, economic geography affects the density of users, which influences whether 4G is a sufficient technology, or if the greater efficiency of 5G is required (even though more sites may need 5G upgrades). The existing legacy infrastructure affects (i) the quantity of required sites which need upgrading or building, and (ii) the prevailing fiber optic density. Only in the case of Malawi, Uganda and Senegal, does the attractiveness of a specific technology choice generally depend on higher levels of capacity demanded per user.

Second, of the four different technological options considered in the modeling, only two ever emerge as least cost for the developing countries considered. These are either 4G (W) (identified in blue font in Table 5) or 5G NSA (identified in black font in Table 5). Notably, both technological options rely on a wireless backhaul, with the use of fiber optic to reach universal broadband never being more cost-effective. In fact, the choice of fiber versus wireless backhaul, turns out to be a larger cost-driver than the choice of 5G over 4G. The findings also illustrate that 5G SA never proves to be a cost-effective technology for meeting universal broadband in any of the country clusters.

Third, while 5G is more cost efficient (per bit of data transferred) than previous generations of technology, the real choice faced by policy makers is between completing a partial 4G deployment or beginning on an entirely new 5G deployment, in order to achieve universal broadband. Hence, the existing level of 4G deployment has a large impact on technology choice (see Table 5). This is the reason why it is cheaper overall to complete 4G deployment in countries like Albania, Peru, and Mexico, where 4G coverage is already relatively high (85–95%). Whereas in countries like Kenya and Pakistan, where current 4G coverage is much lower (30–65%), it is more attractive to deploy 5G NSA to achieve universal broadband. However, the key caveat is whether users would have 5G smartphones in order to access 5G broadband services, as this would not be possible using legacy (e.g. 4G) devices.

4.3. Impact of infrastructure sharing

As discussed, policy makers can significantly influence the cost of reaching universal broadband by creating a regulatory environment that supports different degrees of infrastructure sharing. This ranges from sharing passive infrastructure (e.g. site compounds, towers etc.), to active electronics, through to promoting a single Shared Rural Network in areas where provision of multiple infrastructures would not be viable. For brevity, the financial costs of these different forms of infrastructure sharing are reported in Table 6, for the illustrative case of 5G NSA. Complete results for all technologies are available in the Supplementary Materials Section 3 and give broadly similar results.

The extent of infrastructure sharing is inversely related to the financial cost of reaching universal access (Table 5). The savings provided by passive infrastructure sharing are not insignificant at 12–18% but are dwarfed by much higher savings of around 56–66% available through active infrastructure sharing, and 42–57% that result from adopting a Shared Rural Network. In general, the magnitude of the savings increases with the level of capacity demanded (S1-S3), but only by a few percentage points.

However, there are important caveats. Historically, competition among MNOs has led to falling costs and facilitated rapid market expansion, at least in viable areas. While infrastructure sharing may provide substantial cost savings, by removing competitive pressures between MNOs, these savings could be eroded over time due to mounting inefficiency. Going forward, a balancing act is needed, focusing on blended strategies, which preserve market dynamics in urban and suburban areas (where networks are often capacity-constrained), but promote infrastructure sharing in rural and remote locations (where networks are often coverage-constrained). In extreme situations, where no more than a single network provider is commercially viable, competition may cease to be feasible altogether, and an approach such as the Shared Rural Network may be appropriate. This is where the benefits of static versus dynamic efficiency in telecom markets are an essential consideration for government decisions. There is also the need to be cognizant of the practicalities for how different degrees of sharing might actually take place, as each option would involve specific market governance arrangements which network operators would either need to willingly embrace or be forced to accept through regulation.

Table 6
Financial cost results for infrastructure sharing for 5G NSA (W) technology (NPV 2020–2030).

Infrastructure Sharing Results by Country

			C1		C2		C3	C4	C5	C6
Scenario	Strategy	Metric	Malawi	Uganda	Senegal	Kenya	Pakistan	Albania	Peru	Mexico
S1 (<25 Mbps)	Baseline	Financial Cost ($Bn)	1.6	1.5	0.98	3.5	13	0.19	8.2	40
S1 (<25 Mbps)	Passive	Financial Cost ($Bn)	1.4	1.4	0.84	3.1	10	0.18	7.1	35
S1 (<25 Mbps)	Active	Financial Cost ($Bn)	0.81	0.83	0.43	1.4	3.8	0.11	2.5	18
S1 (<25 Mbps)	SRN	Financial Cost ($Bn)	0.52	0.71	0.46	1.7	8	0.064	2.8	17
S2 (<200 Mbps)	Baseline	Financial Cost ($Bn)	2.4	3.6	1.9	5.9	67	0.25	11	57
S2 (<200 Mbps)	Passive	Financial Cost ($Bn)	2.1	2.6	1.5	4.9	48	0.22	9.2	48
S2 (<200 Mbps)	Active	Financial Cost ($Bn)	0.99	1.3	0.73	2.2	11	0.13	3.2	23
S2 (<200 Mbps)	SRN	Financial Cost ($Bn)	0.9	2	1.3	3.8	54	0.083	5.3	33
S3 (<400 Mbps)	Baseline	Financial Cost ($Bn)	3.3	4.9	2.2	7.8	100	0.32	14	64
S3 (<400 Mbps)	Passive	Financial Cost ($Bn)	2.8	3.7	1.8	6.2	76	0.29	12	53
S3 (<400 Mbps)	Active	Financial Cost ($Bn)	1.2	1.5	0.83	2.7	15	0.16	4	26
S3 (<400 Mbps)	SRN	Financial Cost ($Bn)	1.6	2.6	1.4	4.9	86	0.11	7.6	39

[1] Technology Strategy: 5G NSA with Wireless Backhaul.
[2] Spectrum Pricing Strategy: Baseline.
[3] Taxation Strategy: Baseline.
[4] Results rounded to 2 s.f.

4.4. Impact of spectrum pricing

Spectrum pricing carries significant weight in the cost structure for broadband infrastructure, ranging from 2 to 33 percent of the total industry cost across countries (Fig. 5). Policy makers' decisions about how aggressively to price spectrum resources, thus materially affects the cost of reaching universal broadband. To explore the sensitivity of costs to the lowering or raising of spectrum prices relative to baseline levels, Table 7 reports the private, government and financial costs for S2 based on 5G NSA technology strategy. Complete results for all technologies and capacity levels are available in the Supplementary Materials Section 3 and give broadly similar results.

From a private sector standpoint, the difference between low and high spectrum cost scenarios can increase the costs of deploying broadband infrastructure by approximately between 5 and 30% in most countries. This factor is much higher for the case of Albania where the impact on the private cost is over 60%, reflecting particularly high baseline levels of spectrum pricing in the country.

From a government standpoint, the countries divide into two groups. In a first group of countries (comprising Albania, Kenya, Mexico, Peru and Senegal), universal broadband is commercially viable without recourse to government subsidy. This makes the broadband sector a net contributor to the public purse through fiscal flows, so that the higher level of spectrum prices dramatically increases government revenues from the sector by as much as approximately 200–400%. In a second group of countries (comprising Malawi, Pakistan and Uganda), universal broadband is not commercially viable based on user cross-subsidization alone, requiring some commitment of government subsidy. In Malawi, Pakistan and Uganda, the universal service subsidy requirement entirely offsets the fiscal revenues generated through spectrum pricing and taxation, making broadband infrastructure a net recipient of public funds. In such challenging environments, every dollar gained from spectrum fees translates to a dollar more of required public subsidy, leaving the government's net fiscal position completely unchanged. Thus, any attempts to raise government revenues through spectrum pricing simply generates an off-setting subsidy requirement, with no resulting net impact on government finances.

Nevertheless, it is important to emphasize that any reduction of spectrum pricing would need to be accompanied by a strong regulatory regime to ensure certain objectives are achieved. For example, spectrum pricing regimes need to have coverage obligations attached to avoid private MNOs cashing in on tax breaks via extraction of excess profits from highly viable areas. Achieving total coverage involves user cross-subsidization from profitable (predominantly urban) areas to (predominantly rural and remote) locations that are not commercially viable to cover, requiring incentivization via regulatory instruments such as coverage obligations.

4.5. Subsidy requirement

In principle, it is possible to combine the cost reducing measures explored above by simultaneously permitting infrastructure sharing, while keeping spectrum pricing and taxes at relatively low levels. For the illustrative case of 5G NSA (W), the overall impact of adopting the full range of cost minimization measures is to bring costs down by as much as 75% relative to the baseline, with Pakistan being a good example (Table 8a).

In most countries considered, universal access to broadband is commercially viable for 5G NSA technology. However, for countries where this is not the case (such as Malawi, Pakistan and Uganda), such cost minimization measures can make all the difference between universal service being commercially viable or not. For example, in Pakistan in S2 (<~200 Mbps), commercially viable coverage increases from below 10% to 100% when cost minimization measures are adopted (Table 8b), leading to substantial savings in the requirement for government subsidy, which would otherwise have been as high as $4 billion in NPV terms (Table 8c).

4.6. Aggregation to global level

Results have so far been presented at the level of the individual countries selected to represent each of the six country clusters (recall Fig. 1). These country level results can be aggregated to the global level, using the mean cost per capita within each country cluster, and thereby providing an estimate for the cost of reaching universal broadband across all emerging markets. Hence, Table 9 reports the total cost of universal service for each technology across the developing world, contrasting the baseline estimate with a lowest cost scenario where full infrastructure sharing is permitted, while spectrum prices and taxation are kept at their lowest level. The results are reported both in absolute

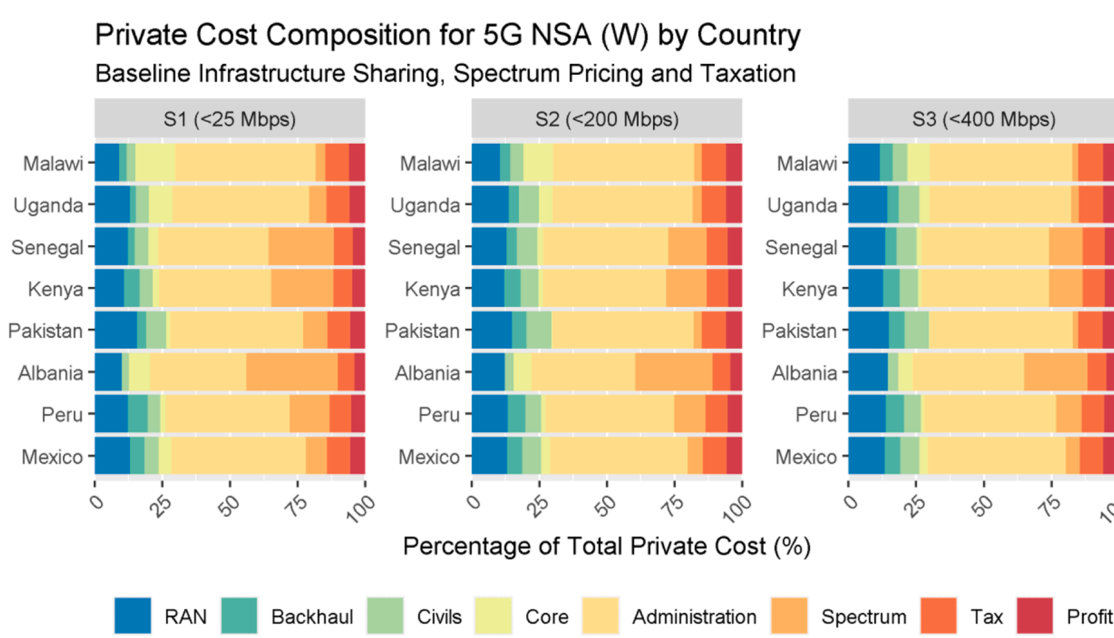

Fig. 5. Breakdown of private costs.

Table 7
Breakdown of financial cost results for spectrum pricing based on 5G NSA (W) and S2.

Spectrum Pricing Results by Country

		C1		C2		C3	C4	C5	C6
Strategy	Metric	Malawi	Uganda	Senegal	Kenya	Pakistan	Albania	Peru	Mexico
Low Prices (-75%)	Private Cost ($Bn)	1.8	3.2	2.1	6.8	45	0.3	13	64
High Prices (+100%)	Private Cost ($Bn)	1.9	3.4	2.7	8.8	48	0.5	15	70
Low-High Ratio (%)	Private Cost ($Bn)	6	6	29	29	7	63	15	9
Low Prices (-75%)	Govt Cost ($Bn)	0.59	0.29	-0.28	-0.89	21	-0.1	-1.5	-6.8
High Prices (+100%)	Govt Cost ($Bn)	0.59	0.29	-0.87	-2.9	21	-0.2	-4.3	-13
Low-High Ratio (%)	Govt Cost ($Bn)	0	0	211	226	0	362	187	91
Low Prices (-75%)	Financial Cost ($Bn)	2.4	3.5	1.9	5.9	66	0.2	11	57
High Prices (+100%)	Financial Cost ($Bn)	2.5	3.7	1.9	5.9	69	0.2	11	57
Low-High Ratio (%)	Financial Cost ($Bn)	4	6	0	0	5	0	0	0

[1] Scenario: S2 (<200 Mbps).
[2] Technology Strategy: 5G NSA with Wireless Backhaul.
[3] Infrastructure Sharing Strategy: Baseline.
[4] Taxation Strategy: Baseline.

dollar terms for the NPV over the period 2020–2030, as well as on an annualized basis as a share of GDP over the same period.

The first point to note is the dramatic impact of combining cost reduction measures. Across all possible technologies and scenarios for capacity demanded per user, the impact of these policy measures is to reduce the cost of providing universal broadband by up to three quarters in some circumstances. Focusing on the 5G NSA (W) technology option, which is lowest cost for most countries, the NPV cost of meeting universal broadband ranges between $1.1–2 trillion depending on the capacity level (S1 versus S3) but drops to the range $0.42–1.2 trillion when the full range of cost minimization measures are introduced. In GDP terms, the same costs translate into 0.35–0.67% of annual GDP for the baseline scenario, and 0.14–0.41% of annual GDP for the minimum cost scenario. Indeed, once cost minimization measures are adopted, even 5G SA can be deployed for 0.2–1.1% of annual GDP in the most ambitious scenario, which would otherwise absorb 0.67–1.7% of annual GDP.

Given the widely varying economic circumstances across the developing world, it is important to examine how the economic burden of reaching universal broadband varies across country income groupings (see Table 10). Generally, the annualized GDP share required to reach universal service is inversely related to country income level. Thus, the financial cost of universal broadband as a percentage of GDP is much higher in low-income countries (approximately 1–2.1%), compared to upper-middle income countries (0.34–0.53%) (for 5G NSA using wireless backhaul), with Fig. 6 providing a graphical example on a country-by-country level. Considering that aggregate spending on all aspects of infrastructure in developing countries – including transport, energy and water as well as public investment in telecommunications – has recently been estimated at around 3% of GDP outside of China (Fay et al., 2019), such figures look implausibly large. However, costs can be reduced considerably if a combination of lowest cost strategies is implemented. For example, for the high-capacity scenario (S3) favored by the UN Broadband Commission, the financial cost of a 5G NSA (W) approach based on full adoption of cost minimization measures can be reduced to 1.3%, 0.89% and 0.29% of GDP for low, lower-middle, and upper-middle income countries respectively. Such figures start to look somewhat more affordable within the overall spending envelope on infrastructure.

5. Discussion and conclusions

In this analysis, a comprehensive scenario-based simulation model was adopted to quantify the deployment of broadband infrastructure in 8 developing countries across 6 different country clusters. The results were then aggregated across all LMICs to provide insight into the financial costs of meeting universal broadband, and how these are affected by government policy choices regarding preferred technology, the extent of infrastructure sharing, and the level of spectrum pricing and taxation. The aim of this activity was to produce analytics which help answer the following research question:

5.1. Is universal broadband both (commercially) viable and (financially) affordable in the developing world?

In terms of the performance of different strategies, the baseline financial cost of universal broadband for all developing countries over the next decade ranged from $0.62 trillion for 4G to $1.1 trillion using 5G NSA (10-Year GDP shares of 0.21% and 0.35% respectively). This is based on meeting minimum capacity requirements for urban (~25 Mbps), suburban (~10 Mbps) and rural (~2 Mbps) users. The cost of meeting the UN Broadband Commission target is estimated at approximately $2 trillion using 4G and 5G NSA, equating to approximately 0.68% and 0.67% of annual GDP respectively for the developing world over the next decade. This is based on meeting minimum capacity requirements for urban (~400 Mbps), suburban (~100 Mbps) and rural (~10 Mbps) users, representing the NPV of the financial cost for building and operating the network over the next decade. However, the key caveat for any 5G strategy will be whether all users have 5G smartphones, as legacy (e.g. 4G) devices will be unable to access the new 5G network. Due to differences in consumer spending power, rural adoption often lags urban adoption, meaning it is not straightforward to deploy a 5G network without the risk of leaving legacy users behind (motivating the need for handset subsidies).

Governments should carefully consider the choice between 4G or 5G NSA technology as the basis for their universal broadband strategies. The study finds that 5G NSA, can be a competitive technology choice in many developing countries relative to 4G when higher capacity per user is required, thanks to added spectral efficiency, leading to a reduction in the number of required sites. This is the case in countries where 4G networks remain incomplete, reaching no more than 50–60% of the population (such as Kenya, Pakistan, and Senegal). On the other hand, in countries that have already made significant progress in extending 4G coverage to 80–90% of the population (such as Albania, Mexico, Peru), it proves more cost-effective to reach universal access by completing the

Table 8
Impact of Cost Minimization on Cost, Viability and Subsidy Requirement.

(A) Financial Cost of Universal Access NPV 2020-2030 by Country

		C1		C2		C3	C4	C5	C6
Scenario	Strategy	Malawi	Uganda	Senegal	Kenya	Pakistan	Albania	Peru	Mexico
S1 (<25 Mbps)	Baseline ($Bn)	1.6	1.5	1	3.5	12.9	0.2	8.2	40.3
S1 (<25 Mbps)	Lowest ($Bn)	0.5	0.7	0.4	1.4	3.8	0.1	2.5	16.9
S2 (<200 Mbps)	Baseline ($Bn)	2.4	3.6	1.9	5.9	67.5	0.2	11	57
S2 (<200 Mbps)	Lowest ($Bn)	0.9	1.3	0.7	2.2	10.7	0.1	3.2	23.4
S3 (<400 Mbps)	Baseline ($Bn)	3.3	4.9	2.2	7.8	103.1	0.3	13.9	63.6
S3 (<400 Mbps)	Lowest ($Bn)	1.2	1.5	0.8	2.7	14.9	0.1	4	25.6

[1] Technology Strategy: 5G NSA with Wireless Backhaul.
[2] Infrastructure Sharing Strategy: Baseline.
[3] Taxation Strategy: Baseline.
[4] Results rounded to 1 d.p.

(B) Commercially Viable Population Coverage by Country

		C1		C2		C3	C4	C5	C6
Scenario	Strategy	Malawi	Uganda	Senegal	Kenya	Pakistan	Albania	Peru	Mexico
S1 (<25 Mbps)	Baseline (%)	80	100	100	100	100	100	100	100
S1 (<25 Mbps)	Lowest (%)	100	100	100	100	100	100	100	100
S2 (<200 Mbps)	Baseline (%)	40	70	100	100	0	100	100	100
S2 (<200 Mbps)	Lowest (%)	100	100	100	100	100	100	100	100
S3 (<400 Mbps)	Baseline (%)	10	30	100	90	0	100	100	100
S3 (<400 Mbps)	Lowest (%)	80	100	100	100	100	100	100	100

[1] Technology Strategy: 5G NSA with Wireless Backhaul.
[2] Infrastructure Sharing Strategy: Baseline.
[3] Taxation Strategy: Baseline.
[4] Results rounded to 1 d.p.

(C) Government Subsidy to Reach Universal Access NPV 2020-2030 by Country

		C1		C2		C3	C4	C5	C6
Scenario	Strategy	Malawi	Uganda	Senegal	Kenya	Pakistan	Albania	Peru	Mexico
S1 (<25 Mbps)	Baseline ($Bn)	0.04	0	0	0	0	0	0	0
S1 (<25 Mbps)	Lowest ($Bn)	0	0	0	0	0	0	0	0
S2 (<200 Mbps)	Baseline ($Bn)	0.12	0.22	0	0	3.74	0	0	0
S2 (<200 Mbps)	Lowest ($Bn)	0	0	0	0	0	0	0	0
S3 (<400 Mbps)	Baseline ($Bn)	0.21	0.41	0	0.11	6.46	0	0	0
S3 (<400 Mbps)	Lowest ($Bn)	0.02	0	0	0	0	0	0	0

[1] Technology Strategy: 5G NSA with Wireless Backhaul.
[2] Infrastructure Sharing Strategy: Baseline.
[3] Taxation Strategy: Baseline.
[4] Results rounded to 1 d.p.

Table 9
Total costs for all technologies across the developing world.

Technology Cost Results for the Developing World

Scenario	Strategy	Total Cost Baseline (US$Tn)	Total Cost Lowest (US$Tn)	10-Year GDP Share Baseline (GDP%)	10-Year GDP Share Lowest (GDP%)
S1 (<25 Mbps)	4G (W)	0.62	0.27	0.21	0.09
S1 (<25 Mbps)	4G (FB)	1	0.48	0.34	0.16
S1 (<25 Mbps)	5G NSA (W)	1.1	0.42	0.35	0.14
S1 (<25 Mbps)	5G SA (FB)	2	0.59	0.67	0.2
S2 (<200 Mbps)	4G (W)	1.3	0.81	0.43	0.27
S2 (<200 Mbps)	4G (FB)	2.1	1.4	0.71	0.46
S2 (<200 Mbps)	5G NSA (W)	1.7	0.97	0.56	0.32
S2 (<200 Mbps)	5G SA (FB)	3.8	2	1.3	0.66
S3 (<400 Mbps)	4G (W)	2	1.3	0.68	0.44
S3 (<400 Mbps)	4G (FB)	3.1	2	1	0.68
S3 (<400 Mbps)	5G NSA (W)	2	1.2	0.67	0.41
S3 (<400 Mbps)	5G SA (FB)	5.2	3.2	1.7	1.1

[1] Infrastructure Sharing Strategy: Baseline.
[2] Spectrum Pricing Strategy: Baseline.
[3] Taxation Strategy: Baseline.
[4] Results rounded to 2 s.f.

Table 10
Cost as a share of GDP broken down by income group.

Technology Cost Results for the Developing World

Scenario	Strategy	Low Income (10-Year GDP%) Baseline LIC	Low Income (10-Year GDP%) Lowest LIC	Lower Middle Income (10-Year GDP%) Baseline LMIC	Lower Middle Income (10-Year GDP%) Lowest LMIC	Upper Middle Income (10-Year GDP%) Baseline UMIC	Upper Middle Income (10-Year GDP%) Lowest UMIC
S1 (<25 Mbps)	4G (W)	1.1	0.54	0.49	0.3	0.13	0.035
S1 (<25 Mbps)	4G (FB)	2	0.89	0.92	0.57	0.18	0.054
S1 (<25 Mbps)	5G NSA (W)	1	0.42	0.35	0.17	0.34	0.13
S1 (<25 Mbps)	5G SA (FB)	2.4	0.76	0.86	0.22	0.6	0.18
S2 (<200 Mbps)	4G (W)	2.2	1.3	1.2	0.9	0.21	0.11
S2 (<200 Mbps)	4G (FB)	3.4	1.8	2.2	1.6	0.31	0.16
S2 (<200 Mbps)	5G NSA (W)	1.7	0.99	0.88	0.64	0.47	0.24
S2 (<200 Mbps)	5G SA (FB)	3.6	1.8	3	1.9	0.81	0.35
S3 (<400 Mbps)	4G (W)	3.6	2.1	2.2	1.6	0.28	0.15
S3 (<400 Mbps)	4G (FB)	5	2.8	3.5	2.5	0.41	0.22
S3 (<400 Mbps)	5G NSA (W)	2.1	1.3	1.2	0.89	0.53	0.29
S3 (<400 Mbps)	5G SA (FB)	4.5	2.5	5	3.6	0.93	0.45

[1] Infrastructure Sharing Strategy: Baseline.
[2] Spectrum Pricing Strategy: Baseline.
[3] Taxation Strategy: Baseline.
[4] Results rounded to 2 s.f.

deployment of 4G networks. Essentially, what matters is whether a country is mostly capacity-constrained (requiring lots of spectrum and cells to meet large traffic demand) or mostly coverage-constrained (requiring lots of cells to thinly cover very large geographic areas). The findings suggest that 5G deployment (specifically 5G NSA with wireless backhaul) can be more viable in capacity-constrained countries such as Pakistan, in contrast with coverage-constrained countries such as Malawi or Uganda, where 4G is competitive at providing low user capacities. Whether 4G or 5G NSA technology is selected, wireless backhaul proves to be much lower cost than reliance on fiber optic to reach rural and remote areas. However, this does not contradict the essential importance of fiber backhaul to support both 4G and 5G technologies (as well as future generations) in high demand areas.

The viability and affordability aspects of the UN universal broadband

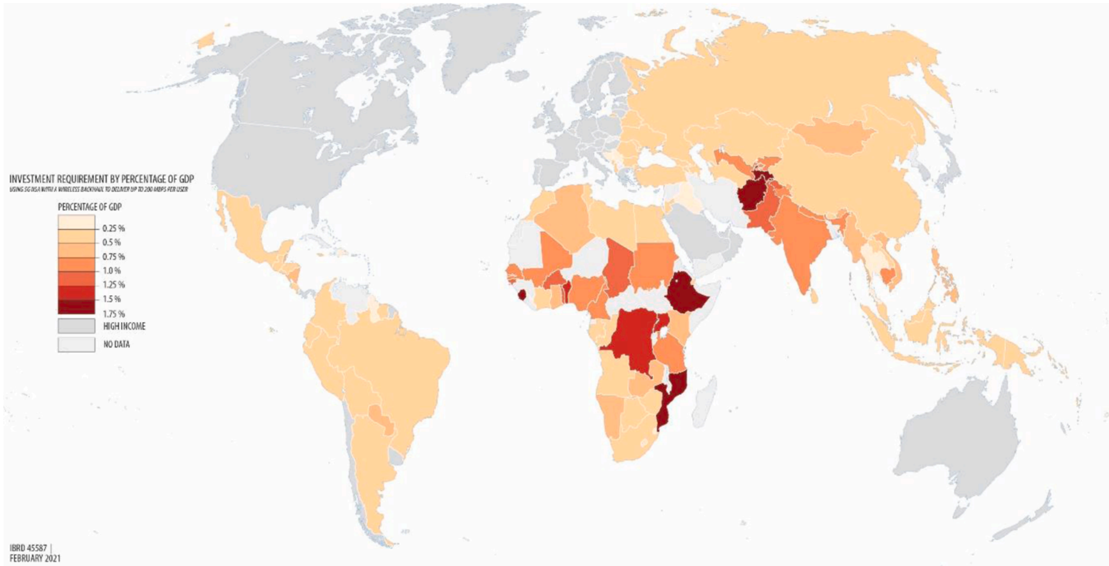

Fig. 6. Example country by country investment for 5G NSA (Wireless) for S2 (<200 Mbps).

goal will now be considered. Government policy choices can dramatically reduce the cost of reaching universal broadband, and thereby improve commercial viability, avoiding (or at least reducing) the need for public subsidy. Across the two most plausible technological choices, 4G (W) and 5G NSA, the creation of a regulatory environment supportive of infrastructure sharing is predicted to reduce the financial cost of reaching universal broadband by approximately 10–70%, with a Shared Rural Network providing the single largest cost reduction. If, at the same time, spectrum pricing is kept at about half of historic levels, overall savings relative to the baseline costs reported above could be further reduced by up to 75% of the required investment. While raising spectrum revenue can be alluring for governments, the results demonstrate how this increases the financial cost of universal broadband. Moreover, in less developed contexts, where universal service may not be commercially viable and government subsidy is required to close the viability gap, raising spectrum pricing is found to have no net impact on government revenues as it simply translates, dollar for dollar, into a larger subsidy requirement for the sector.

Future research should seek to apply the model to understand how many MNOs can viably be supported in different locations, ensuring competition benefits can be maximized. This trade-off between static versus dynamic efficiency in telecom markets has been an ongoing area of debate for previous generations of cellular technologies, but with the development, standardization, and deployment of 5G, this topic warrants further investigation. Such enquiry should focus on the division between infrastructure-based and service-based competition in the provision of broadband services, recognizing that many of the 3 billion hitherto unconnected broadband users reside in areas with struggling economic viability. Given falling ARPU in telecom markets across the globe, infrastructure consolidation is becoming a more likely option, but competition economists are duly cautious about any potentially negative ramifications for dynamic market efficiency. At least with the method developed and applied within this paper, it will be easier for policy analysts to identifying those places where a single network cannot be viably supported in any circumstance, with these being prime locations to explore implementing more radical options such as a Shared Rural Network. Future research, which was beyond the scope of this analysis, should focus on how supply-side agents may respond to changes in relative prices depending on heterogenous market structures.

Credit authorship contribution statement

Edward J. Oughton: Conceptualization, Methodology, Software, Visualization, Writing – original draft. **Niccol`o Comini:** Conceptualization, Methodology, Data curation. **Vivien Foster:** Conceptualization, Methodology, Writing – original draft. **Jim W. Hall:** Conceptualization, Methodology, Writing – review & editing.

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Supplementary materials

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References

3GPP, 2019. Specification # 21.915, Release 15. 3rd Generation Partnership Project. Valbonne, France.
5G. NORMA, 2016. Deliverable D2.1: use cases, scenarios and requirements. 5G PPP.
Afraz, N., Slyne, F., Gill, H., Ruffini, M., 2019. evolution of access network sharing and its role in 5G networks. Appl. Sci. 9, 4566. https://doi.org/10.3390/app9214566.
Ahmad, W., Ahmed, T., Ahmad, B., 2019. Pricing of mobile phone attributes at the retail level in a developing country: hedonic analysis. Telecomm Policy 43, 299–309. https://doi.org/10.1016/j.telpol.2018.10.002.
Asongu, S.A., Nwachukwu, J.C., 2016. The mobile phone in the diffusion of knowledge for institutional quality in Sub-Saharan Africa. World Dev. 86, 133–147. https://doi.org/10.1016/j.worlddev.2016.05.012.
Avilés, J.M., 2020. A tale of two reforms: telecommunications reforms in Mexico. Telecomm Policy 44, 101942. https://doi.org/10.1016/j.telpol.2020.101942.

Bahia, K., Castells, P., 2019. The impact of spectrum prices on consumers (SSRN Scholarly Paper No. ID 3427173). Soc. Sci. Res. Netw. https://doi.org/10.2139/ssrn.3427173.
Bali Swain, R., Ranganathan, S., 2021. Modeling interlinkages between sustainable development goals using network analysis. World Dev. 138, 105136 https://doi.org/10.1016/j.worlddev.2020.105136.
Batista, C., Vicente, P.C., 2020. Improving access to savings through mobile money: experimental evidence from African smallholder farmers. World Dev. 129, 104905 https://doi.org/10.1016/j.worlddev.2020.104905.
Benseny, J., Töyli, J., Hämmäinen, H., Arcia-Moret, A., 2019. The mitigating role of regulation on the concentric patterns of broadband diffusion. The case of Finland. Telematics Inform. https://doi.org/10.1016/j.tele.2019.04.008.
Bertschek, I., Niebel, T., 2016. Mobile and more productive? Firm-level evidence on the productivity effects of mobile internet use. Telecomm Policy 40, 888–898. https://doi.org/10.1016/j.telpol.2016.05.007.
Björkegren, D., 2019a. The adoption of network goods: evidence from the spread of mobile phones in Rwanda. Rev. Econ. Stud. 86, 1033–1060. https://doi.org/10.1093/restud/rdy024.
Björkegren, D., 2019b. Competition in network Industries: evidence from the Rwandan mobile phone network (SSRN Scholarly Paper No. ID 3527028). Soc. Sci. Res. Netw. https://doi.org/10.2139/ssrn.3527028. Rochester, NY.
Boik, A., Greenstein, S., Prince, J., 2019. The persistence of broadband user behavior: implications for universal service and competition policy. Telecomm Policy 43, 101820. https://doi.org/10.1016/j.telpol.2019.04.004.
Bourreau, M., Feasey, R., Nicolle, A., 2020. Assessing fifteen years of State Aid for broadband in the European Union: a quantitative analysis. Telecomm Policy 44, 101974. https://doi.org/10.1016/j.telpol.2020.101974.
Briglauer, W., Gugler, K., 2019. Go for gigabit? First evidence on economic benefits of high-speed broadband technologies in Europe. JCMS J. Common Mark. Stud. 57, 1071–1090. https://doi.org/10.1111/jcms.12872.
Cave, M., 2018. How disruptive is 5G? Telecommunications Policy, The implications of 5G networks: paving the way for mobile innovation? 42, 653–658. 10.1016/j.telpol.2018.05.005.
Cave, M., 2017. 40 years on: an account of innovation in the regulation of UK telecommunications, in 3½ chapters. Telecommun. Policy 41, 904–915. https://doi.org/10.1016/j.telpol.2016.10.006. Celebrating 40 Years of Telecommunications Policy – A Retrospective and Prospective View.
Cave, M., 2006. Encouraging infrastructure competition via the ladder of investment. Telecomm Policy 30, 223–237. https://doi.org/10.1016/j.telpol.2005.09.001.
Cave, M., Genakos, C., Valletti, T., 2019. The European framework for regulating telecommunications: a 25-year appraisal. Rev. Ind. Organ. 55, 47–62. https://doi.org/10.1007/s11151-019-09686-6.
Cave, M., Nicholls, R., 2017. The use of spectrum auctions to attain multiple objectives: policy implications. Telecommun. Policy Opt. Spectrum Use 41, 367–378. https://doi.org/10.1016/j.telpol.2016.12.010.
Cave, M., Pratt, N., 2016. Taking account of service externalities when spectrum is allocated and assigned. Telecomm Policy.
Cave, M.E., Mariscal, E.V., 2020. The impact of telecommunications regulation on less well-off Mexican households. Telecomm Policy 44, 101907. https://doi.org/10.1016/j.telpol.2019.101907.
Chen, K., Ren, Z., Mu, S., Sun, T.Q., Mu, R., 2020. Integrating the Delphi survey into scenario planning for China's renewable energy development strategy towards 2030. Technol. Forecast Soc. Change 158, 120157. https://doi.org/10.1016/j.techfore.2020.120157.
Collins Bartholomew, 2019. Mobile Coverage Explorer [WWW Document]. CollinsBartholomew. URL. https://www.collinsbartholomew.com/mobile-coverage-maps/mobile-coverage-explorer/ (accessed 5.18.20).
Crawford, M.M., 2019. A comprehensive scenario intervention typology. Technol. Forecast. Soc. Change 149, 119748. https://doi.org/10.1016/j.techfore.2019.119748.
Curien, N., 1991. The theory and measure of cross-subsidies: an application to the telecommunications industry. Int. J. Ind. Organiz. 9, 73–108. https://doi.org/10.1016/0167-7187(91)90006-7.
Czernich, N., Falck, O., Kretschmer, T., Woessmann, L., 2011. Broadband infrastructure and economic growth. Econ. J. 121, 505–532. https://doi.org/10.1111/j.1468-0297.2011.02420.x.
Dasgupta, K., Gibson, T., Williams, M., 2021. Technological and geographic heterogeneity in broadband markets: the challenge for regulation. Telecomm Policy 45, 102042. https://doi.org/10.1016/j.telpol.2020.102042.
De Andrade, M., Tornatore, M., Pattavina, A., Hamidian, A., Grobe, K., 2015. Cost models for BaseBand Unit (BBU) hotelling: from local to cloud. In: Proceedings of the IEEE 4th International Conference on Cloud Networking (CloudNet). Presented at the 2015 IEEE 4th International Conference on Cloud Networking (CloudNet), pp. 201–204. https://doi.org/10.1109/CloudNet.2015.7335306.
Elbahnasawy, N.G., 2014. E-Government, Internet Adoption, and Corruption: an Empirical Investigation. World Dev. 57, 114–126. https://doi.org/10.1016/j.worlddev.2013.12.005.
Fay, M., Han, S., Lee, H.I., Mastruzzi, M., Cho, M., 2019. Hitting the Trillion Mark: a Look at How Much Countries Are Spending on Infrastructure. Policy Research Working Papers World Bank. https://doi.org/10.1596/1813-9450-8730.
Forge, S., Vu, K., 2020. Forming a 5G strategy for developing countries: a note for policy makers. Telecomm Policy 44, 101975. https://doi.org/10.1016/j.telpol.2020.101975.
Frias, Z., Pérez, J., 2012. Techno-economic analysis of femtocell deployment in long-term evolution networks. J. Wireless Com. Netw. 288 https://doi.org/10.1186/1687-1499-2012-288, 2012.
Frith, D., Tapinos, E., 2020. Scenario planning: is the 'box' black or clear? It depends. Technol. Forecast. Soc. Change 158, 120170. https://doi.org/10.1016/j.techfore.2020.120170.
Gallardo, R., Whitacre, B., Kumar, I., Upendram, S., 2020. Broadband metrics and job productivity: a look at county-level data. Ann. Reg. Sci. https://doi.org/10.1007/s00168-020-01015-0.
Gerli, P., Van der Wee, M., Verbrugge, S., Whalley, J., 2018. The involvement of utilities in the development of broadband infrastructure: a comparison of EU case studies. Telecommun. Policy Broadband Policy Evaluat. 42, 726–743. https://doi.org/10.1016/j.telpol.2018.03.001.
Glass, V., Tardiff, T., 2021. Reforming funding of universal access to telecommunications and broadband services: approaches for the new decade. Telecomm Policy 45, 102037. https://doi.org/10.1016/j.telpol.2020.102037.
Gnangnon, S.K., Iyer, H., 2018. Does bridging the Internet Access Divide contribute to enhancing countries' integration into the global trade in services markets? Telecomm Policy 42, 61–77. https://doi.org/10.1016/j.telpol.2017.08.004.
Goetzendorff, A., Bichler, M., Goeree, J.K., 2018. Synergistic valuations and efficiency in spectrum auctions. Telecomm Policy 42, 91–105. https://doi.org/10.1016/j.telpol.2017.08.006.
Gomez, M., Weiss, M., Krishnamurthy, P., 2019. Improving liquidity in secondary spectrum markets: virtualizing spectrum for fungibility. IEEE Trans. Cogn. Commun. Netw. 5, 252–266. https://doi.org/10.1109/TCCN.2019.2901787.
Gordon, A.V., 2020. Limits and longevity: a model for scenarios that influence the future. Technol. Forecast. Soc. Change 151, 119851. https://doi.org/10.1016/j.techfore.2019.119851.
Grajek, M., Gugler, K., Kretschmer, T., Mişçişin, I., 2019. Static or dynamic efficiency: horizontal merger effects in the wireless telecommunications industry. Rev. Ind. Organ. 55, 375–402. https://doi.org/10.1007/s11151-019-09723-4.
Gruber, H., 2005. The Economics of Mobile Telecommunications. Cambridge University Press.
GSMA, 2020. GSMA intelligence global data [WWW document]. URL https://www.gsmaintelligence.com /(accessed 2.5.20).
GSMA, 2019. The 5G Guide: A Reference for Operators. GSMA, London.
Hackl, A., 2018. Mobility equity in a globalized world: reducing inequalities in the sustainable development agenda. World Dev. 112, 150–162. https://doi.org/10.1016/j.worlddev.2018.08.005.
Haenssgen, M.J., Ariana, P., 2017. The social implications of technology diffusion: uncovering the unintended consequences of people's health-related mobile phone use in rural India and China. World Dev. 94, 286–304. https://doi.org/10.1016/j.worlddev.2017.01.014.
Haenssgen, M.J., Charoenboon, N., Zanello, G., 2021. You've got a friend in me: how social networks and mobile phones facilitate healthcare access among marginalised groups in rural Thailand and Lao PDR. World Dev. 137, 105156 https://doi.org/10.1016/j.worlddev.2020.105156.
Hameed, A., Mian, A.N., Qadir, J., 2018. Low-cost sustainable wireless Internet service for rural areas. Wireless Netw. 24, 1439–1450. https://doi.org/10.1007/s11276-016-1415-8.
Hartigan, J.A., Wong, M.A., 1979. Algorithm AS 136: a k-means clustering algorithm. J. R. Stat. Soc. Ser. C (Appl. Stat.) 28, 100–108.
Hasbi, M., Dubus, A., 2020. Determinants of mobile broadband use in developing economies: evidence from Sub-Saharan Africa. Telecomm Policy 44, 101944. https://doi.org/10.1016/j.telpol.2020.101944.
Hilbert, M., 2010. When is cheap, cheap enough to bridge the digital divide? Modeling income related structural challenges of technology diffusion in Latin America. World Dev. 38, 756–770. https://doi.org/10.1016/j.worlddev.2009.11.019.
Hjort, J., Poulsen, J., 2019. The arrival of fast internet and employment in Africa. Am. Econ. Rev. 109, 1032–1079. https://doi.org/10.1257/aer.20161385.
Hothorn, T., Everitt, B.S., 2014. A Handbook of Statistical Analyses Using R. Chapman and Hall/CRC.
Hou, J., Sun, L., Shu, T., Xiao, Y., Krunzz, M., 2019. Strategic network infrastructure sharing through backup reservation in a competitive environment. In: Proceedings of the 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON), pp. 1–9. https://doi.org/10.1109/SAHCN.2019.8824849. Presented at the 2019 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON).
Hutajulu, S., Dhewanto, W., Prasetio, E.A., 2020. Two scenarios for 5G deployment in Indonesia. Technol. Forecast. Soc. Change 160, 120221. https://doi.org/10.1016/j.techfore.2020.120221.
Ignacio, P.E., Joel, A.V., Olga, M.M., Cesar, C.B., Javier, S.R., Darwin, A.Q., Alejandro, B.F., Andrés, M.F., 2020. Small rural operators techno-economic analysis to bring mobile services to isolated communities: the case of Peru Amazon rainforest. Telecomm Policy 44, 102039. https://doi.org/10.1016/j.telpol.2020.102039.
Ioannou, N., Katsianis, D., Varoutas, D., 2020. Comparative techno-economic evaluation of LTE fixed wireless access, FTTdp G.fast and FTTC VDSL network deployment for providing 30 Mbps broadband services in rural areas. Telecomm Policy 44, 101875. https://doi.org/10.1016/j.telpol.2019.101875.
Jefferson, M., 2020. Scenario planning: evidence to counter 'Black box' claims. Technol. Forecast. Soc. Change 158, 120156. https://doi.org/10.1016/j.techfore.2020.120156.
Jeon, C., Han, S.H., Kim, H.J., Kim, S., 2020. The effect of government 5G policies on telecommunication operators' firm value: evidence from China. Telecomm Policy 102040. https://doi.org/10.1016/j.telpol.2020.102040.
Johansson, K., Furuskar, A., Karlsson, P., Zander, J., 2004. Relation between base station characteristics and cost structure in cellular systems. In: Proceedings of the 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Vol.4, pp. 2627–2631. https://doi.org/10.1109/

PIMRC.2004.1368795, 2004. PIMRC 2004. Presented at the 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2004. PIMRC 2004.
Jung, J., López-Bazo, E., 2020. On the regional impact of broadband on productivity: the case of Brazil. Telecomm Policy 44, 101826. https://doi.org/10.1016/j.telpol.2019.05.002.
Kanyam, D.A., Kostandini, G., Ferreira, S., 2017. The mobile phone revolution: have mobile phones and the internet reduced corruption in Sub-Saharan Africa? World Dev. 99, 271–284. https://doi.org/10.1016/j.worlddev.2017.05.022.
Kayser, V., Shala, E., 2020. Scenario development using web mining for outlining technology futures. Technol. Forecast. Soc. Change 156, 120086. https://doi.org/10.1016/j.techfore.2020.120086.
Kenny, R., Kenny, C., 2011. Superfast broadband: is it really worth a subsidy? Info : the Journal of Policy. Regulat. Strategy Telecommun. Inform. Med. 13, 3–29. https://doi.org/10.1108/14636691111146127.
Kishita, Y., Mizuno, Y., Fukushige, S., Umeda, Y., 2020. Scenario structuring methodology for computer-aided scenario design: an application to envisioning sustainable futures. Technol. Forecast. Soc. Change 160, 120207. https://doi.org/10.1016/j.techfore.2020.120207.
Koutroumpis, P., 2019. The economic impact of broadband: evidence from OECD countries. Technol. Forecast. Soc. Change 148, 119719. https://doi.org/10.1016/j.techfore.2019.119719.
Koutroumpis, P., 2009. The economic impact of broadband on growth: a simultaneous approach. Telecomm Policy 33, 471–485. https://doi.org/10.1016/j.telpol.2009.07.004.
Koutroumpis, P., Castells, P., Bahia, K., 2021. To share or not to share? The impact of mobile network sharing for consumers and operators. Oxford Martin Work. Pap. Ser. Econ. Technol. Change. Working Paper No. 2021-9.
Lee, H., Jeong, S., Lee, K., 2021. Estimating the deployment costs of broadband universal service via fiber networks in Korea. Telecomm Policy 45, 102105. https://doi.org/10.1016/j.telpol.2021.102105.
Lehr, W., 2020. Economics of spectrum sharing, valuation, and secondary markets. Spectrum Sharing. John Wiley & Sons, Ltd, pp. 361–388. https://doi.org/10.1002/9781119551539.ch18.
Liu, C., Wang, L., 2021. Who is left behind? Exploring the characteristics of China's broadband non-adopting families. Telecomm Policy 45, 102187. https://doi.org/10.1016/j.telpol.2021.102187.
Lobo, B.J., Alam, M.R., Whitacre, B.E., 2020. Broadband speed and unemployment rates: data and measurement issues. Telecomm Policy 44, 101829. https://doi.org/10.1016/j.telpol.2019.101829.
Macher, J.T., Mayo, J.W., Ukhaneva, O., Woroch, G.A., 2017. From universal service to universal connectivity. J. Regul. Econ. 52, 77–104. https://doi.org/10.1007/s11149-017-9336-8.
Maksymyuk, T., Gazda, J., Han, L., Jo, M., 2019. Blockchain-based intelligent network management for 5G and beyond. In: Proceedings of the 3rd International Conference on Advanced Information and Communications Technologies (AICT), pp. 36–39. https://doi.org/10.1109/AIACT.2019.8847762. Presented at the 2019 3rd International Conference on Advanced Information and Communications Technologies (AICT).
Markendahl, J., Mäkitalo, Ö., 2010. A comparative study of deployment options, capacity and cost structure for macrocellular and femtocell networks. In: Proceedings of the IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops), pp. 145–150. https://doi.org/10.1109/PIMRCW.2010.5670351. Presented at the 2010 IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops).
Matracia, M., Kishk, M., Alouini, .M..-S., 2021. Coverage analysis for uav-assisted cellular networks in rural areas. IEEE Open J. Vehicular Technol. 1. https://doi.org/10.1109/OJVT.2021.3076814. PP–1.
Meadows, M., O'Brien, F.A., 2020. The use of scenarios in developing strategy: an analysis of conversation and video data. Technol. Forecast. Soc. Change 158, 120147. https://doi.org/10.1016/j.techfore.2020.120147.
Meddour, D.-.E., Rasheed, T., Gourhant, Y., 2011. On the role of infrastructure sharing for mobile network operators in emerging markets. Comput. Netw. Recent Adv. Netw. Converg. 55, 1576–1591. https://doi.org/10.1016/j.comnet.2011.01.023.
Medeiros, V., Ribeiro, R.S.M., Amaral, P.V.M.do, 2021. Infrastructure and household poverty in Brazil: a regional approach using multilevel models. World Dev. 137, 105118 https://doi.org/10.1016/j.worlddev.2020.105118.
METIS, 2017. METIS 2020 - Deliverable D1.2 - Quantitative Techno-Economic Feasibility Assessment [WWW Document]. METIS, 2020URL. https://www.metis2020.com (accessed 5.25.20).
Metz, A., Hartley, P., 2020. Scenario development as valuation: opportunities for reflexivity. Technol. Forecast. Soc. Change 155, 120027. https://doi.org/10.1016/j.techfore.2020.120027.
Mir, M., Dangerfield, B., 2013. Propagating a digital divide: diffusion of mobile telecommunication services in Pakistan. Technol. Forecast. Soc. Change 80, 992–1001. https://doi.org/10.1016/j.techfore.2012.08.006.
Montenegro, L.O., Araral, E., 2020. Can competition-enhancing regulation bridge the quality divide in Internet provision? Telecomm Policy 44, 101836. https://doi.org/10.1016/j.telpol.2019.101836.
Moshi, G.C., Mwakatumbula, H.J., 2017. Effects of political stability and sector regulations on investments in African mobile markets. Telecommunications Policy. ICT Develop. Africa Infrastruct. Appl. Policies 41, 651–661. https://doi.org/10.1016/j.telpol.2017.07.005.
Muto, M., Yamano, T., 2009. The impact of mobile phone coverage expansion on market Participation: panel data evidence from Uganda. World Dev. 37, 1887–1896. https://doi.org/10.1016/j.worlddev.2009.05.004.
NERA Economic Consulting, 2017a. Effective Spectrum pricing: Supporting better Quality and More Affordable Mobile Services. NERA, London.
NERA Economic Consulting, 2017b. Effective Spectrum Pricing in Latin America: Policies to Support Better Quality and More Affordable Mobile Services. NERA, London.
Nikolikj, V., Janevski, T., 2014. A Cost Modeling of High-capacity LTE-advanced and IEEE 802.11ac based Heterogeneous Networks, Deployed in the 700MHz, 2.6GHz and 5GHz Bands. In: Proceedings of the Computer Science, Fourth International Conference on Selected Topics in Mobile & Wireless Networking (MoWNet'2014), 40, pp. 49–56. https://doi.org/10.1016/j.procs.2014.10.030.
Ofcom, 2018. Final statement: mobile call termination market review 2018-21 [WWW Document]. Ofcom. URL https://www.ofcom.org.uk/consultations-and-statements/category-1/mobile-call-termination-market-review (accessed 5.25.20).
Oladejo, S.O., Falowo, O.E., 2020. Latency-aware dynamic resource allocation scheme for multi-tier 5g network: a network slicing-multitenancy scenario. IEEE Access 8, 74834–74852. https://doi.org/10.1109/ACCESS.2020.2988710.
Osoro, O.B., Oughton, E.J., 2021. In: A Techno-Economic Framework for Satellite networks Applied to Low Earth Orbit Constellations: Assessing Starlink, OneWeb and Kuiper. IEEE. https://doi.org/10.1109/ACCESS.2021.3119634. Access 1–1.
Oughton, E., 2021. Policy options for digital infrastructure strategies: a simulation model for broadband universal service in Africa. arXiv:2102.03561 [cs, econ, q-fin].
Oughton, E., Lehr, W., 2021. Next-G wireless: learning from 5G techno-economics to inform next generation wireless technologies (SSRN Scholarly Paper No. ID 3898099). Soc. Sci. Res. Netw.. https://doi.org/10.2139/ssrn.3898099. Rochester, NY.
Oughton, E., Tyler, P., Alderson, D., 2015. Who's Superconnected and who's not? Investment in the UK's information and communication technologies (ICT) Infrastructure. Infrastruct. Complexity 2, 6. https://doi.org/10.1186/s40551-015-0006-7.
Oughton, E.J., 2019. Python simulator for integrated modelling of 5G (pysim5G) [WWW Document]. URL https://github.com/edwardoughton/pysim5g (accessed 9.26.19).
Oughton, E.J., Frias, Z., 2018. The cost, coverage and rollout implications of 5G infrastructure in Britain. Telecommun. Policy Implic. 5G Netw. Pav. Way Mob. Innov.? 42, 636–652. https://doi.org/10.1016/j.telpol.2017.07.009.
Oughton, E.J., Frias, Z., 2016. Exploring the cost, Coverage and Rollout Implications of 5G in Britain: A report For the UK's National Infrastructure Commission. Centre for Risk Studies. Cambridge Judge Business School, Cambridge.
Oughton, E.J., Frias, Z., Dohler, M., Whalley, J., Sicker, D., Hall, J.W., Crowcroft, J., Cleevely, D.D., 2018a. The strategic national infrastructure assessment of digital communications. Digit. Policy Regulat. Gov. 20, 197–210. https://doi.org/10.1108/DPRG-02-2018-0004.
Oughton, E.J., Frias, Z., Russell, T., Sicker, D., Cleevely, D.D., 2018b. Towards 5G: scenario-based assessment of the future supply and demand for mobile telecommunications infrastructure. Technol. Forecast. Soc. Change 133, 141–155. https://doi.org/10.1016/j.techfore.2018.03.016.
Oughton, E.J., Frias, Z., van der Gaast, S., van der Berg, R., 2019a. Assessing the capacity, coverage and cost of 5G infrastructure strategies: analysis of the Netherlands. Telematics Inform. 37, 50–69. https://doi.org/10.1016/j.tele.2019.01.003.
Oughton, E.J., Jha, A., 2021. Supportive 5G infrastructure policies are essential for universal 6G: assessment using an open-source techno-economic simulation model utilizing remote sensing. IEEE Access 9, 101924–101945. https://doi.org/10.1109/ACCESS.2021.3097627.
Oughton, E.J., Lehr, W., Katsaros, K., Selinis, I., Bubley, D., Kusuma, J., 2021. Revisiting wireless internet connectivity: 5G vs Wi-Fi 6. Telecomm Policy 45, 102127. https://doi.org/10.1016/j.telpol.2021.102127.
Oughton, E.J., Mathur, J., 2021. Predicting cell phone adoption metrics using machine learning and satellite imagery. Telematics Inform. 62, 101622 https://doi.org/10.1016/j.tele.2021.101622.
Oughton, E.J., Russell, T., 2020. The importance of spatio-temporal infrastructure assessment: evidence for 5G from the Oxford–Cambridge Arc. Comput. Environ. Urban Syst. 83, 101515 https://doi.org/10.1016/j.compenvurbsys.2020.101515.
Ovando, C., 2020. Challenges of the first 5G radio spectrum assignment in Mexico. Strategy Technol. Soc. 9.
Ovando, C., Pérez, J., Moral, A., 2015. In: LTE techno-economic assessment: the case of rural areas in Spain, 39, pp. 269–283. https://doi.org/10.1016/j.telpol.2014.11.004. Telecommunications Policy, New empirical approaches to telecommunications economics: opportunities and challengesMobile phone data and geographic modelling.
Paolini, M., Fili, S., 2012. The economics of small cells and Wi-Fi offload. Senza Fili Consulting Tech. Rep.
Paunov, C., Rollo, V., 2016. Has the internet fostered inclusive innovation in the developing World? World Dev. 78, 587–609. https://doi.org/10.1016/j.worlddev.2015.10.029.
Peha, J.M., 2017. Cellular economies of scale and why disparities in spectrum holdings are detrimental. Telecomm Policy 41, 792–801. https://doi.org/10.1016/j.telpol.2017.06.002.
Prado, T.S., Bauer, J.M., 2021. Improving broadband policy design using market data: a general framework and an application to Brazil. Telecomm Policy 45, 102111. https://doi.org/10.1016/j.telpol.2021.102111.
Preissl, B., Howell, B., 2021. The demand for broadband. Telecomm Policy 102223. https://doi.org/10.1016/j.telpol.2021.102223.
Prieger, J.E., 2013. The broadband digital divide and the economic benefits of mobile broadband for rural areas. Telecomm Policy 37, 483–502. https://doi.org/10.1016/j.telpol.2012.11.003.

Rajabiun, R., Middleton, C., 2014. Rural broadband development in Canada's provinces: an overview of policy approaches. J. Rural Commun. Dev. 8.
Rebato, M., Mezzavilla, M., Rangan, S., Zorzi, M., 2016. Resource sharing in 5G mmWave cellular networks. In: Proceedings of the IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp. 271–276. https://doi.org/10.1109/INFCOMW.2016.7562085. Presented at the 2016 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS).
Reddick, C.G., Enriquez, R., Harris, R.J., Sharma, B., 2020. Determinants of broadband access and affordability: an analysis of a community survey on the digital divide. Cities 106, 102904. https://doi.org/10.1016/j.cities.2020.102904.
Rendon Schneir, J., Ajibulu, A., Konstantinou, K., Bradford, J., Zimmermann, G., Droste, H., Canto, R., 2019. A business case for 5G mobile broadband in a dense urban area. Telecomm Policy. https://doi.org/10.1016/j.telpol.2019.03.002.
Rendón Schneir, J., Whalley, J., Amaral, T.P., Pogorel, G., 2018. The implications of 5G networks: paving the way for mobile innovation? Telecommunications Policy. Implicat. 5G Netw. Pav. way Mob. Innov.? 42, 583–586. https://doi.org/10.1016/j.telpol.2018.06.001.
Research ICT Africa, 2018. After Access surveys. Research ICT Afr. URL https://researchictafrica.net/data/after-access-surveys/ (accessed 6.9.20).
Rhinesmith, C., Reisdorf, B., Bishop, M., 2019. The ability to pay for broadband. Commun. Res. Pract. 5, 121–138. https://doi.org/10.1080/22041451.2019.1601491.
Rosston, G.L., Wallsten, S.J., 2020. Increasing low-income broadband adoption through private incentives. Telecomm Policy 44, 102020. https://doi.org/10.1016/j.telpol.2020.102020.
Samdanis, K., Costa-Perez, X., Sciancalepore, V., 2016. From network sharing to multi-tenancy: the 5G network slice broker. IEEE Commun. Mag. 54, 32–39. https://doi.org/10.1109/MCOM.2016.7514161.
Sanguanpuak, T., Guruacharya, S., Hossain, E., Rajatheva, N., Latva-aho, M., 2018. Infrastructure sharing for mobile network operators: analysis of trade-offs and market. IEEE Trans. Mob. Comput. 17, 2804–2817. https://doi.org/10.1109/TMC.2018.2822291.
Sanguanpuak, T., Niyato, D., Rajatheva, N., Latva-aho, M., 2019. Radio resource sharing and edge caching with latency constraint for local 5G operator: geometric programming meets stackelberg game. IEEE Trans. Mob. Comput. 1–1 https://doi.org/10.1109/TMC.2019.2948630.
Shapiro, R.J., Hassett, K.A., 2012. In: The Employment Effects of Advances in Internet and Wireless Technology: Evaluating the Transitions from 2G to 3G and from 3G to 4G. New Policy Institute and NDN, Washington, DC. ReportAvailable at. http://www. sonecon. com/docs/studies/Wireless_Technology_and_Jobs-Shapiro_Hassett-January_2012. pdf.
Shehata, M., Elbanna, A., Musumeci, F., Tornatore, M., 2017. C-RAN baseband pooling: cost model and multiplexing gain analysis. In: Proceedings of the 19th International Conference on Transparent Optical Networks (ICTON), pp. 1–4. https://doi.org/10.1109/ICTON.2017.8025123. Presented at the 2017 19th International Conference on Transparent Optical Networks (ICTON).
Smail, G., Weijia, J., 2017. Techno-economic analysis and prediction for the deployment of 5G mobile network. In: Proceedings of the 20th Conference on Innovations in Clouds, Internet and Networks (ICIN), pp. 9–16. https://doi.org/10.1109/ICIN.2017.7899243. Presented at the 2017 20th Conference on Innovations in Clouds, Internet and Networks (ICIN).
Souza, M.A.D., Kuribayashi, H.P., Saraiva, P.A., Farias, F.D.S., Vijaykumar, N.L., Francês, C.R.L., Costa, J.C.W.A., 2021. A techno-economic framework for installing broadband networks in rural and remote areas. IEEE Access 9, 58421–58447. https://doi.org/10.1109/ACCESS.2021.3071919.
Speedtest, 2020. Speedtest global index – monthly comparisons of internet speeds from around the world [WWW Document]. Speedtest Glob. Index. URL. https://www.speedtest.net/global-index (accessed 10.4.20).
Strover, S., Riedl, M.J., Dickey, S., 2021. Scoping new policy frameworks for local and community broadband networks. Telecomm Policy 102171. https://doi.org/10.1016/j.telpol.2021.102171.
Sutton, A., 2019. Design and deployment of the EE 5G network. Instit. Telecommun. Profess. J.
Sutton, A., 2018. Base station antenna systems. ITP (Instit. Telecommun. Profess.) J. 12, 35–39.
Tadesse, G., Bahiigwa, G., 2015. Mobile phones and farmers' marketing. Decis. Ethiopia World Develop. 68, 296–307. https://doi.org/10.1016/j.worlddev.2014.12.010.
Tatem, A.J., 2017. WorldPop, open data for spatial demography. Sci. Data 4, 1–4. https://doi.org/10.1038/sdata.2017.4.
Thoung, C., Beaven, R., Zuo, C., Birkin, M., Tyler, P., Crawford-Brown, D., Oughton, E.J., Kelly, S., 2016. Future demand for infrastructure services. The Future of National Infrastructure: A System-Of-Systems Approach. Cambridge University Press, Cambridge.
TowerXchange, 2019a. TowerXchange Europe Dossier 2019. TowerXchange, London.
TowerXchange, 2019b. TowerXchange MENA Dossier 2019. TowerXchange, London.
TowerXchange, 2018a. TowerXchange Asia Dossier 2018. TowerXchange, London.
TowerXchange, 2018b. TowerXchange Africa Dossier 2018. TowerXchange, London.
TowerXchange, 2017. TowerXchange CALA Dossier 2017. TowerXchange, London.
Tranos, E., 2012. The causal effect of the internet infrastructure on the economic development of european city regions. Spat. Econ. Anal. 7, 319–337. https://doi.org/10.1080/17421772.2012.694140.
Vuojala, H., Mustonen, M., Chen, X., Kujanpää, K., Ruuska, P., Höyhtyä, M., Matinmikko-Blue, M., Kalliovaara, J., Talmola, P., Nyström, A.G., 2019. Spectrum access options for vertical network service providers in 5G. Telecommun. Policy, 101903. https://doi.org/10.1016/j.telpol.2019.101903.
WACC Expert, 2020. WACC Expert Calculator [WWW Document]. WACC Exper. URL. http://www.waccexpert.com. /(accessed 11.26.20).
Wallsten, S.J., 2001. An econometric analysis of telecom competition, privatization, and regulation in Africa and Latin America. J. Ind. Econ. 49, 1–19. https://doi.org/10.1111/1467-6451.00135.
Wantchekon, L., Riaz, Z., 2019. Mobile technology and food access. World Dev. 117, 344–356. https://doi.org/10.1016/j.worlddev.2019.01.006.
Weiss, M.B.H., Werbach, K., Sicker, D.C., Bastidas, C.E.C., 2019. On the application of blockchains to spectrum management. IEEE Trans. Cogn. Commun. Netw. 5, 193–205. https://doi.org/10.1109/TCCN.2019.2914052.
Williams, C., Strusani, D., Vincent, D., Kovo, D., 2013. The economic impact of next-generation mobile services: how 3G connections and the use of mobile data impact GDP growth. Glob. Inform. Technol. Rep 77–80.
World Bank, 2020. World Bank Open Data | Data [WWW Document]. World Bank. URL. https://data.worldbank.org/ (accessed 5.16.20).
WorldPop, 2019. WorldPop : population [WWW Document]. URL https://www.worldpop.org/project/categories?id=3 (accessed 1.2.20).
Wright, D., Stahl, B., Hatzakis, T., 2020. Policy scenarios as an instrument for policymakers. Technol. Forecast. Soc. Change 154, 119972. https://doi.org/10.1016/j.techfore.2020.119972.
Yoo, C.S., 2017. An unsung success story: a forty-year retrospective on U.S. communications policy. Telecommun. Policy 891–903. https://doi.org/10.1016/j.telpol.2017.08.002. Celebrating 40 Years of Telecommunications Policy – A Retrospective and Prospective View 41.
Yrjola, S., 2020. Technology antecedents of the platform-based ecosystemic business models beyond 5G. In: Proceedings of the IEEE Wireless Communications and Networking Conference Workshops (WCNCW), pp. 1–8. https://doi.org/10.1109/WCNCW48565.2020.9124823. Presented at the 2020 IEEE Wireless Communications and Networking Conference Workshops (WCNCW).
Yunas, S.F., Niemelä, J., Valkama, M., Isotalo, T., 2014. Techno-economical analysis and comparison of legacy and ultra-dense small cell networks. In: Proceedings of the 39th Annual IEEE Conference on Local Computer Networks Workshops. IEEE, pp. 768–776.

Edward Oughton received the M.Phil. and Ph.D. degrees from Clare College, at the University of Cambridge, U.K., in 2010 and 2015, respectively. He later held research positions at both Cambridge and Oxford. He is currently an Assistant Professor in the College of Science at George Mason University, Fairfax, VA, USA, developing open-source research software to analyze digital infrastructure deployment strategies. He received the Pacific Telecommunication Council Young Scholars Award in 2019, Best Paper Award 2019 from the Society of Risk Analysis, and the TPRC48 Benton Early Career Award 2021.

Niccolò Comini is an Economist in the Digital Development Global Practice of the Infrastructure Vice Presidency at the World Bank Group focusing on ICT competition and regulatory issues in emerging countries. Examples include advising governments on 5G network deployment, data infrastructure, and digital platforms. Prior to joining the World Bank, he worked at the OECD in Mexico City and Paris as a competition expert. Niccolò is fluent in Italian, English and Spanish. He holds a MSc in Competition and Market Regulation from the Barcelona Graduate School of Economics and a M.A. in Law and Economics from the University of Bologna.

Vivien Foster is the Chief Economist for the Infrastructure Vice-Presidency of the World Bank covering Digital Development, Energy & Extractives, Transport and Infrastructure Finance. During her 20 years at the World Bank she has played a variety of leadership roles. Prior to joining the World Bank, Vivien worked as a Managing Consultant of Oxford Economic Research Associates Ltd in the UK. She is a graduate of Oxford University, and also holds a Master's from Stanford University and a Doctorate from University College London, both in Economics.

Jim Hall is Professor of Climate and Environmental Risks in the University of Oxford and Director of Research in the School of Geography and the Environment. Before joining the University of Oxford in 2011, Prof Hall held academic positions in Newcastle University and the University of Bristol. Prof Hall is internationally recognized for his research on risk analysis and decision making under uncertainty for water resource systems, flood and coastal risk management, infrastructure systems and adaptation to climate change.