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Zagdanski, Jakub; Castells, Pau

Conference Paper

The impact of spectrum policy on carbon emissions

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THE IMPACT OF SPECTRUM POLICY ON CARBON EMISSIONS

Abstract

By assigning rights and conditions of use, spectrum policy regulates how radio frequencies can be used by mobile networks. We develop a parameterised calculator tool to estimate the impact of various spectrum policy aspects on the emissions of the mobile sector. We model the impacts during the main phase of 5G rollout (2022-2031) in representative medium-sized low-income and high-income countries. (population: 80 million). We find that the carbon footprint of the mobile sector can increase between 1% (up to 0.4 MtCO2e) as a result of fragmented 5G spectrum, and up to 9% (up to 2.6 MtCO2e) as a result of a two year-delay to 5G assignment Importantly, we find that the potential impact on the emissions of other sectors and households as a result of lower adoption of emission-saving use cases could be many times greater. A two-year delay to assignment of 5G spectrum could lead to emissions in other sectors and households increasing by up to 37 MtCO2e.

Article information

JEL classification: Q54; Q58; D44

Keywords: Radio spectrum, spectrum policy, emissions, climate change

1. Introduction

Radio frequencies are a limited natural resource. How this resource is managed impacts the mobile sector by changing how networks can be deployed and operated. Relevant policies include the timely assignment of spectrum, the amount and type of spectrum assigned, whether the assignments are fragmented into narrower channels, and whether there are any additional restrictions placed on its use that could prevent re-use of spectrum to support latest networks (refarming). Building on previous analyses of the carbon impact of the mobile sector, consultations with the mobile sector, and other sources, we present a logic model outlining the link between spectrum policy choices and carbon emissions.

With mobile data traffic projected to increase five-fold by 2028 (Ericsson, 2022), mobile operators need to achieve substantial carbon savings to meet their own environmental impact targets and contribute to global and national commitments. While the mobile sector has its own footprint, it plays a key role as an enabler of emission-saving use cases for households and other sectors. Examples include video calling (lowering emissions from physical travel) and connected smart grid systems (enabling efficiencies in the energy sector). These use cases are made possible by mobile devices such as smartphones, fixed wireless access terminals, and IoT devices.

The mobile sector therefore has a bidirectional impact on emissions: it is a net carbon emitter itself, but it also enables the reduction of emissions in other sectors. To fully account for the impact of spectrum policy, we additionally investigate how spectrum policy interacts with the mobile enablement effect.

While there is a significant body of research examining the energy efficiency of mobile networks, it frequently focuses on either measuring the energy efficiency of mobile networks (Lundén, Malmodin, Bergmark, & Lövehagen, 2022; Pihkola, Hongisto, Apilo, & Lasanen, 2018; GSMA, 2021), or examining the impact of particular technological solutions on energy consumption of networks (Wang, Vasilakos, Chen, Liu, & Kwon, 2012; Fehske, Richter, & Fettweis, 2009).

However, the impact of spectrum policy on carbon emissions has only become an object of examination most recently (Schoentgen, et al., 2021; Matinmikko-Blue, 2021). These studies relied on an evidence review to identify the potential linkages from spectrum policy to emissions of various wireless technologies, as well as the emissions . The collected evidence and developed frameworks suggest that spectrum policy can influence crucial aspects of network deployment and operations, whether considering the award process options, the attached obligations or building-in green incentives.

Drawing on previous research and following the recommendations (Schoentgen, et al., 2021), our research contributes a new type of evidence based on quantitative modelling. We examine the carbon footprint of the mobile sector under illustrative spectrum policy choices and compare these results to obtain estimates of the impact on carbon emissions. In addition, we expand our calculations to examine the size of the mobile enablement effect under these spectrum policy scenarios, in order to measure impacts on the emissions of other sectors and households.

These carbon impact estimates offer an insight on the magnitude of effects that can be expected as a result of core policy choices. This allows for meaningful comparisons and evaluation of trade-offs in key spectrum policy decisions. As spectrum policy is frequently concerned with maximising the benefits stemming from its use as a natural resource, carbon emissions are an important outcome from the perspective of societal welfare. The social cost of carbon, at between 50 to 100 USD per tonne (OECD, 2015; Rennert & Kingdon, 2019), indicates it is a relevant object of analysis for the welfare-maximising spectrum managers.

Firstly, we outline the mechanism of impact between spectrum policy and carbon emissions (Chapter 2). Secondly, we develop a parameterised calculator tool characterising these mechanisms, in order to be able to estimate the impacts (Chapter 3). Lastly, we provide resulting estimates for illustrative spectrum policy scenarios (Chapter 4). In Chapter 5 we provide conclusions and recommendations.

2. Logic model

We rely on a framework identifying each spectrum policy that can be linked to emissions of the mobile sector. For each aspect of spectrum policy we outline the mechanism of action behind the emissions impact.

2.1 Delayed assignments of spectrum for 5G

Late allocation of spectrum to 5G can delay adoption of more efficient network technologies and increase emissions. Each successive mobile technology generation (2G, 3G, 4G, 5G) has been significantly more efficient in terms of the energy use per unit of data. Estimates (Pihkola, Hongisto, Apilo, & Lasanen, 2018) show that 3G networks consume ten times less energy per unit of data compared to 2G networks. The energy efficiency improvement between 3G and 4G meant nearly 30 times lower energy consumption per unit of data (Malmodin & Lundén, 2018). Similar order of magnitude in improvement is also expected for 5G (Orange, 2020).

Energy efficiency of RAN is paramount because RAN is the largest component of energy consumption by the operators. Estimates show that emissions linked to RAN can account for between 57% and 73% of the total operators' footprint (Elsa, 2014) (GSMA, 2021).

2.2 With less spectrum more base transceiver stations (BTS) are needed, leading to higher emissions through the supply chain

The dominant theme for the rollout of the latest generation of network has been densification, meaning dense deployment of cells and utilising larger portions of radio spectrum in diverse bands (Bhushan, et al., 2014). This is due to the constraint of so called spectral efficiency, that is, the limits to amount of data can be transmitted per unit of spectrum in a given time and location (Alouini & Goldsmith, 1999). Spectral efficiency of a network can be measured in terms of throughput, for example: bit/s/Hz per unit area; or bit/s/Hz per base transceiver station (BTS). Thus, demand for throughput and availability of spectrum are factors driving density of BTS.

On the other hand, radio signal is subject to attenuation as its distance of travel increases. Depending on its propagation characteristics, the signal strength limits, and real world conditions, the typical intersite distance for effective operation of BTS could range from hundreds of meters (urban) to kilometres (rural). Thus, providing sufficient coverage over large areas could also be a factor driving density of BTS in a mobile network.

However, to satisfy the anticipated throughput needs, the average density of 5G BTS is anticipated to rise up to 40-50 BTS/km2 in certain places (Ge, Tu, Mao, Wang, & Han, 2016). Therefore, the density of mobile networks will primarily be dictated by network throughput limitations rather than the needs to provide coverage.

In this setting, utilising more spectrum or building a denser network of BTS are substitute inputs to deliver the required network throughput. Considering this, spectrum policy restricting the amount of spectrum available to mobile networks would force operators to build more BTS, provided it is economical to do so. Empirical evidence on this suggests that MNOs with large spectrum bandwidth use, on average, 42% fewer sites in dense urban environments, and about 23% fewer sites in suburban areas (Frias, Mendo, & Oughton, 2020).

The amount of emissions embodied in manufacturing, transportation and construction of BTS is non-trivial. For example, countries such as the UK or Germany currently have each tens of thousands of BTS. Each BTS can have tonnes of CO2e embodied in it, depending on the type (Ding, et al., 2022).

2.3 Fragmented spectrum reduces its utilisation, resulting in network inefficiencies and higher emissions

Spectrum fragmentation refers to allocation of spectrum bands that are narrow and scattered. For example, a single mobile operator may only be assigned two 50 MHz-wide channels, each separated by allocations to other operators, instead of a single contiguous 100 MHz-wide band.

Such fragmentation can reduce utilisation of spectrum. Parts of spectrum need to be used as guard bands in order to prevent radio interference. Studies show that fragmentation into non-contiguous 50 MHz channels can reduce spectrum utilisation by 2.5%, compared to a contiguous 100 MHz channel (ECC, 2018).

Separately, in order to deliver fast service in presence of fragmented spectrum, network operators need to rely on carrier aggregation technology (Yuan, Zhang, Wang, & Yang, 2010). However, carrier aggregation uses up some of the bandwidth to transmit data necessary to co-ordinate network activity (signalling overhead). This reduces the useful bandwidth for the user data, and also, increases the energy consumption per unit of user data. Studies show that the signalling overhead can roughly double from about 6% for a single 100MHz channel to about 12% when two separate 50MHz channels are used (ECC, 2018).

Combined, these two effects constrain maximum network throughput per BTS, increasing the number of BTS throughput, and emissions embodied through their supply chain.

Use of carrier aggregation can also impact power consumption of user equipment. Tests show that the power consumption of smartphone can increase by 13% when relying on carrier aggregation (Santos, Salehi, Pires, Ortega, & Bazzo, 2020). Increased power consumption of smartphones generates additional emissions in the energy sector as the demand for grid electricity increases.

2.4 Reliance on higher spectrum bands can increase the energy consumption per unit of data

The energy efficiency of a network can also be affected by the band in which it operates. Empirical data on the performance of the network equipment shows that the energy efficiency of power amplifiers boosting the mobile signal can decrease when amplifying higher band signal (Wang, et al., 2020). Network energy consumption could increase if the operators are forced to use high bands where it is not optimal to do so.

However, there are other differences between the higher and lower spectrum bands, including the propagation characteristics[1] of the signal or the availability of sufficient spectrum to enable wide channels. Therefore, low and high band spectrum are not direct substitutes from the perspective of efficiency of mobile networks, Rather, they are complementary resources that can be used to enable mobile connectivity in various conditions. Therefore, we do not specifically examine such linkage in our modelling introduced in Chapter 2.

2.5 Channels of impact from spectrum policy to emissions of other sectors and households

The mobile enablement effect refers to mobile communications increasing connectivity, improving efficiency or helping behavioural change that ultimately results in lower emissions across other sectors of the economy and households (GSMA, 2019). Examples or such applications include (GSMA, 2019):

1) Reducing the need for travel, video calling with friends and family, and remote working can save 79 kg of CO2 per smartphone, per year.

2) Thanks to behavioural change, each smart meter in a residential setting can enable 60 kg of CO2 savings annually.

3) Mobile-enabled smart agriculture can improve efficiency and boost productivity, saving 11 tonnes of CO2 per farm, per year.

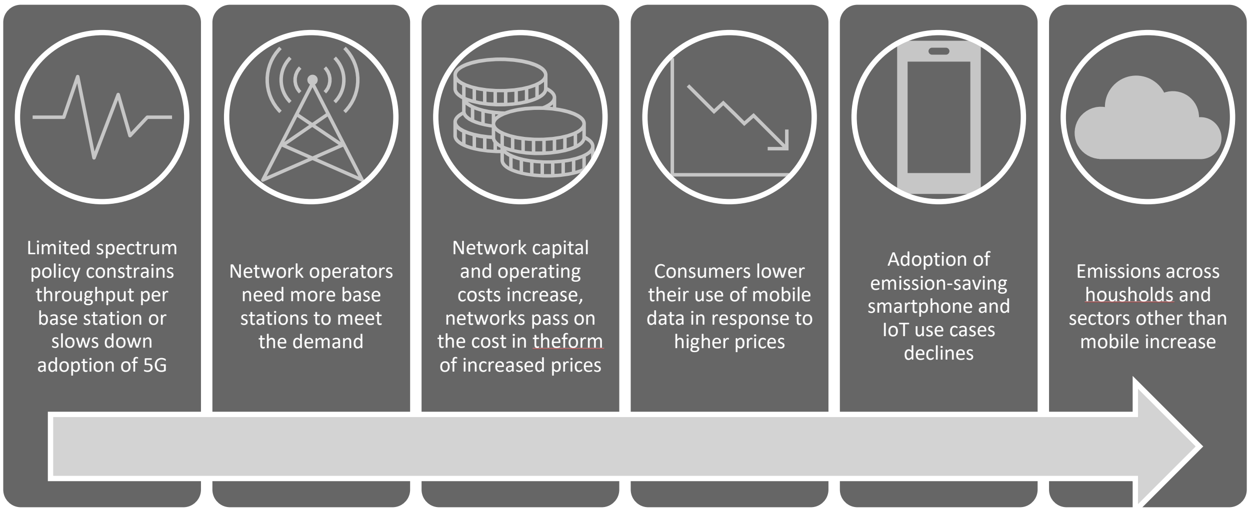
According to the estimates, the mobile sector can enable emission savings ten times greater than its own footprint (GSMA, 2019; AT&T, 2021).

Figure 2-1 illustrates the causal link between spectrum policy and emissions across households and other sectors as a result of the enablement effect. Initially, inefficient spectrum policy can constrain the maximum throughput per base station or slow the adoption of the latest mobile technologies. This introduces inefficiencies into the network, increasing the costs of construction if more base stations are required and increasing energy costs if the spectrum policy hinders transition to more efficient technologies.

Higher costs can lead to higher prices, reduced data use and lower adoption of mobile-enabled emission-saving use cases. This could increase emissions generated by households and other sectors relying on mobile connectivity.

[1] Propagation characteristics refers to the properties of radio signal which determine how it travels, including signal's strength, reach, and penetration of obstacles such as buildings.

Figure 2-1 Mechanisms of impact between spectrum policy and the enablement effect



Source: Authors' analysis.

Because of their wide area coverage, mobile networks are the default connectivity option to support a range of mobile telecoms service levels, which in turn are uniquely suited to enable a broad range of emission-saving use cases (Lehr, Queder, & Haucap, 2021; Ericsson, 2020). However, some emission-saving use cases could also be supported, to a varying degree, by fixed or line-of-sight wireless networks. Thus, examining the potential link between spectrum policy and their adoption is difficult, given the uncertainty about how responsive the uptake of these emission-saving use cases could be to changes in price or quality of mobile connectivity.

3. Quantitative modelling

3.1 Structure of the model

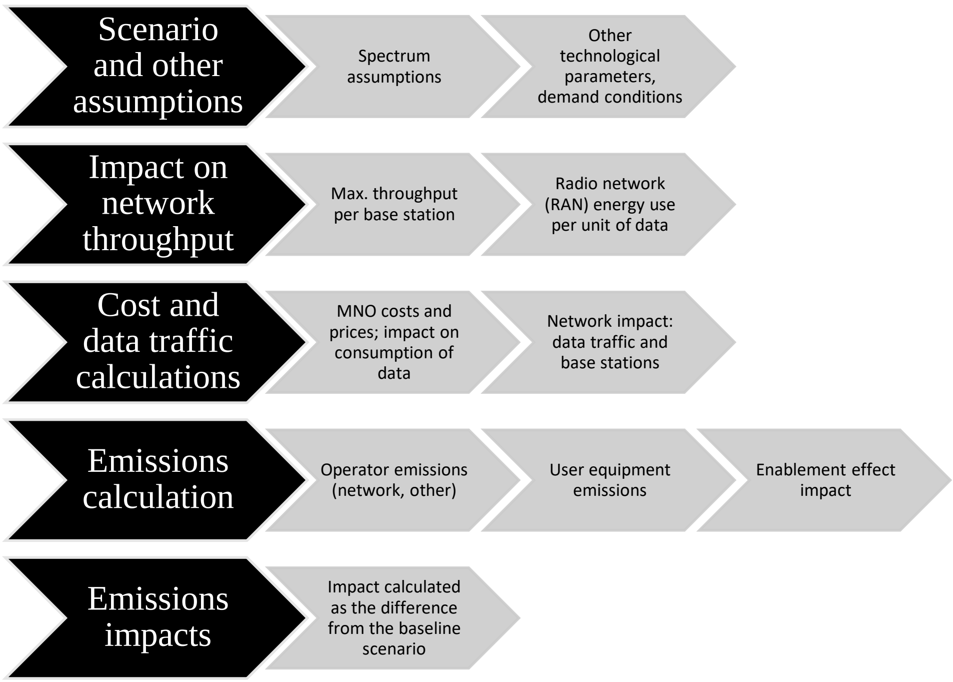
To assess the carbon impact of different spectrum policies, we develop a parameterised calculator tool. The tool relies on a number of equations that characterise the key relationships governing the sector's behaviour, such as those between spectrum availability and network topology; network topology and its energy consumption and operator costs; operator costs and consumer prices; and consumer prices and demand for mobile data and smartphones and IoT devices.

As shown in Figure 3-1, the calculation comprises four steps. First, we populate the model with assumptions of the baseline spectrum policy, as well as four alternative scenarios with different, sub-optimal spectrum policy choices. In this step, we also populate the model with other key parameters and assumptions that do not vary across the scenarios, such as the projected baseline demand for mobile data, and the technical parameters on the energy efficiency of different mobile network generations.

Second, we use the parameters and various equations to calculate the impact on network throughput, given the available spectrum. The key intermediate output of this calculation is the estimated maximum throughput per base station, which depends on the availability of spectrum for different network generations (from 2G to 5G).

Third, we rely on the intermediate outputs from previous steps to calculate how the number of base stations and energy consumption of the network are affected by spectrum policy. We estimate the number of base stations needed to meet the peak-hour throughput associated with baseline demand. In turn, the impact on the number of base stations and their energy consumption has secondary effects on network operator costs, which in our calculations impact consumer prices. We use further equations to model how a change in consumer prices impacts consumer demand for mobile data. Closing the cycle of calculations in the third stage, the newly estimated consumer demand is used to estimate the updated number of base stations needed and their energy consumption. Performing these calculations in the cycle iteratively, we obtain a convergent solution as the mobile traffic demand (in gigabytes per annum), along with variables describing the network (number of base stations, RAN energy consumption and others). In the final step, we apply various carbon intensity factors to convert these impacts into emissions impact.

Figure 3-1: Logic of the model used to estimate the impact on the mobile sector's emissions



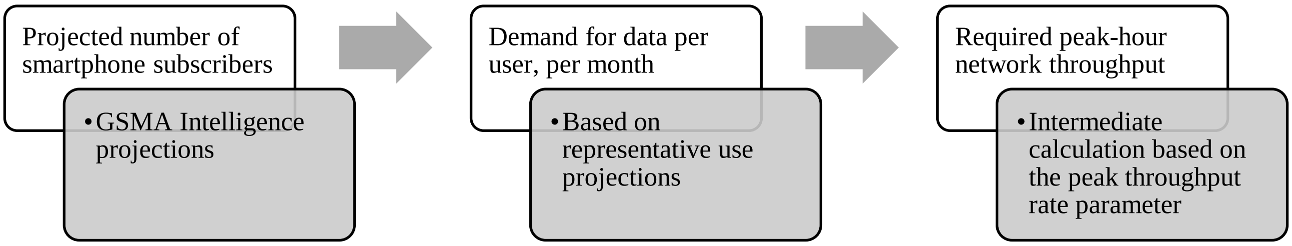
Source: GSMA Intelligence

The model performs calculations based on a range of input parameters and equations. The following sections describe the steps used in each step of calculations.

3.2 Baseline demand and throughput requirement assumptions

We develop calculations to estimate the baseline country-level demand for mobile data. Using additional calculations, we estimate the network throughput required to meet demand for mobile data (Figure 3-2).

Figure 3-2: Estimating total demand for data and required peak-hour network throughput



Source: Authors' analysis.

These demand assumptions are used to form a view of the future demand for mobile data in the baseline scenario. The baseline projections of the number of smartphones are based on representative GSMA Intelligence projections for benchmark, real-world low-income and high-income countries (GSMA Intelligence, 2022). To obtain annual data traffic, the projected number of smartphone subscribers is multiplied by the assumed demand for mobile data per subscriber. The assumptions are based on the current data traffic per user, and a projected growth in traffic per user for regions corresponding to our representative countries: Southeast Asia for the low-income country and Western Europe for the high-income country (Ericsson, 2022). The baseline data traffic estimates are shown in the Appendix (Table A-1).

In the last step, additional intermediate calculations and assumptions are used to convert the annual mobile traffic (GB/year) into the throughput (bytes per second) that a network needs to provide to serve the traffic. This calculation includes an additional assumption on the peak-hour throughput. This assumption is used to adjust the required throughput, given that the network load varies in a daily cycle. The peak-hour throughput is assumed at 8% (Nokia Siemens Networks, 2010), meaning that in the single busy hour the network needs to be able to serve 8% of the daily volume of data (rather than 1/24th of it). Hence the required peak-hour throughput to serve the given annual demand is calculated as specified in Equation 1:

Equation 1

$$Peak\ hour\ throughput\ (bytes\ per\ second) = \frac{Annual\ data\ traffic\ (bytes)}{Days\ in\ a\ year\ * Seconds\ in\ an\ hour} * Peak\ hour\ rate$$

Source: Authors' analysis.

3.3 Impact on network throughput: capacity per BTS

We use additional calculations to estimate the maximum throughput per BTS, given the spectrum available to operators. To do this, we multiply the amount of spectrum available to all operators (MHz) for all network generations and in each band by the spectral efficiency parameters sourced from the literature (Appendix Table A-2).

We develop estimates of maximum throughput per base station for two sizes of BTS: macro BTS, with three sectors of operation permitting higher throughput; and a micro base station, with a single sector of operation.

Among these, we distinguish between 5G-enabled and legacy BTS. 5G-enabled BTS can utilise all spectrum holdings dedicated to 5G networks, boosting their throughput. In contrast, legacy

BTS throughput is limited to throughput offered by spectrum assigned to 2G, 3G and 4G networks.

Maximum throughput for each type of BTS is calculated using the following formula:

Equation 2

$$\begin{aligned}Maximum\ throughput\ per\ BTS\\ &= Allocated\ spectrum\\ &\times ((Downlink\ spectral\ efficiency\ \ * Downlink\ ratio)\\ &+ (Uplink\ spectral\ efficiency\ * (1 - Downlink\ ratio))\ \times Sectors\end{aligned}$$

Source: Authors' analysis.

As traffic amount to and from a mobile device is typically asymmetric, downlink ratio is the assumed share of downlink data in the total mobile traffic, at 75%. This is similar to the ratio of downlink to uplink traffic from empirical studies of mobile networks (Kerttula, Marttinen, Ruttik, Jäntti, & Nazrul Alam , 2016). Using the calculated maximum throughput per BTS and additional assumptions on the share of each type of sites allows us to calculate the share of each network generation in the total traffic handled by each BTS. We assume that this share will be proportional to the throughput offered by each network generation, given the spectrum allocated to it. Thus, our assumption is simplified as, in practice, utilisation of different networks may differ from the maximum throughput offered by them. Nevertheless, we employ checks on the share of each technology in total data traffic (Figure A-7 and Figure A-8) to calibrate spectrum assigned to each network so that the share of total data traffic handled by each generation of mobile networks conforms to the observed shares and the expected trends over the next decade.

In the same step, we calculate the average energy consumption per unit of data, given the available spectrum. The energy efficiency of networks is typically measured in Watt hours per megabyte of transmitted data (Wh/MB). According to the surveyed estimates (Appendix Table A-3), the energy efficiency of networks varies significantly across different generations. To estimate combined network energy efficiency, we weight the energy efficiencies of different network generations by their share in network throughput.

These assumptions provide approximate values, which can vary with network topology, topography, or network load. For example, instantaneously, energy consumption of a BTS may not be directly proportional to the amount of traffic handled, as some energy is consumed to maintain the standby state of the components. However, the operators anticipating spectrum availability and demand, could in the long-run optimise network density (or inter-site distance). With greater availability of spectrum, BTS sites could be placed further apart, reducing their number and their standby energy consumption, thus maintaining the energy efficiency of networks. Therefore, describing efficiency in per-unit-of-data terms provides a useful approximation for calculation of networks' energy consumption when considering an impact of long-term spectrum policy decisions. Given their duration frequently exceeds 10 or 20 years, spectrum policy could be a key determinant of network investment decisions (Bahia & Castells, 2022) (Chikitani, Michel, & Sorana, 2023).

An important feature of the model's design is that the past outcomes can have an impact on future outcomes. For example, the investment decisions driven by past spectrum policy will affect the opening stock of BTS in the following year.

3.4 Cost and data traffic calculations

In the next steps, we calculate the baseline network costs for each year of analysis (2022–2031).

To estimate capital and operating cost of physical network, we use a stock-flow model to calculate the composition of types of BTSs and their number required to meet the data traffic.

1. For the baseline scenario, we estimate the throughput of already existing BTSs using on the spectrum holdings in a given year. Based on an assumed 10-year lifespan of a BTS, we assume that 10% of the existing stock of BTSs needs to be replaced with new equipment. If 5G spectrum has been available to the operators in that year, the operators replace them with 5G-enabled BTSs. Otherwise, these will be replaced with legacy-type BTSs (unable to use 5G spectrum).

2. Completion of the previous step allows us to calculate the network throughput gap for the existing stock of BTSs, after any upgrades. We calculate the throughput gap as the difference between the peak hour throughput (Equation 1) and the throughput offered by existing BTSs.

3. Using the estimated network throughput gap, we calculate the number of additional BTSs needed to meet the throughput gap. In a similar way to the previous step, we assume that the newly added BTSs will be 5G-enabled if 5G spectrum is available to operators, or legacy-type if 5G spectrum has not yet been assigned.

To accurately represent multiple network operators who do not share physical infrastructure, we multiply the estimated number of BTSs by three, assuming that the sites and equipment need to be set up separately for each operator. We effectively assume three operators per country, which is the typical number of large operators in medium-sized countries.

We use additional assumptions to account for imperfect utilisation of BTSs in the peak hour. To account for this, we further scale up the estimated number of BTSs three-fold. This adjustment is supported by evidence showing that, even in busy networks, resources are not utilised 75–90% of the time (RCR WIreless News, 2022). One example of a contributing factor to underutilisation is the daily cycle of movement from residential to commercial areas. Meeting peak hour demand of populations that change their concentration from place to place requires greater network throughput in any given area, compared to a situation where population distribution remained static.

Steps 1 to 3 outlined above provide us with the number of BTSs and a breakdown of their number by type in the first year of estimation. Combined with the throughput per BTS parameters, these figures allow us to estimate the share of each network generation in total network traffic.

In further steps, we shift to cost calculation. For the baseline scenario, we use additional parameters on the setup and annual running cost per BTS (Table A-4), which we multiply by the number of BTS obtained in previous steps. In the last step, we sum the costs to estimate the baseline network cost and network cost per unit of data.

3.5 Alternative scenario costs and network variables

In the calculation of alternative scenarios, we dynamically model the relationship between the key network variables (number of BTSs, throughput, costs), prices and demand for data.

The first two steps of the calculation are analogous to the calculation of the baseline scenario. For each year, starting with the initial year 2021, we use the alternative spectrum assignment assumptions to estimate the throughput per each BTS, the combined throughput of the existing stock of BTS, and the throughput gap to meet demand for data.

This allows us to estimate:

1. The alternative capital costs, based on the stock of BTS, which determines the number of BTS to be replaced (at 10% of the stock, in line with the depreciation rate) and the number of new BTSs to be added.
2. Similarly, we calculate operational costs, including the energy cost component. The energy cost component change is estimated cost according to the change in the weighted energy efficiency per unit of data. The weighted network's energy efficiency is calculated using the weights of each network generation (2G to 5G) in total data traffic, as outlined in Section 3.3. For example, if less available 5G spectrum decreases the share of 5G network in total traffic and the weighted energy consumption of the network increases from 0.1 Wh/MB to 0.11 Wh/MB (a 10% increase in consumption of energy per unit of data), we scale up the energy cost by 10%. Other operational costs are assumed to be fixed in per-base-station terms, or in other words, proportional to the number of BTSs.

In the next step, we sum all the costs to obtain the difference in total network cost in the alternative scenario. Given the data traffic, we obtain the percentage difference in network cost per unit of data. This estimate is used in a further equation to calculate how the prices of data will change. We use the following formula to estimate the impact on consumer prices (Equation 3). The calculation is underpinned by further assumptions on the share of network costs in total operator costs and cost pass-through ratio (Table 3-1).

Equation 3 Impact on consumer prices

$$\begin{aligned}\%\ change\ in\ price\ per\ unit\ of\ data \\ &= \%\ change\ in\ network\ cost\ per\ unit\ of\ data \\ &\times RAN\ cost\ as\ a\ share\ of\ total\ MNO\ costs \times Cost\ pass\text{-}through\ ratio\end{aligned}$$

Source: Authors' analysis.

Table 3-1 Cost calculation parameters used in modelling

Parameter	Value	Source
Cost pass-through ratio	80%	Illustrative assumptions based on pass-through of mobile taxation (GSMA, 2020)
RAN cost as a share of total MNO costs	29%	Baseline scenario assumption based on European network data (GSMA, 2012)
Price elasticity of demand	–0.9	Based on the estimate of ownership elasticity with respect to the cost of services for low- income countries (GSMA, 2020)

To translate the impact on data prices into an impact on demand, we multiply it by the price elasticity of demand. This results in an estimate of the impact on demand for mobile data as a percentage difference from the baseline, which we subsequently apply to the baseline demand projection.

The previous step results in new, updated demand for data in the alternative scenario, given the spectrum policy assumptions. This step marks the end of one iteration in the process of dynamic estimation of demand and costs for a single year of estimation. Consecutively for each year, the estimation steps are repeated until the calculations converge on an iterative solution for demand and costs for a given year of estimation of the alternative scenario. Once a convergent solution is obtained for the year, the calculations begin for the next year of analysis in the same fashion.

By modelling the demand for mobile services as responsive to costs and prices, our modelling accounts for rebound effects that could affect the emissions of the mobile sector (Gillingham, Rapson, & Wagner, 2015). In our model, lower energy efficiency of the network and higher number of BTSs translate into a cost impact, which is partly passed onto consumers, who adjust their demand for mobile services.

3.6 Emissions calculations

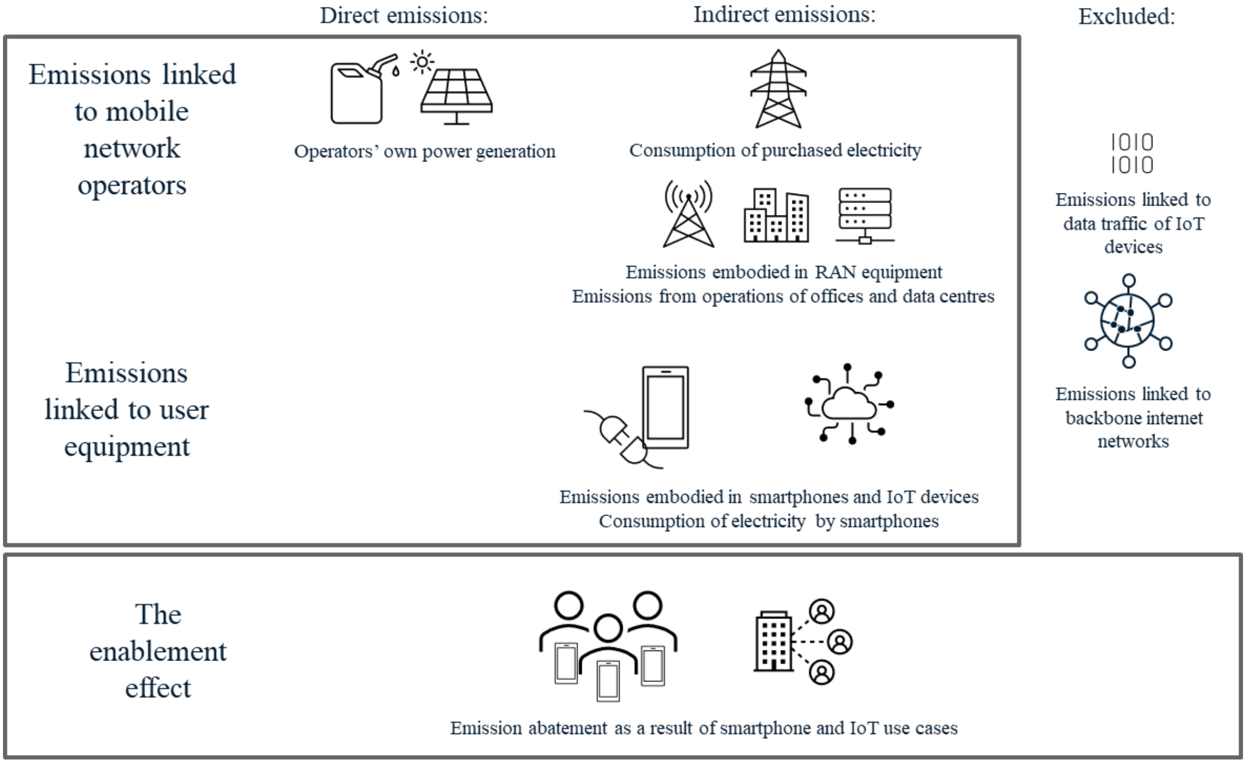
In the last step of calculations, we translate the impacts calculated earlier into emissions impact estimates for the mobile sector and the impacts on emissions of other sectors and households through the enablement effect. The emissions within scope of our calculations are shown in Figure 3-3.

Calculations include the impact on operator emissions, including emissions from operators' own production of electricity, emissions linked to purchased electricity and operations of offices and data centres, as well as emissions generated through the supply chain (emissions linked to the manufacture and construction of BTSs).

In addition, we calculate the emissions impact through user equipment. The calculations cover emissions embodied in manufacturing of smartphones and IoT devices relying on mobile connectivity, as well as emissions linked to the electricity consumption of smartphones.

The calculations of impact exclude the impact on emissions as a result of data traffic generated by IoT devices, as the vast majority of IoT devices consume less than a few megabytes of data per month (James Brehm & Associates, n.d.). We also exclude from the calculation emissions linked to the operation of the backbone internet network (outside of an MNO's operations) as they are relatively low (Ficher, et al., 2021).

Figure 3-3 Emissions in scope of impact calculations



Source: Authors' analysis.

3.7 Emissions calculations – mobile sector

In the calculations, we use various emissions intensity parameters to convert the activity of the mobile sector (such as energy consumption and purchases through the supply chain) into carbon impacts (in tonnes of CO2e), as outlined in Table A-3.

For example, to calculate the emissions embodied in BTSs each year, we multiply the number of refurbished and newly added BTSs by their embodied emissions parameter.

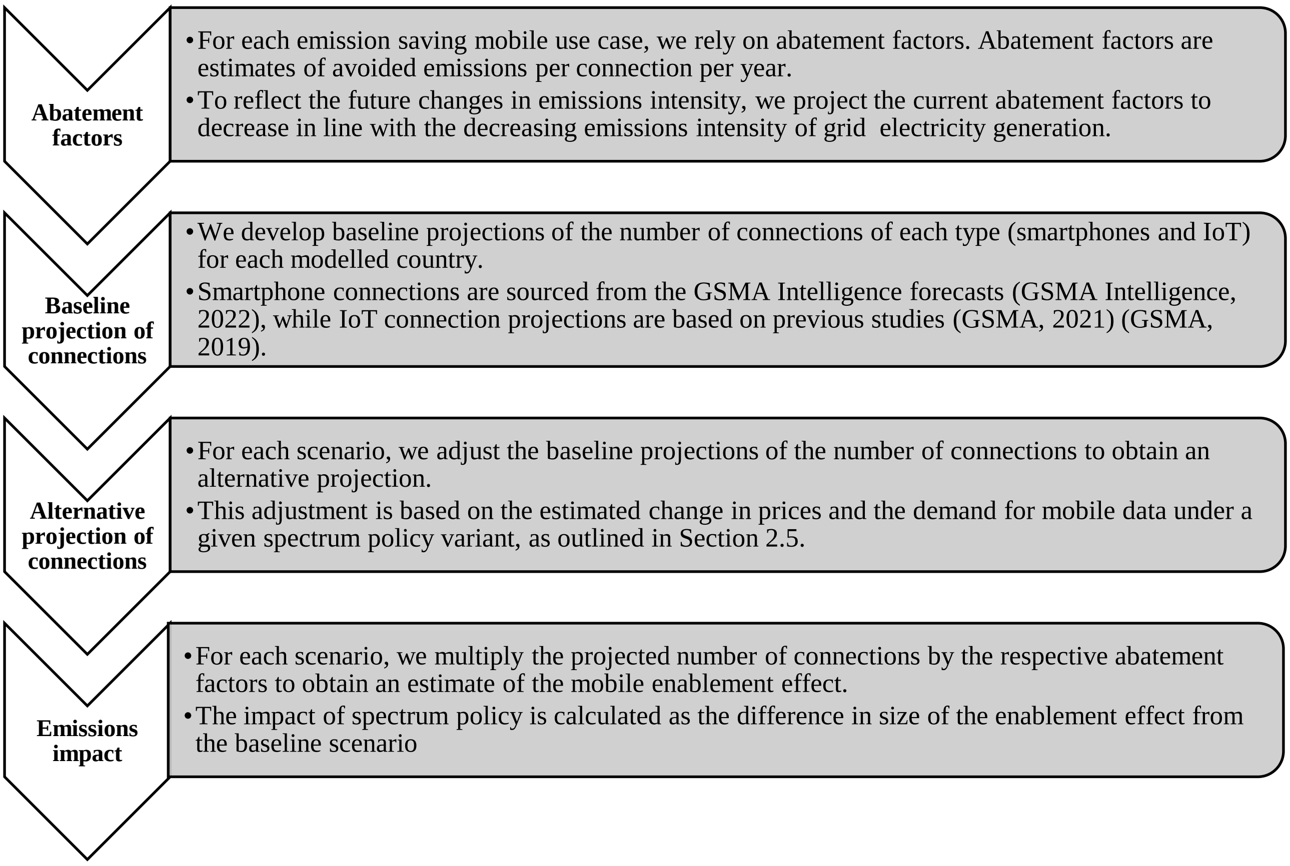
Similarly, we calculate the emissions as a result of electricity consumed by the radio network by multiplying the annual data traffic (in MB) by the weighted average electricity consumption per unit of data (Wh/MB) and the emissions intensity of electricity powering the network (gCO2e/kWh). The emissions intensity of electricity powering the network is a weighted average of the carbon emissions intensity of electricity purchased by network operators from the grid as well as the emissions intensity of electricity generated by network operators. The weights are based on assumptions on the share of diesel and solar-powered off-grid BTSs, as outlined in Table A-3.

To estimate the impact on emissions in any given spectrum policy alternative, the combined emissions of the mobile sector are simply subtracted from the baseline emissions.

3.8 Emissions calculations – enablement effect

To estimate the size of emission saving impact of mobile connectivity under different spectrum policy scenarios, we rely on previous analyses on the size of the enablement effect (GSMA, 2021) (GSMA, 2019). The calculation steps are outlined in Figure 3-4.

Figure 3-4: Approach to modelling the impact of spectrum policy through the enablement effect.



Source: Authors' analysis.

We develop baseline projections of the number of IoT connections (Figure A-1 and Figure A-2) relying on previous world-region-level projections (GSMA, 2019) (GSMA, 2021). We scaled these down in proportion to the GDP share of our illustrative high and low income countries in their respective regions (Europe and Asia) using World Development Indicators data (World Bank, 2022).

To obtain the estimates of the mobile enablement effect, we multiply the projected number of connections by the corresponding carbon abatement factors (avoided emissions per smartphone or IoT connection per year), as shown in the Appendix Figure A-3 and Figure A-4. We adapted the figures for the corresponding regions (Asia for the low-income country and Europe for the high-income country) and performed additional scaling of abatement factors to account for differences in GDP per capita between our representative countries and their regions. For example, given that our low-income country's GDP per capita is lower than the Asia's average, we scaled down the abatement factors.

To account for the changing carbon intensity throughout the economy, we project the abatement factors to decline at the same rate as the grid carbon intensity in each country.

To estimate the size of the mobile enablement effect under alternative spectrum policy scenarios, for each use case we adjust the baseline effect by the estimated change in the uptake in response to changing prices of mobile data. We use the following assumptions:

1. Uptake of smartphone emission-saving use cases reduces proportionally to changes in demand for mobile data. Thus, the implicit elasticity of adoption of emission saving use cases with respect to mobile data prices is -0.9, in line with the assumption on the elasticity of demand for mobile data.
2. For use cases supported by IoT connections, we assume a very low elasticity of their uptake with respect to data prices, at -0.2. This means that 1% increase in prices of mobile data results in a 0.2% decline in the uptake of IoT emission saving use cases. This assumption reflects that a vast majority of IoT connections typically use less than a few megabytes of data per month (James Brehm & Associates, n.d.), so their uptake is likely to respond to the prices of data only very modestly.

With respect to the latter parameter, due to lack of empirical evidence, we could not back up such an assumption with a specific estimate of the elasticity of demand for IoT use cases with respect to mobile connectivity prices. However, our assumption is conservative. For comparison, estimates show that own price elasticity of demand for basic commodities, such as residential demand for water, is most frequently found at between -0.26 and -0.5 (Epsey, Epsey, & Shaw, 1997). Thus, we assume that adoption of IoT emission-saving use cases responds to prices of mobile connectivity only very slightly.

To estimate the impact on emissions through enablement effect, we calculate the difference in the size of the enablement effect between the alternative and the baseline scenario.

4. Modelling results

4.1 Modelled scenarios

The assessment covers the 10 years between 2022 and 2031, corresponding to the main period of 5G rollout. The assumptions for each of the modelled policy scenarios are shown in Table 4-1. The reference scenario (Baseline) is used as a comparator against four different spectrum policy scenarios, each highlighting a separate aspect of policy.

Scenario 1 illustrates the impact of a two-year delay to 5G spectrum assignment. Scenario 2 illustrates the impact of a constrained amount of spectrum assigned, with a representative example of 100 MHz less 5G spectrum than in the baseline. Scenario 3 illustrates the impact of fragmented 5G spectrum, divided into 40 MHz bands (versus 100 MHz bands in the baseline). Scenario 4 is designed to showcase the impact of restrictions to spectrum refarming.

In contrast to the baseline, it assumes that the operators will not have the flexibility to use existing 3G/4G spectrum assignments for 5G networks.

Therefore, the spectrum policy assumptions are a combination of two aspects: the amount of spectrum assigned to each generation of networks for each year of calculation; and the level of fragmentation of 5G spectrum.

In the model, we aggregate spectrum holdings at a country level to estimate overall capacity across all mobile networks. The fragmentation assumption is simplified to two options: either the spectrum channels are fragmented into 40 MHz channels (scenario 3) or wider 100 MHz channels (scenarios 1, 2 and 4). This is an illustrative assumption as in some years total available 5G spectrum may not be divisible by 100 or by 40. Hence, the assumption is meant to represent a relative impact of spectrum fragmentation comparable to the difference between 100 MHz and 40 MHz channels.

Table 4-1 Spectrum policy assumptions used in the modelled scenarios

	Baseline scenario	**1: Delayed 5G assignments**	**2: Restricted 5G assignments**	**3: Fragmented 5G**	**4: No refarming to 5G**
5G assignment	Scenario representing a reference spectrum policy case, with assignment of 5G spectrum in 2023 (low-income country) or 2021 (high-income country)	Assignment of 5G delayed by two years to 2025 (low-income country) or 2023 (high-income country)	Assignment timing as in the baseline, but 5G spectrum assignment lower by 100 MHz of spectrum in upper mid-band (3.5 GHz to 6 GHz)	Same as baseline	Same as baseline
Spectrum refarming	From 2026, gradual refarming of parts of 3G and 4G spectrum to 5G network use (about 300 MHz total refarmed by 2031)	Refarming delayed by two years compared to baseline	Same as baseline	Same as baseline	No refarming of existing 3G and 4G spectrum
Spectrum fragmentation	Spectrum utilisation consistent with contiguous 100 MHz channels of 5G spectrum.[1]	Same as baseline	Same as baseline	5G spectrum fragmented into 40 MHz channels.[1] Requires carrier aggregation	Same as baseline

Notes: [1] This is an illustrative assumption as in some years total available spectrum may not be divisible by 100 or by 40. Hence, the assumption is meant to represent an impact of spectrum fragmentation comparable to the difference between 100 MHz and 40 MHz channels.
Source: Authors' assumptions.

We consider the effects of t spectrum policy choices on two hypothetical countries. As shown in Table 4-2 (with data for 2021), the two hypothetical countries have the same populations but differ in their level of economic development and adoption of mobile technologies.

Another important difference between the countries is the share of renewables in energy purchased by the mobile operators from the grid. In line with real-world differences, we assume that mobile operators in the high-income country primarily purchase renewable energy (GSMA, 2022). This translates into a lower carbon footprint and impacts from the operation of the radio network in the high-income country.

As a reference point to the presented further emissions impacts, we estimate the current total carbon emissions of the low-income country at about 160 megatonnes of CO2 equivalent (MtCO2e), and 750 MtCO2e for the high-income country. However, by 2030, the emissions of the low-income country are expected to almost double, primarily as a result of a rapid economic growth and some growth in population. In contrast, the high-income country aims to reduce its emissions by nearly a half. These projections of targets are based on the Paris Climate Agreement targets for benchmark countries.

Table 4-2 Comparison of hypothetical countries used in modelling

	Low-income country	High-income country
Population (2021)	80 million	80 million
GDP per capita (2021)	$6,000	$60,000
Smartphone connections (2021)	40 million	100 million
Mobile data per subscriber, per month (2021)	6 GB	15 GB
Share of renewables-only energy purchased by the operators (2021)	5%	71%
Carbon emissions (country total)	2021: 162 megatonnes CO2e, 2030 target: 300	2021: 750 megatonnes CO2e 2030 target: 440

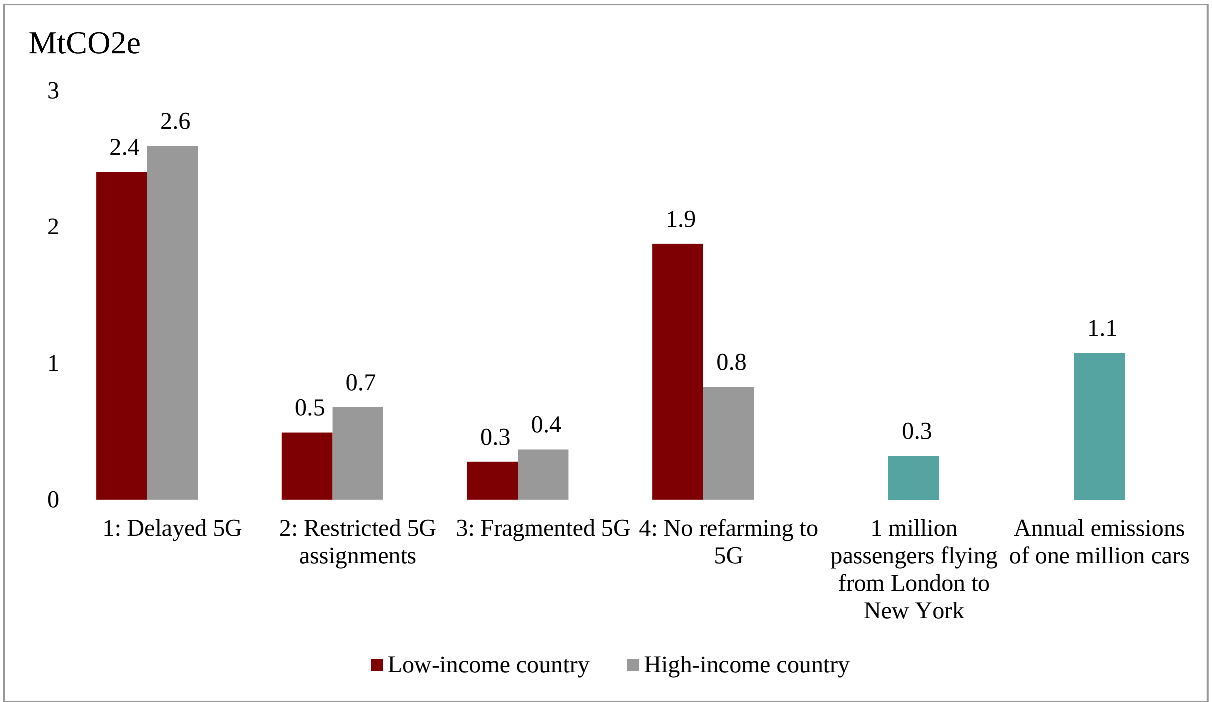
Notes: All figures are approximate. GDP per capita quoted in purchasing power parity terms (2021 international USD).
Source: Authors' analysis.

4.2 Impact on the emissions of the mobile sector

Figure 4-1 presents the cumulative emissions impact for the representative low- and high income countries over the 10 years between 2022 and 2031, which corresponds to the main period of 5G rollout. The estimates presented in Figure 4-1 concern only the impact on the emissions of the mobile sector: the emissions of mobile network operators and those linked to user devices (smartphones and IoT devices).

We estimate that a two-year delay to assignment of 5G spectrum can lead to additional 2.5 MtCO2e emitted by the mobile sector in our hypothetical low-income country, and a 2.6 MtCO2e of additional emissions in the high-income country. A restricted (100 MHz less) assignment of 5G spectrum could lead to an additional 0.5 MtCO2e in the low-income country, and a 0.7 MtCO2e in the high-income country. Spectrum fragmentation affects the emissions of the mobile sector to a lower extent, leading to an additional 0.3 MtCO2e in the low-income country and 0.4 MtCO2e in the high income country. Non-neutral assignment preventing spectrum refarming (Scenario 4) could lead to an additional 1.9 MtCO2e in the low-income country and a 0.8 MtCO2e in the high income country.

Figure 4-1 Impact on emissions of the mobile sector (MtCO2e): cumulative impact 2022-2031



Source: Authors' modelling.

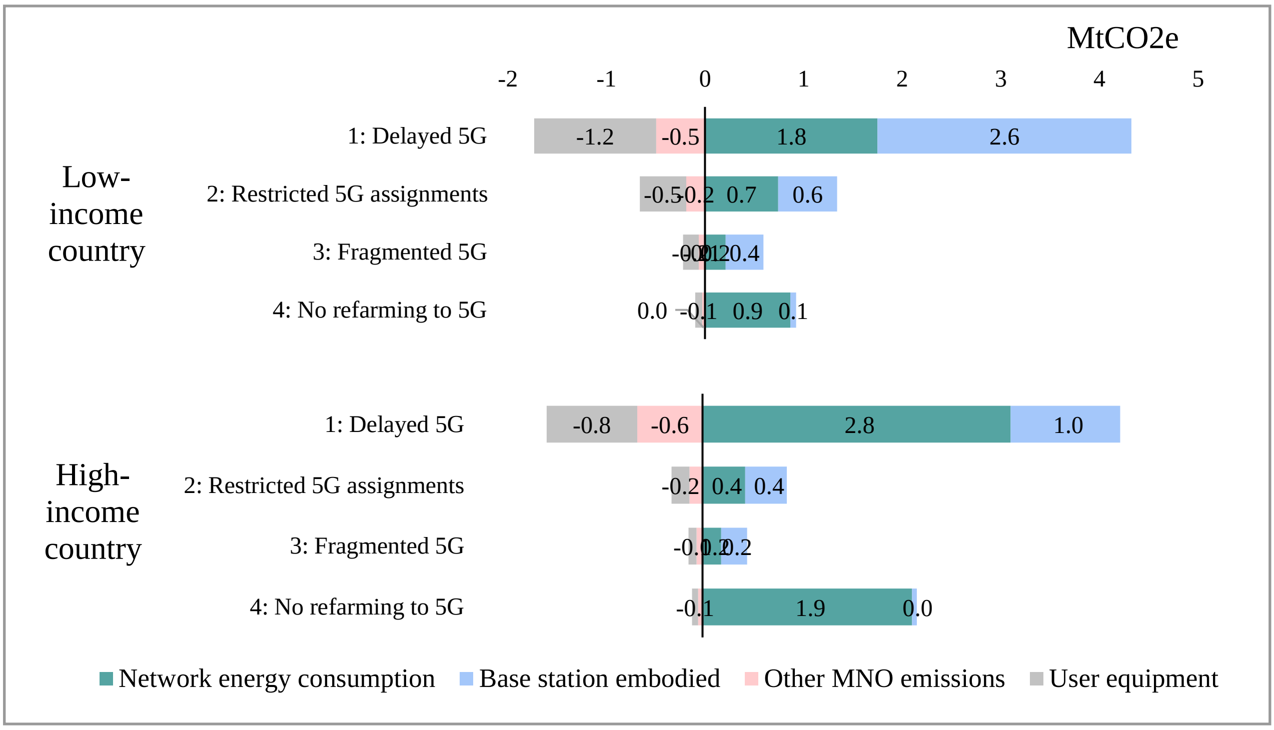
Figure 4-2 provides a breakdown of impacts by source. The categories include the energy consumption of operator networks (RAN and core components of the network), the emissions embodied in manufacturing and construction of BTSs, other operator emissions (the running of offices and data centres) and user equipment (emissions related to the manufacture of smartphones and IoT devices, and the energy consumption of smartphones).

For the low-income country, in all scenarios, the emissions increase primarily due to higher consumption of electricity by the network, followed by an increase in emissions embodied in BTSs. In the high-income country, emissions as a result of increased network energy consumption account for a relatively smaller contribution. This is because according to our assumptions, and in-line with real-world behaviour, operators purchase more than 70% of energy powering the network from renewable sources. This greatly mitigates the emissions impact of RAN energy consumption, abating the amount of additional emissions in all four scenarios.

In Scenario 4 (no refarming to 5G), the distribution of impacts differs from other scenarios as emissions embodied in BTSs increase only negligibly. We estimate only a slight increase in BTSs needed to serve mobile traffic due to the lower spectral efficiency of 3G and 4G. However, extended reliance on 3G and 4G increases network energy consumption, which is the main source of the estimated emissions impact.

For all scenarios, we estimate smaller, emission-reducing impacts from other operations of mobile operators (the running of data centres and offices) and user equipment (emissions related to devices and the energy consumption of smartphones). These impacts are negative because restrictive spectrum policy reduces demand for mobile communications, which causes a fall in the need for mobile devices and scaled down operator activities. These de Nevertheless, the reductions are much smaller than the increases in emissions linked to network energy consumption and embodied in BTSs. Hence, the net impact for all considered scenarios is an overall increase in the emissions. Moreover, lower adoption of mobile connectivity can have further effects on emissions outside the mobile sector, as examined in Section 4.3.

Figure 4-2: Impact on the emissions of the mobile sector: cumulative 2022-2031 impact.



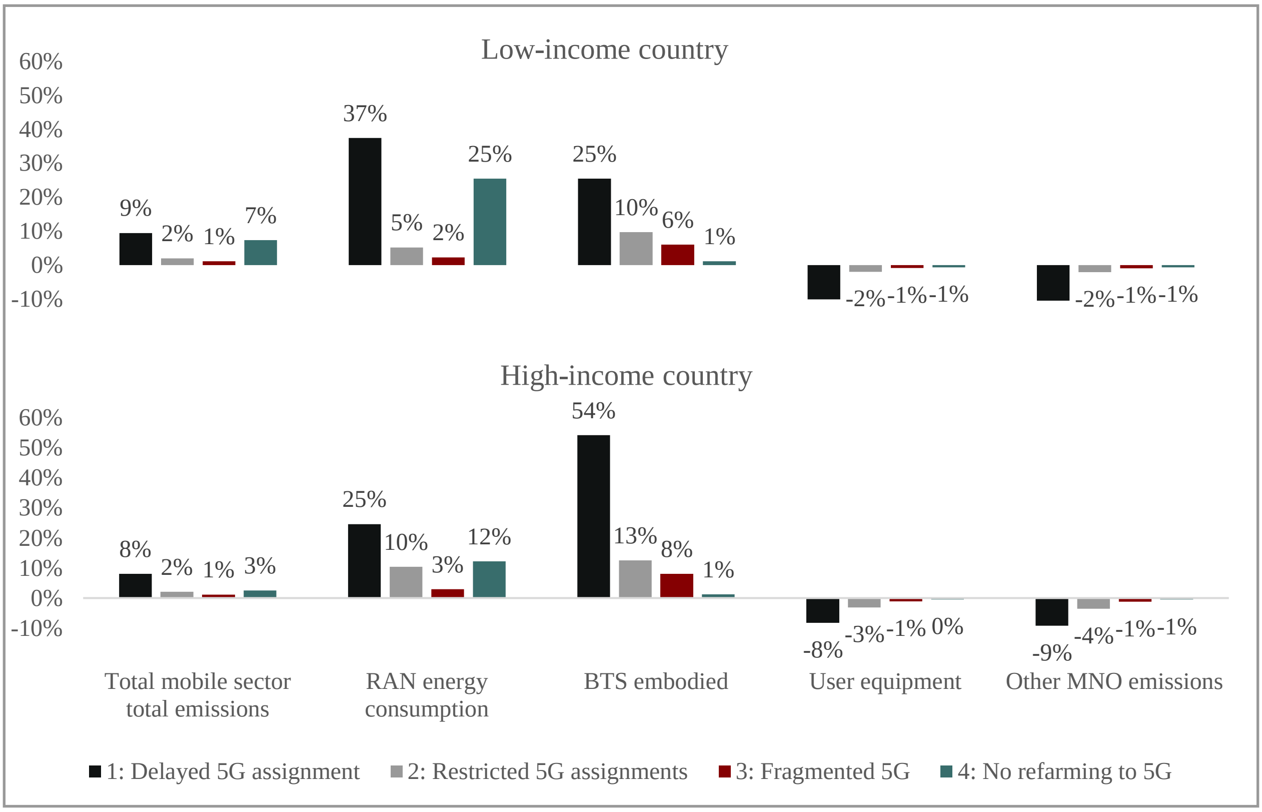
Source: Authors' modelling.

Alternatively, the impacts can be expressed as a share of baseline scenario emissions (Figure 4-3). Delayed 5G assignment can increase emissions of the mobile sector by 8%, compared to the baseline estimate for 2022-2031. We see smaller impacts for other scenarios, ranging from 1% (3: Fragmented 5G) to 3% (4: No refarming to 5G).

Emissions linked to electricity consumption of the network can increase by up to a quarter (1: Delayed 5G), although these are also markedly higher when refarming of spectrum is prevented (Scenario 4).

We estimate the largest relative impacts on the emissions linked to energy consumption by the networks and the emissions embodied in BTS equipment. For example, a two-year delay to 5G assignment can increase emissions embodied in BTSs by just over a half, correspondingly to the need for densification to meet the mobile traffic demand with less spectrum. Importantly, network densification and the impact on embodied emissions of BTSs is less important in scenario assuming no refarming of existing spectrum holdings to 5G (Scenario 4). This is because in this scenario network density is only slightly higher, as in all years the available spectrum remains identical to the baseline scenario. This minor increase in density is due to a lower spectral efficiency of 4G versus 5G, which under this scenario will remain a significant carrier of data for longer.

Figure 4-3 Impact on the emissions of the mobile sector, as a share of baseline emissions (%): cumulative 2022-2031 impact.

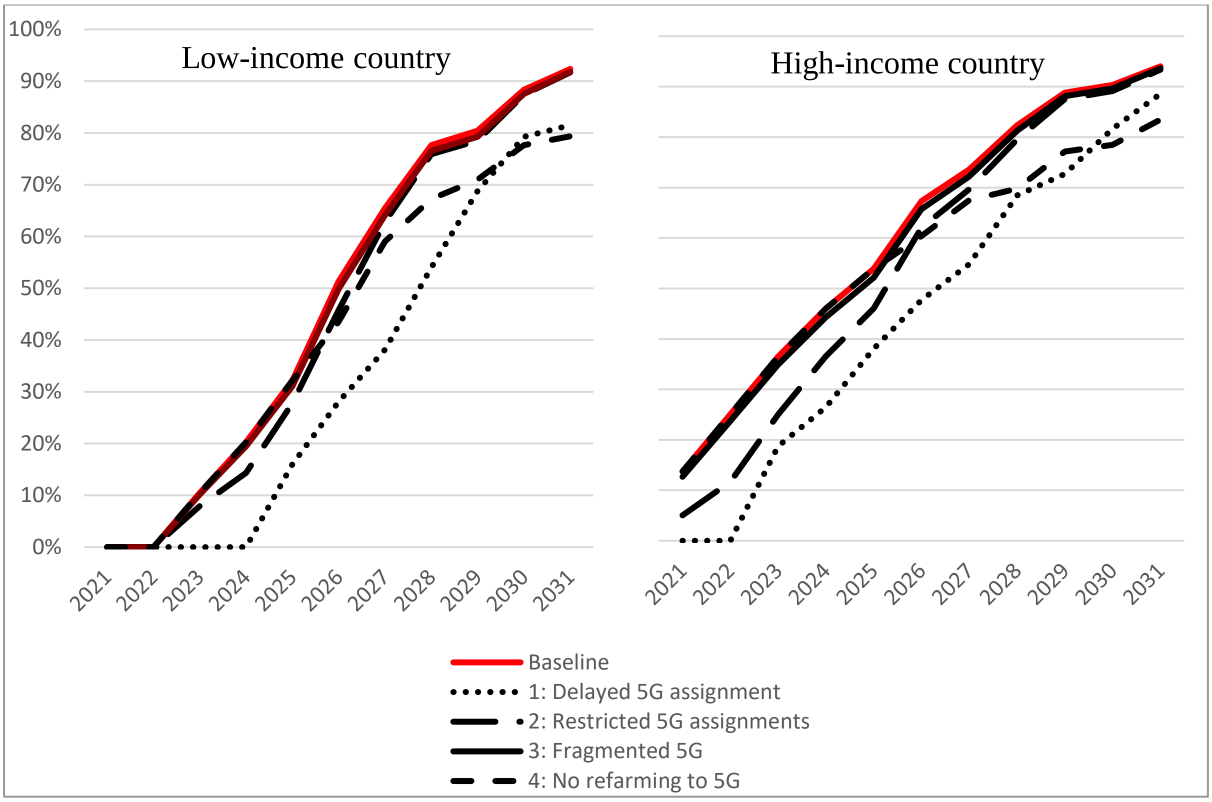


Source: Authors' modelling.

The mechanism behind the carbon impact through the network energy consumption can be further illustrated by changing shares of each mobile network generation in total data traffic. As shown in Figure 4-4, the share of 5G in total data traffic decreases the most as a result of delayed 5G assignment or non-neutral assignments preventing refarming of spectrum to 5G. This reduces the overall network energy efficiency, given that a higher share of data traffic will be transmitted over older generations, in particular, 4G.

The impact on adoption of 5G is relatively smaller in case of scenario 2: Restricted 5G assignments. However, it should be noted that this scenario assumes about 100 MHz less upper-mid band spectrum assigned to 5G. While this is a relatively large portion of the initially-assigned spectrum to 5G during the first years of the roll-out, it will become a relatively smaller share of spectrum available to 5G in latter years Therefore, the impact on the amount of traffic will become less important towards the end of the analysed period. A detailed presentation of the share of each network generation in total data traffic is shown in the Appendix (Figure A-7 and Figure A-8).

Figure 4-4 Share of 5G in total data traffic, by scenario



Source: Authors' modelling.

4.3 Impact on emissions of other sectors and households: the enablement effect

We calculate the impact of spectrum policy on the emissions of other sectors and households by comparing the size of carbon abatement effect of smartphone and IoT use cases under different variants of spectrum policy. The estimates for all four scenarios are shown in Figure 4-5. We advise caution when interpreting these impacts. This is because of the uncertainty about the parameters used in calculations of the enablement effect impact and a possible rebound effect, as explained in detail in Section 3.6.

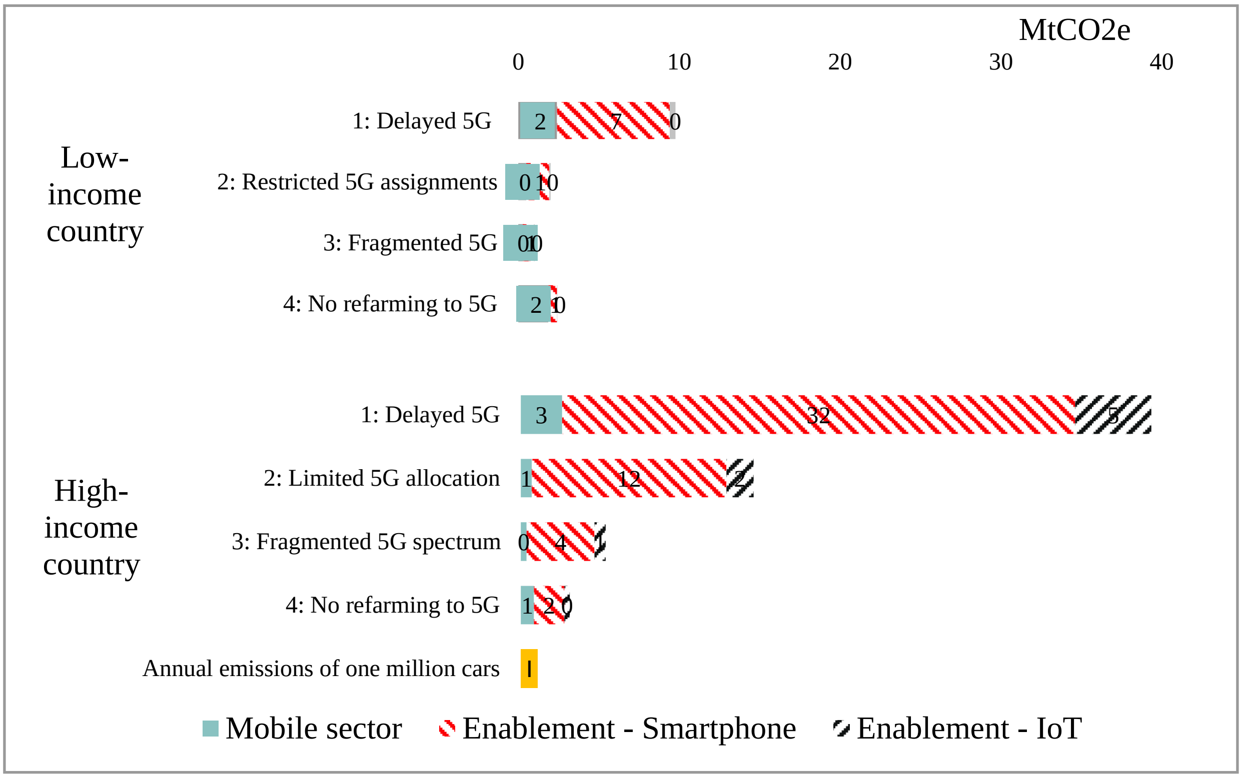
When 5G assignment is delayed (Scenario 1) or spectrum assignments are restricted (2) or fragmented (3), the enablement effect impact is markedly greater than the impact on the mobile sector's own emissions, with up to tens of millions of tonnes of additional CO2 emissions.

When spectrum refarming to 5G is not permitted, the knock-on impact through the enablement effect is relatively less important. This is because the number of BTS required to serve the traffic is impacted only very mildly, so operators' capital costs are less affected than in other scenarios. This results in a relatively smaller impact on the adoption of emission-saving use cases. However, some enablement effect opportunity is still missed because the lower network energy efficiency of 3G and 4G increases network energy costs, and thus, translates into prices of mobile connectivity and lowers adoption of emission-saving use cases.

We also find that the impact through the enablement effect is greater in the high-income country. This is unsurprising, given the overall greater adoption of emission-saving smartphone and IoT use cases.

Across all scenarios, the impact of the enablement effect is lower for IoT-based use cases than smartphone-based use cases. This is because demand for – and adoption of – IoT use cases is relatively unresponsive to the cost of data. Most IoT devices transmit little data, making cost a less important factor.

Figure 4-5: Impact on the emissions of the mobile sector and impact through the enablement effect: cumulative 2022-2031 impact



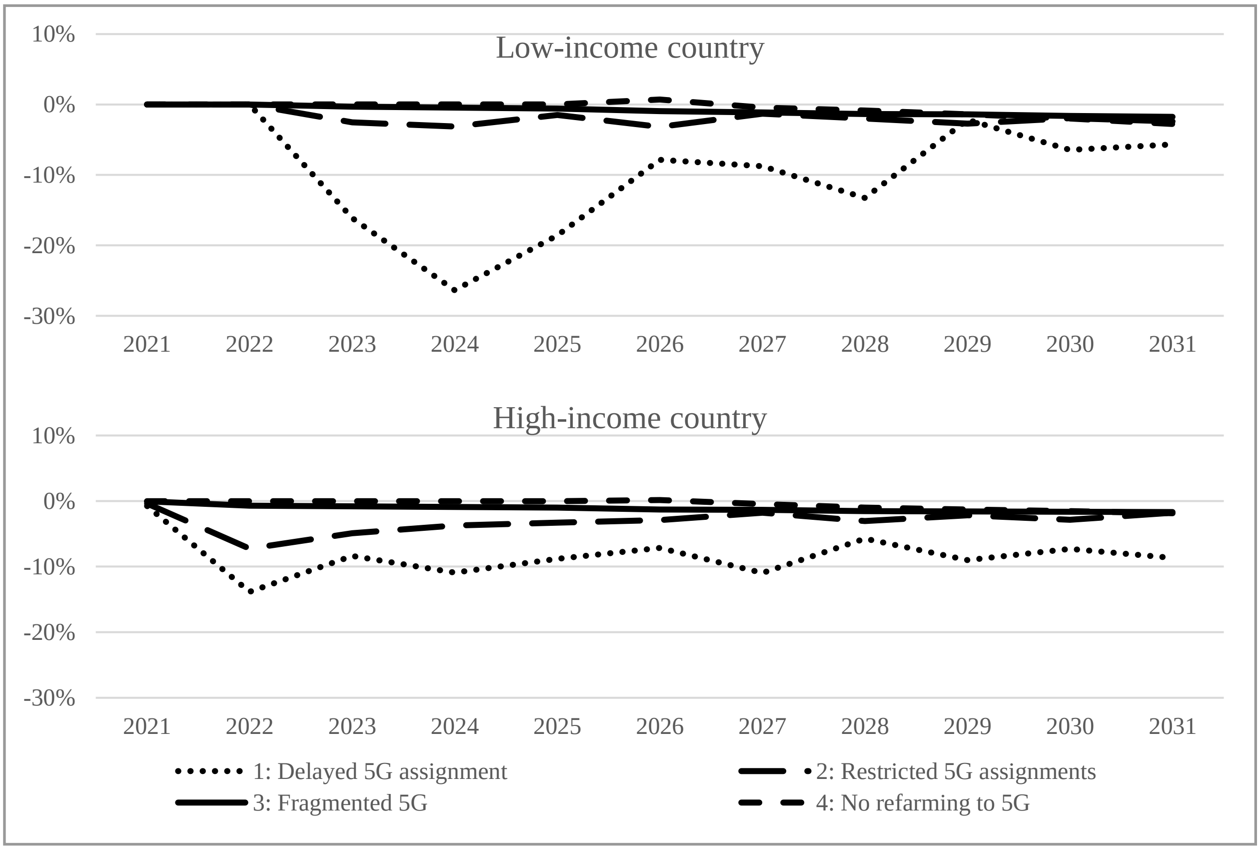
Source: Authors' modelling.

To illustrate the intermediate outcomes of the spectrum policy variants in the calculation of the enablement effect, we plot the estimated impacts on mobile data traffic as the difference from the baseline traffic scenario (Figure 4-6).

We estimate the greatest impact on mobile data traffic (and adoption of emission-saving use cases) under scenario 1: Delay to 5G assignment. As a result of a two-year delay to assignment of 5G spectrum in the low-income country, mobile data traffic can be 26% lower compared to the baseline scenario in year 2024. However, the gap narrows to less than 10% in later years. Similarly, in the same scenario we see the greatest negative impact on data traffic in the high income country in the initial years when 5G spectrum is not available, before the impact subsides to a circa 10% decrease in mobile data demand.

In other scenarios, we see lower impacts on data demand, typically less than 4% below the baseline. This illustrates that even with such relatively modest impacts on demand for mobile connectivity and a proportional decrease in adoption of the emission saving use cases, the impact on emissions of other sectors and households can reach the order of millions of tonnes of additional CO2 emissions. As shown in detail in the Appendix (Table A-8 and Table A-9), we estimate that by 2031 the emission-saving impact of mobile connectivity will reach over 10 MtCO2e annually in the low-income country and over 80 MtCO2e in the high-income country. This means that even a relatively small decline in adoption of mobile connectivity (as proxied by mobile data traffic) can have a major emissions impact through the enablement effect.

Figure 4-6: Impact on mobile data traffic: difference from the baseline scenario



Source: Authors' modelling.

5. Conclusions and recommendations

In recent years, regulators have started to explore the potential role of spectrum policy as a climate policy tool. As this area expands, regulators may consider incorporating assessments of climate change into existing spectrum policy frameworks and roadmaps, on top of the existing economic impact assessments.

Non-monetary impacts, such as carbon emissions impacts, should not be overlooked as they have a real effect on quality of life and productivity globally, and will continue to have an impact for future generations. Estimates show that the social cost of carbon, though uncertain, could be between \$50 and \$100 per tonne of CO2 and will likely increase in the future (OECD, 2015; Rennert & Kingdon, 2019). More directly, effective spectrum policy will contribute to the achievement of climate action goals set nationally and internationally.

The illustrative scenarios for the two hypothetical medium-sized countries show that spectrum policy can have a substantial impact on carbon emissions. The impacts of spectrum policies could reach tens of millions of tonnes in the representative countries, which is comparable to the annual emissions of millions of cars.

These additional emissions arise as a result of increased emissions from the mobile sector itself, where we find that policies delaying transition to more efficient 5G technology could slow down the improvements in network energy efficiency. Similarly, restricting spectrum available to mobile networks could increase emissions linked to manufacturing, transportation and construction of base station equipment. Spectrum fragmentation can negatively affect spectrum utilisation, effectively leading to a similar outcome of restricted throughput per site, greater network density, and greater emissions.

Nevertheless, we find that the greatest emissions impacts arise as a result of the interplay between spectrum policy and the mobile enablement effect. Spectrum policy that affects deployment of networks by increasing costs will reduce adoption of emission-saving use cases enabled by smartphones and mobile IoT devices. This will result in greater emissions throughout the economy, across sectors other than mobile and across households.

Therefore, public policies that minimise climate impact are also closely aligned with the realisation of the economic benefits of mobile connectivity (GSMA, 2022). Sufficient spectrum should therefore be assigned in a timely manner to promote adoption of the newest and most efficient mobile technologies. This can be further supported by assigning contiguous blocks of frequencies and removing any restrictions requiring use of particular technologies in a given band, which will enable optimal transition to the latest technologies.

These spectrum policy principles could lead to mobile networks that are not only more energy efficient but also more cost-effective to build and operate. This ensures the long-term affordability of communications services, maximising their potential to deliver economic benefit while facilitating the adoption of emission-saving use cases and helping to support sustainable development.

The parameterised calculator tool we develop provides a well-grounded analysis of technical aspects of network operations and links these to carbon footprint estimates. The resulting impact estimates offer a meaningful way for the policymakers to evaluate the environmental importance of the examined core spectrum policy choices, in addition to the existing economic assessment frameworks. Therefore, these estimates and methodologies can be used alongside the existing economic cost-benefit analyses used by spectrum managers. With additional steps, carbon emissions impacts could be converted to damage estimates, and combined into a single monetary measure useful in cost-benefit analyses supporting spectrum decisions.

There are, however, areas which will benefit from further research, and we acknowledge a level of uncertainty and model dependence in our estimates. A limitation of our approach is the simplified modelling of the impact of spectrum availability on network topology and operators' costs. In our approach, we characterise network density as driven by capacity needs, rather than coverage needs. In practice, in rural areas the density of networks may be primarily driven by the objective of achieving coverage, which could specifically be dependent on availability of low-band spectrum (sub 1 GHz). This is because low-band spectrum offers superior propagation characteristics, allowing for economically-viable mobile services in rural areas. In the future, the impact of availability of low-band spectrum and coverage as a driver of network design could be examined by more advanced geospatial modelling of both demand and network capacity. Additionally, future approaches could rely on geospatial modelling of demand and supply in representative urban and rural areas. This could utilise representative population density data to estimate local demand. On the supply side, geospatial signal propagation simulations could be used to estimate the required network density to provide coverage, considering differences in propagation characteristics of different radio bands.

Secondly, our approach provides a simplified treatment of mobile operators' behaviour based on cost recovery. Alternative approaches could consider modelling of profit-optimising behaviour according to different competition models. This could better reflect how the impact on network cost could translate into market performance measures, such as prices or the quality of mobile connectivity.

Thirdly, our approach to modelling the impact on energy consumption of the network is based on global parameters of average energy consumption per unit of data for different network generations. This is a simplification because the relationship between energy consumption and data traffic may not be linear. In particular, this could be true of the initial years of operation of 5G networks, and the last years of operations for legacy networks. In these stages, the networks may not be optimally utilised. However, during their main phase of operators, these should in the long-run converge onto optimal path, consistent with the target demand. Hence, the life-cycle energy consumption of networks should be approximately directly variant with the amount of data traffic. Conversely, our assumptions on energy efficiency per unit of data may not be an accurate reflection of energy consumption of legacy networks at a stage when traffic approaches amounts well below their target operating utilisation, just before their shut-down. With idle network energy consumption, reduced data traffic will effectively lead to lower energy efficiency per unit of data.

Lastly, we acknowledge the greater uncertainty in our estimates of the impact on emissions of other sectors and households through the enablement effect. Key parameters, such as projections of the number of connections such as IoT and smartphones, or carbon abatement per connection, are based on illustrative estimates from previous studies (GSMA, 2021) (GSMA, 2019). Further work could seek to empirically establish how adoption of mobile-enabled use cases impacts behavioural changes. Similarly, future research could use empirical methods to study the elasticity of adoption of mobile-enabled use cases with respect to the cost of mobile connectivity, as any impacts through the enablement effect will be directly proportional to the elasticity of demand with respect to mobile connectivity prices. At the same time, the elasticity can vary across different use cases, given the availability of alternative connectivity models which to a varying extent can support the emission-saving use cases.

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A. Appendix

Table A-1 Population and baseline demand assumptions for the modelled countries

Assumption	Unit	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
						Low-income country						
Population projection	millions	84	85	87	89	90	92	93	95	96	98	99
Smartphone connections	millions	40	46	50	55	59	63	68	72	77	82	87
Data demand	GB per user per month	6.1	7.8	10.0	12.8	16.4	21.0	26.8	34.3	44.0	56.3	72.0
						High-income country						
Population projection	millions	84	84	84	84	83	83	83	83	83	83	83
Smartphone connections	millions	97	98	101	102	104	106	108	111	114	116	119
Data demand	GB per user per month	15.1	18.8	22.2	26.2	30.9	36.4	43.0	50.8	59.9	70.7	83.4

Table A-2 Spectral efficiency parameters

Downlink/uplink	Generation	Spectral efficiency (bit/s/MHz)	Notes/source
Downlink	2G	0.30	Based on EDGE (Rysavy Research, 2014)
	3G	0.90	Based on HSDPA (Rysavy Research, 2014)
	4G	1.70	Based on MIMO 4×2 (Rysavy Research, 2014)
	5G	Between 1.80 (low bands) and 6.00 (high bands)	(Coleago Consulting, 2021)

Uplink	2G	0.09	Based on 1/3 of HSUPA, as for DL (Rysavy Research, 2014)
	3G	0.26	Based on HSUPA (Rysavy Research, 2014)
	4G	1.30	Based on MU-MIMO 4×2 (Rysavy Research, 2014)
	5G	Between 1.80 (low bands) and 4.10 (high bands)	(Coleago Consulting, 2021)

Table A-3 Assumptions on energy efficiency of networks

Downlink/uplink	Generation	Energy use (Wh/MB)	Notes/source
Same for both uplink and downlink traffic	2G	37.00	(Malmodin & Lundén, 2018)
	3G	2.90	(Malmodin & Lundén, 2018)
	4G	0.10	(Pihkola, Hongisto, Apilo, & Lasanen, 2018)
	5G	Linearly decreasing from 0.05 in 2022 to 0.005 in 2031	Assuming initially twice as efficient as 4G in 2021, later improving efficiency in line with projections by Orange (Orange, 2020)

Table A-4 Radio access network cost assumptions

Parameter	Value	Source
Capital expenditure per BTS	Macro: $135,000 Micro: $17,000	Illustrative assumption based on 5G NORMA.
Opeating expenditure per BTS, per annum	Macro: $45,000 Micro: $5,667	Assumed at approximately 30% of capex, based on the evidence on 5G networks (Gabriel, 2019).
Share of energy costs in operating expenditure	21%	Based on the evidence on 5G networks (Gabriel, 2019). In the baseline scenario assumed constant throughout the modelled period.

Table A-5 Parameters used in calculation of carbon impacts

Parameter	Low-income country	High-income country
Electricity supply mix of the network	Macro BTS: Purchased electricity: 94% Own diesel generation: 3%	Purchased electricity: 100%

	Own solar: 3% Small sites: Purchased electricity: 100%	
Share of purchased grid electricity by type	Regular grid electricity: 95% Renewables-only electricity: 5%, based on Southeast Asia share (GSMA, 2022)	Regular grid electricity: 29% Renewables-only electricity: 71%, based on European share (GSMA, 2022)
Emissions intensity of regular grid electricity	Based on a reference Asian country (Climate Transparency, 2020): 2022: 350 gCO2e/kWh 2031: 270 gCO2e/kWh Linearly interpolated between the years to decline at the same rate as Asia-Pacific in Ener Blue Scenario (EnerData, 2022)	Based on reference European country: 2022: 322 gCO2e/kWh 2031: 197 gCO2e/kWh Linearly interpolated between the years to decline at the same rate as Europe in Ener Blue Scenario (EnerData, 2022)
Grid share of renewables	Based on reference Asian country (GSMA, 2022): 25%	Based on reference European country (GSMA, 2022): 36%
Emissions intensity of renewables-only grid electricity	53 gCO2e/kWh, Based on the mid-point of estimates for of Poly-SI PV, roof mounted (UNECE, 2021)	
Carbon intensity of operators' own electricity generation	Diesel: 987 gCO2e/kWh, authors' calculations based on carbon emissions per one litre of diesel (BEIS, 2022) Solar: 53 gCO2e/kWh, based on the mid-point of estimates for of Poly-SI PV, roof mounted (UNECE, 2021)	
Share of offices and data centres in total operator emissions	43%, based on a representative operator (Elsa, 2014)	
Carbon embodied in BTS	128 tCO2e per macro BTS 42 tCO2e per micro BTS Authors' calculations based on projected emissions for China's 5G network (Ding, et al., 2022), assuming 10-year life span and including emissions embodied in manufacturing, construction and transport of BTS.	
Emissions embodied in smartphone devices	Figures (Ericsson, n.d.) adapted and annualised assuming a three-year lifespan: 15.2 kgCO2e in 2022, 8.7 kgCO2e in 2031. Linearly interpolated between the years.	
Emissions embodied in IoT devices	Baseline scenario: 2022: 0.02 MtCO2e 2031: 0.1 MtCO2e	Baseline scenario: 2022: 0.1 MtCO2e 2031: 0.2 MtCO2e
	Global IoT manufacturing emissions in 2028 obtained as the average of the best and worst case scenario (Pirson & Bol, 2021). Further scaled down proportionally to our high and low income country shares in total IoT connections in each year of analysis. Annualised assuming a ten-year lifespan of device. 15.2 kgCO2e in 2022, 8.7 kgCO2e in 2031. Linearly interpolated between the years.	

Emissions as a result of energy consumption of smartphones	Excluding network usage: 0.46 kgCO2e/device/year Adapted by the authors from Ericsson (n.d.) Based on a representative grid intensity of 0.6kg/kWh. Assumed constant: while grid electricity intensity will decrease, it is possible that due to denser energy capacity of batteries and more data use, the energy consumption s could increase.
Smartphone network module energy consumption	Without carrier aggregation: 2022: 0.0010 kWh/GB 2031: 0.00015 kWh/GB With carrier aggregation: 2022: 0.0011 kWh/GB 2031: 0.00017 kWh/GB Adopted from Santos, Salehi, Pires, Ortega, & Bazzo (2020) and (Yan, et al., 2019). based on evidence on power consumption in carrier aggregation scenarios and a representative use case of video calling

Figure A-1 Smartphone and IoT connections relying on mobile networks (millions) – baseline assumption in low-income country

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Smartphones	40	46	50	55	59	63	68	72	77	82	87
Crop management	0.012	0.015	0.018	0.022	0.027	0.030	0.033	0.035	0.038	0.041	0.044
Building energy management systems (electricity commercial)	0.149	0.185	0.228	0.282	0.349	0.382	0.415	0.449	0.482	0.516	0.552
Building energy management systems (gas commercial)	0.013	0.016	0.020	0.025	0.031	0.034	0.037	0.040	0.043	0.046	0.049
HVAC control – commercial buildings	0.055	0.069	0.085	0.105	0.130	0.142	0.155	0.167	0.180	0.192	0.206
Smart meters (electricity residential)	3.747	4.649	5.736	7.090	8.774	9.617	10.459	11.301	12.144	12.986	13.887
Electric vehicle connection	0.001	0.001	0.002	0.002	0.003	0.003	0.003	0.003	0.003	0.004	0.004
Micro generation (solar)	0.002	0.003	0.003	0.004	0.005	0.006	0.006	0.007	0.007	0.008	0.008

Micro generation (wind business)	0.002	0.002	0.003	0.003	0.004	0.004	0.005	0.005	0.006	0.006	0.006
Smart grids – electric network management	0.066	0.082	0.102	0.126	0.155	0.170	0.185	0.200	0.215	0.230	0.246
Inventory management	0.042	0.052	0.065	0.080	0.099	0.108	0.118	0.127	0.137	0.146	0.157
Car sharing (car clubs)	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Fleet vehicle driver behaviour improvement	0.456	0.566	0.698	0.863	1.068	1.170	1.273	1.375	1.478	1.580	1.690
Sea fleet – efficient routing	0.001	0.001	0.002	0.002	0.002	0.003	0.003	0.003	0.003	0.003	0.004
Smart logistics – efficient routing and fleet management	0.457	0.567	0.699	0.864	1.069	1.172	1.274	1.377	1.480	1.582	1.692
Smart logistics – loading optimisation	0.456	0.566	0.699	0.864	1.069	1.172	1.274	1.377	1.479	1.582	1.692
Traffic congestion management	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.003	0.003
Traffic congestion monitoring (road signs and traffic lights)	0.001	0.002	0.002	0.003	0.003	0.004	0.004	0.004	0.005	0.005	0.006
Usage-based car insurance	0.283	0.326	0.372	0.422	0.475	0.501	0.527	0.554	0.580	0.606	0.634

Source: GSMA Intelligence analysis based on: (GSMA, 2019) (GSMA, 2021)

Figure A-2 Smartphone and IoT connections relying on mobile networks (millions) – baseline assumption in high-income country

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Smartphones	97	98	101	102	104	106	108	111	114	116	119
Crop management	0.071	0.085	0.100	0.118	0.138	0.148	0.158	0.168	0.178	0.188	0.199
Building energy management systems (electricity commercial)	0.998	1.189	1.403	1.649	1.929	2.068	2.208	2.348	2.487	2.627	2.774
Building energy management systems (gas commercial)	0.088	0.105	0.124	0.146	0.171	0.183	0.196	0.208	0.220	0.233	0.246
HVAC control – commercial buildings	0.375	0.446	0.526	0.619	0.724	0.776	0.828	0.881	0.933	0.986	1.041

Smart meters (electricity residential)	21.250	25.304	29.865	35.106	41.053	44.026	46.999	49.972	52.945	55.918	59.058
Electric vehicle connection	0.008	0.010	0.011	0.013	0.015	0.017	0.018	0.019	0.020	0.021	0.022
Micro generation (solar)	0.012	0.014	0.016	0.019	0.022	0.024	0.026	0.027	0.029	0.031	0.032
Micro generation (wind business)	0.017	0.020	0.023	0.027	0.032	0.034	0.037	0.039	0.041	0.044	0.046
Smart grids – electric network management	0.385	0.459	0.541	0.637	0.744	0.798	0.852	0.906	0.960	1.014	1.071
Inventory management	0.268	0.319	0.376	0.442	0.517	0.554	0.592	0.629	0.667	0.704	0.744
Car sharing (car clubs)	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.006	0.007	0.007	0.007
Fleet vehicle driver behaviour improvement	2.780	3.310	3.906	4.592	5.370	5.759	6.148	6.537	6.925	7.314	7.725
Sea fleet – efficient routing	0.006	0.007	0.009	0.010	0.012	0.013	0.013	0.014	0.015	0.016	0.017
Smart logistics – efficient routing and fleet management	2.778	3.308	3.905	4.590	5.367	5.756	6.145	6.534	6.922	7.311	7.722
Smart logistics – loading optimisation	2.779	3.309	3.905	4.590	5.368	5.757	6.145	6.534	6.923	7.312	7.722
Traffic congestion management	0.004	0.005	0.006	0.007	0.008	0.009	0.009	0.010	0.010	0.011	0.012
Traffic congestion monitoring (road signs and traffic lights)	0.008	0.010	0.012	0.014	0.016	0.017	0.018	0.020	0.021	0.022	0.023
Usage-based car insurance	2.591	2.799	2.988	3.172	3.351	3.441	3.531	3.621	3.711	3.801	3.893

Source: GSMA Intelligence analysis based on: (GSMA, 2019) (GSMA, 2021)

Figure A-3 Carbon abatement factors in low-income country (kgCO2e of avoided emissions per connection per annum)

Connection	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Smartphone	117	115	113	111	108	104	101	98	95	92

Crop management	306	301	296	291	281	273	264	256	248	240
Building energy management systems (electricity commercial)	284	279	274	269	261	253	245	237	230	222
Building energy management systems (gas commercial)	1,571	1,544	1,517	1,491	1,444	1,399	1,355	1,312	1,271	1,231
HVAC control – commercial buildings	2,131	2,094	2,058	2,023	1,960	1,898	1,838	1,780	1,725	1,670
Smart meters (electricity residential)	18	18	18	18	17	16	16	15	15	14
Electric vehicle connection	278	274	269	264	256	248	240	233	225	218
Micro generation (solar)	126,097	123,933	121,807	119,716	115,953	112,308	108,777	105,358	102,046	98,838
Micro generation (wind business)	23,825	23,416	23,014	22,619	21,908	21,220	20,553	19,906	19,281	18,675
Smart grids – electric network management	208	204	200	197	191	185	179	173	168	163
Inventory management	8,546	8,400	8,256	8,114	7,859	7,612	7,373	7,141	6,916	6,699
Car sharing (car clubs)	941	925	909	893	865	838	812	786	761	737
Fleet vehicle driver behaviour improvement	292	287	282	277	268	260	252	244	236	229
Sea fleet – efficient routing	141,790	139,357	136,966	134,615	130,383	126,285	122,315	118,470	114,746	111,139
Smart logistics – efficient routing and fleet management	207	203	200	196	190	184	178	173	167	162
Smart logistics – loading optimisation	83	81	80	78	76	74	71	69	67	65
Traffic congestion management	8,149	8,009	7,872	7,736	7,493	7,258	7,030	6,809	6,595	6,387
Traffic congestion monitoring (road signs and traffic lights)	10,063	9,891	9,721	9,554	9,254	8,963	8,681	8,408	8,144	7,888
Usage-based car insurance	86	85	84	82	80	77	75	72	70	68

Source: GSMA Intelligence analysis based on: (GSMA, 2019) (GSMA, 2021)

Figure A-4 Carbon abatement factors in high-income country (kgCO2e of avoided emissions per connection per annum)

Connection	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Smartphone	278	265	252	240	228	218	207	197	188	179
Crop management	728	693	660	628	598	569	542	516	491	468
Building energy management systems (electricity commercial)	674	642	611	582	554	528	502	478	455	434
Building energy management systems (gas commercial)	3,735	3,556	3,386	3,224	3,070	2,923	2,783	2,649	2,523	2,402
HVAC control – commercial buildings	5,067	4,825	4,593	4,374	4,164	3,965	3,775	3,594	3,422	3,258
Smart meters (electricity residential)	44	42	40	38	36	34	33	31	30	28
Electric vehicle connection	662	630	600	572	544	518	493	470	447	426
Micro generation (solar)	299,845	285,486	271,816	258,800	246,407	234,608	223,373	212,677	202,493	192,796
Micro generation (wind business)	56,653	53,940	51,357	48,898	46,556	44,327	42,204	40,183	38,259	36,427
Smart grids – electric network management	493	470	447	426	406	386	368	350	333	317
Inventory management	20,322	19,349	18,423	17,540	16,701	15,901	15,139	14,414	13,724	13,067
Car sharing (car clubs)	2,237	2,130	2,028	1,931	1,838	1,750	1,667	1,587	1,511	1,438
Fleet vehicle driver behaviour improvement	693	660	629	598	570	542	517	492	468	446
Sea fleet – efficient routing	337,161	321,015	305,644	291,008	277,073	263,805	251,172	239,145	227,693	216,790
Smart logistics – efficient routing and fleet management	491	468	445	424	404	384	366	348	332	316
Smart logistics – loading optimisation	197	187	178	170	161	154	146	139	133	126
Traffic congestion management	19,377	18,449	17,566	16,724	15,924	15,161	14,435	13,744	13,086	12,459

Traffic congestion monitoring (road signs and traffic lights)	23,929	22,783	21,692	20,654	19,665	18,723	17,826	16,973	16,160	15,386
Usage-based car insurance	206	196	186	178	169	161	153	146	139	132

Source: Authors' analysis based on (GSMA, 2019) (GSMA, 2021).

Table A-6 Mobile data traffic estimates (exabytes): low-income country

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Baseline	17.5	22.2	26.8	32.0	38.4	46.4	56.0	67.6	81.7	98.6	119.1
1: Delayed 5G assignment	17.4	19.1	24.6	28.5	35.0	43.0	49.8	63.8	74.4	91.5	108.8
2: Restricted 5G assignments	17.5	20.6	25.5	30.8	37.2	45.0	55.0	65.6	80.0	95.8	117.0
3: Fragmented 5G	17.5	22.0	26.6	31.8	38.1	45.8	55.2	66.6	80.4	97.0	117.1
4: No refarming to 5G	17.5	22.2	26.8	32.0	38.4	46.4	55.7	67.0	80.6	97.1	116.9

Table A-7 Mobile data traffic estimates (exabytes): high-income country

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Baseline	2.9	4.3	6.0	8.4	11.5	15.9	21.8	29.8	40.7	55.5	75.6
1: Delayed 5G assignment	2.9	4.3	5.1	6.2	9.4	14.6	19.9	25.8	39.8	51.9	71.3
2: Restricted 5G assignments	2.9	4.3	5.9	8.1	11.4	15.4	21.5	29.2	39.6	54.4	73.8
3: Fragmented 5G	2.9	4.3	6.0	8.3	11.5	15.7	21.5	29.4	40.1	54.5	74.3
4: No refarming to 5G	2.9	4.3	6.0	8.4	11.5	16.0	21.7	29.5	40.1	54.3	73.5

Table A-8 Emissions by scenario and source (tCO2e): low-income country

Source		2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Baseline											
Mobile sector total		2,548,895	2,167,992	2,358,731	2,345,888	2,655,196	2,253,349	2,423,132	2,790,443	2,659,795	3,245,962
of which:	*RAN*	722,770	728,942	774,539	781,238	791,389	709,128	675,094	763,255	778,033	841,929
	BTS embodied	46,809	16,204	197,648	146,421	429,781	166,201	391,349	601,383	443,231	914,974
	User equipment	734,068	772,942	802,243	828,874	837,014	843,063	847,408	850,016	851,595	853,920
	Other MNO emissions	545,247	549,904	584,301	589,355	597,013	534,957	509,281	575,789	586,937	635,139
Enablement effect total		-7,085,624	-7,888,652	-8,711,751	-9,619,683	-10,075,134	-10,506,635	-10,916,405	-11,304,767	-11,675,212	-12,057,860
of which:	*Smartphone use cases*	-5,348,928	-5,785,417	-6,159,857	-6,519,542	- 6,785,734	- 7,042,937	- 7,292,618	- 7,534,379	- 7,771,021	- 8,015,096
	IoT use cases	-1,736,696	-2,103,235	-2,551,894	-3,100,141	- 3,289,401	- 3,463,698	- 3,623,787	- 3,770,388	- 3,904,190	- 4,042,764
1: Delayed 5G assignment											
Mobile sector total		2,548,895	2,273,961	2,486,036	2,466,519	2,970,218	2,599,036	2,912,875	3,002,931	2,922,958	3,669,094
of which:	*RAN*	722,770	840,559	1,007,302	1,028,463	1,166,302	1,157,583	1,143,362	1,107,502	1,027,051	1,196,063
	BTS embodied	546,809	320,775	451,399	277,927	480,413	181,396	588,187	499,952	547,373	1,066,224
	User equipment	734,068	651,401	597,064	680,312	773,476	771,978	739,683	832,211	799,413	807,778
	Other MNO emissions	545,247	461,226	430,271	479,817	550,027	488,080	441,643	563,266	549,121	599,029
Enablement effect total		-7,085,624	-6,918,009	-7,013,175	-8,343,932	- 9,512,325	- 9,855,762	- 9,894,392	-11,131,789	-11,146,583	-11,576,633
of which:	*Smartphone use cases*	-5,348,928	-4,852,459	-4,536,027	-5,307,813	- 6,251,689	- 6,425,788	- 6,324,081	- 7,370,512	- 7,270,341	- 7,559,407
	IoT use cases	-1,736,696	-2,065,550	-2,477,148	-3,036,119	- 3,260,637	- 3,429,975	- 3,570,312	- 3,761,276	- 3,876,241	- 4,017,226
2: Restricted 5G assignments											
Mobile sector total		2,548,895	2,191,033	2,405,134	2,371,006	2,739,737	2,273,456	2,467,683	2,880,513	2,708,696	3,355,686
of which:	*RAN*	722,770	728,998	802,681	816,937	848,965	756,880	720,908	822,268	835,366	903,884
	BTS embodied	546,809	172,248	258,719	156,679	501,248	155,841	416,048	669,742	461,906	997,537
	User equipment	734,068	753,823	777,769	816,864	811,448	832,654	831,468	828,218	835,894	834,450
	Other MNO emissions	545,247	535,965	565,965	580,526	578,076	528,082	499,259	560,285	575,530	619,815
Enablement effect total		-7,085,624	-7,736,077	-8,509,544	-9,516,857	- 9,848,303	-10,411,180	-10,764,963	-11,090,614	-11,515,759	-11,853,638
of which:	*Smartphone use cases*	-5,348,928	-5,638,765	-5,966,548	-6,421,876	- 6,570,495	- 6,952,428	- 7,149,100	- 7,331,507	- 7,619,999	- 7,821,712
	IoT use cases	-1,736,696	-2,097,312	-2,542,996	-3,094,981	- 3,277,808	- 3,458,752	- 3,615,863	- 3,759,107	- 3,895,760	- 4,031,926

3: Fragmented 5G											
Mobile sector total		2,548,895	2,170,942	2,365,349	2,354,365	2,681,539	2,271,897	2,456,796	2,839,314	2,708,123	3,330,597
of which:	*RAN*	722,770	728,788	778,320	788,991	806,910	727,262	697,380	793,099	812,271	882,347
	BTS embodied	546,809	123,523	206,253	154,942	453,867	181,487	420,444	639,667	479,768	984,041
	User equipment	734,068	770,512	798,960	824,404	829,434	834,166	836,603	838,854	838,711	840,185
	Other MNO emissions	545,247	548,118	581,816	586,028	591,329	528,982	502,369	567,694	577,373	624,024
Enablement effect total		-7,085,624	-7,869,105	-8,684,344	-9,580,937	-10,007,057	-10,423,676	-10,811,964	-11,192,957	-11,541,519	-11,909,737
of which:	*Smartphone use cases*	-5,348,928	-5,766,629	-6,133,656	-6,482,740	- 6,721,135	- 6,964,276	- 7,193,642	- 7,428,459	- 7,644,397	- 7,874,834
	IoT use cases	-1,736,696	-2,102,476	-2,550,688	-3,098,197	- 3,285,922	- 3,459,400	- 3,618,322	- 3,764,498	- 3,897,122	- 4,034,903
4: No refarming to 5G											
Mobile sector total		2,548,895	2,167,992	2,358,731	2,345,888	2,727,300	2,404,229	2,695,106	3,129,621	3,080,804	3,866,753
of which:	*RAN*	722,770	728,942	774,539	781,238	881,896	861,405	957,588	1,105,173	1,215,963	1,463,710
	BTS embodied	546,809	116,204	197,648	146,421	401,553	170,767	392,083	617,976	454,341	954,188
	User equipment	734,068	772,942	802,243	828,874	842,608	839,439	840,435	838,650	835,266	831,264
	Other MNO emissions	545,247	549,904	584,301	589,355	601,243	532,618	505,001	567,823	575,233	617,590
Enablement effect total		-7,085,624	-7,888,652	-8,711,751	-9,619,683	-10,125,814	-10,474,162	-10,851,723	-11,194,738	-11,511,604	-11,823,992
of which:	*Smartphone use cases*	-5,348,928	-5,785,417	-6,159,857	-6,519,542	- 6,833,823	- 7,012,147	- 7,231,320	- 7,430,146	- 7,616,064	- 7,793,639
	IoT use cases	-1,736,696	-2,103,235	-2,551,894	-3,100,141	- 3,291,991	- 3,462,016	- 3,620,402	- 3,764,592	- 3,895,540	- 4,030,353

Table A-9 Emissions by scenario and source (tCO2e): high-income country

Source		2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Baseline											
Mobile sector total		3,936,139	3,561,631	3,418,615	3,363,985	3,297,754	2,784,865	3,324,083	2,691,289	3,396,344	2,416,436
of which:	*RAN*	857,209	840,179	812,653	789,575	745,465	648,310	633,562	588,469	624,228	575,989
	BTS embodied	787,456	462,032	399,470	407,824	467,734	169,731	775,836	261,083	941,061	80,011
	User equipment	1,644,807	1,625,601	1,593,438	1,570,942	1,522,188	1,477,749	1,436,734	1,397,804	1,360,146	1,325,918
	Other MNO emissions	646,667	633,819	613,054	595,644	562,368	489,076	477,950	443,932	470,909	434,518
Enablement effect total		-76,680,922	-79,830,322	-82,914,212	-86,459,809	-86,232,815	-85,866,733	-85,353,844	-84,682,658	-83,851,713	-83,048,889
of which:	*Smartphone use cases*	-40,419,797	-39,298,448	-37,782,721	-36,458,235	-35,370,827	-34,360,563	-33,399,987	-32,459,319	-31,520,156	-30,608,166

Source		2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
	IoT use cases	-36,261,125	-40,531,874	-45,131,491	-50,001,574	-50,861,988	-51,506,170	-51,953,857	-52,223,339	-52,331,557	-52,440,722
Mobile sector total		4,434,708	3,791,651	3,690,994	3,571,434	3,500,250	3,050,123	3,563,446	2,921,086	3,703,924	2,556,540
of which:	*RAN*	949,626	960,806	962,388	950,602	943,505	902,963	888,639	792,707	789,789	724,994
	BTS embodied	1,499,322	752,590	749,836	632,514	610,826	378,015	859,867	435,748	1,202,101	205,453
	User equipment	1,428,598	1,497,591	1,432,668	1,445,159	1,423,876	1,333,714	1,364,357	1,288,654	1,275,425	1,229,209
	Other MNO emissions	557,162	580,665	546,102	543,159	522,042	435,431	450,584	403,978	436,609	396,884
Enablement effect total		-70,528,820	-76,156,930	-78,240,291	-82,757,765	-83,291,228	-81,470,171	-83,110,899	-81,239,033	-81,132,300	-79,893,255
of which:	*Smartphone use cases*	-34,825,346	-36,002,739	-33,656,449	-33,245,732	-32,834,482	-30,591,719	-31,487,573	-29,537,935	-29,224,272	-27,957,188
	IoT use cases	-35,703,474	-40,154,191	-44,583,842	-49,512,033	-50,456,747	-50,878,452	-51,623,326	-51,701,097	-51,908,028	-51,936,067
2: Restricted 5G assignments											
Mobile sector total		4,241,720	3,692,098	3,491,054	3,418,318	3,341,408	2,741,657	3,404,141	2,677,622	3,496,584	2,364,529
of which:	*RAN*	916,439	927,108	907,341	884,747	831,979	723,029	703,151	647,142	685,373	631,393
	BTS embodied	1,194,084	611,803	455,636	433,176	480,946	84,032	839,139	224,325	1,026,695	-
	User equipment	1,531,433	1,550,516	1,538,041	1,524,219	1,482,445	1,454,257	1,398,432	1,371,775	1,327,036	1,306,269
	Other MNO emissions	599,764	602,671	590,035	576,176	546,038	480,339	463,420	434,380	457,480	426,867
Enablement effect total		-73,457,043	-77,677,720	-81,307,288	-85,086,632	-85,041,647	-85,150,666	-84,162,927	-83,859,360	-82,787,046	-82,407,319
of which:	*Smartphone use cases*	-37,488,144	-37,367,168	-36,364,082	-35,266,641	-34,343,758	-33,746,733	-32,384,569	-31,760,878	-30,621,303	-30,069,198
	IoT use cases	-35,968,900	-40,310,552	-44,943,206	-49,819,991	-50,697,889	-51,403,934	-51,778,358	-52,098,482	-52,165,743	-52,338,121
3: Fragmented 5G											
Mobile sector total		3,971,041	3,588,008	3,444,916	3,392,845	3,339,565	2,809,095	3,386,145	2,722,122	3,468,053	2,438,012
of which:	*RAN*	863,725	851,916	828,700	809,513	769,088	670,114	659,113	614,562	654,669	603,147
	BTS embodied	831,657	493,545	428,090	436,729	510,766	195,796	838,502	291,839	1,008,556	99,976
	User equipment	1,633,685	1,613,753	1,580,541	1,556,906	1,504,665	1,460,612	1,417,869	1,378,874	1,341,596	1,307,660
	Other MNO emissions	641,974	628,794	607,585	589,697	555,046	482,572	470,661	436,846	463,232	427,229
Enablement effect total		-76,358,379	-79,483,042	-82,532,439	-86,040,310	-85,698,680	-85,333,729	-84,756,361	-84,071,910	-83,243,086	-82,437,692
of which:	*Smartphone use cases*	-40,126,491	-38,986,875	-37,445,681	-36,094,209	-34,910,275	-33,903,659	-32,890,552	-31,941,194	-31,006,318	-30,094,713
	IoT use cases	-36,231,888	-40,496,168	-45,086,758	-49,946,101	-50,788,404	-51,430,071	-51,865,809	-52,130,716	-52,236,768	-52,342,978
4: No refarming to 5G											
Mobile sector total		3,936,139	3,561,631	3,418,615	3,363,985	3,320,913	2,872,681	3,485,281	2,851,407	3,611,399	2,595,249
of which:	*RAN*	857,209	840,179	812,653	789,575	783,911	740,944	787,830	760,483	824,746	784,083
	BTS embodied	787,456	462,032	399,470	407,824	449,677	173,466	800,241	271,159	980,978	79,796
	User equipment	1,644,807	1,625,601	1,593,438	1,570,942	1,524,088	1,471,474	1,423,971	1,381,643	1,341,994	1,304,905
	Other MNO emissions	646,667	633,819	613,054	595,644	563,237	486,798	473,240	438,120	463,682	426,466
Enablement effect total		-76,680,922	-79,830,322	-82,914,212	-86,459,809	-86,296,175	-85,680,057	-84,967,774	-84,181,730	-83,278,712	-82,373,675
of which:	*Smartphone use cases*	-40,419,797	-39,298,448	-37,782,721	-36,458,235	-35,425,458	-34,200,539	-33,070,810	-32,034,359	-31,036,395	-30,040,934
	IoT use cases	-36,261,125	-40,531,874	-45,131,491	-50,001,574	-50,870,717	-51,479,517	-51,896,964	-52,147,371	-52,242,316	-52,332,741

Table A-10 Spectrum availability assumptions by scenario, network generation and band (MHz): low-income country

Gen	Band	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Baseline												
2G	**Low (<1GHz)**	10	10	9	9	8	8	7	7	6	6	5
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	0	0	0	0	0	0	0	0	0	0	0
	Lower mid (1GHz-2.6GHz)	40	40	40	40	40	30	20	10	10	10	10
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	180	180	230	280	330	280	280	230	230	180	130
	Lower mid (1GHz-2.6GHz)	169	169	219	269	319	269	269	219	219	169	119
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
5G	**Low (<1GHz)**	0	0	0	0	0	60	70	130	130	180	230
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	50	50	100	100	150	200
	Upper mid(3.5GHz-6GHz)	0	0	200	200	300	300	400	400	400	400	400
	High (24GHz-40GHz)	0	0	0	0	0	0	50	100	100	200	200
1: Delayed 5G												
2G	**Low (<1GHz)**	10	10	10	10	9	9	8	8	7	7	6
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	0	0	0	0	0	0	0	0	0	0	0
	Lower mid (1GHz-2.6GHz)	40	40	40	40	40	40	40	30	20	10	10
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	180	180	180	180	230	280	330	280	280	230	230
	Lower mid (1GHz-2.6GHz)	169	169	169	169	219	269	319	269	269	219	219
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
5G	**Low (<1GHz)**	0	0	0	0	0	0	0	60	70	130	130

Gen	Band	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	0	0	50	50	100	100
	Upper mid(3.5GHz-6GHz)	0	0	0	0	200	200	300	300	400	400	400
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	50	100	100
2: Restricted 5G assignments												
2G	**Low (<1GHz)**	10	10	9	9	8	8	7	7	6	6	5
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	0	0	0	0	0	0	0	0	0	0	0
	Lower mid (1GHz-2.6GHz)	40	40	40	40	40	30	20	10	10	10	10
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	180	180	230	280	330	280	280	230	230	180	130
	Lower mid (1GHz-2.6GHz)	169	169	219	269	319	269	269	219	219	169	119
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
5G	**Low (<1GHz)**	0	0	0	0	0	60	70	130	130	180	230
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	50	50	100	100	150	200
	Upper mid(3.5GHz-6GHz)	0	0	100	100	200	200	300	300	300	300	300
	High (24GHz-40GHz)	0	0	0	0	0	0	50	100	100	200	200
3: Fragmented 5G spectrum												
2G	**Low (<1GHz)**	10	10	9	9	8	8	7	7	6	6	5
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	0	0	0	0	0	0	0	0	0	0	0
	Lower mid (1GHz-2.6GHz)	40	40	40	40	40	30	20	10	10	10	10
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	180	180	230	280	330	280	280	230	230	180	130
	Lower mid (1GHz-2.6GHz)	169	169	219	269	319	269	269	219	219	169	119
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
5G	**Low (<1GHz)**	0	0	0	0	0	60	70	130	130	180	230
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	50	50	100	100	150	200
	Upper mid(3.5GHz-6GHz)	0	0	200	200	300	300	400	400	400	400	400
	High (24GHz-40GHz)	0	0	0	0	0	0	50	100	100	200	200

Gen	Band	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
4: No refarming to 5G												
2G	**Low (<1GHz)**	10	10	9	9	8	8	7	7	6	6	5
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	0	0	0	0	0	0	0	0	0	0	0
	Lower mid (1GHz-2.6GHz)	40	40	40	40	40	40	40	40	40	40	40
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	180	180	230	280	330	330	330	330	330	330	330
	Lower mid (1GHz-2.6GHz)	169	169	219	269	319	319	319	319	319	319	319
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
5G	**Low (<1GHz)**	0	0	0	0	0	0	0	0	0	0	0
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	0	0	0	0	0	0
	Upper mid(3.5GHz-6GHz)	0	0	200	200	300	300	400	400	400	400	400
	High (24GHz-40GHz)	0	0	0	0	0	0	50	100	100	200	200

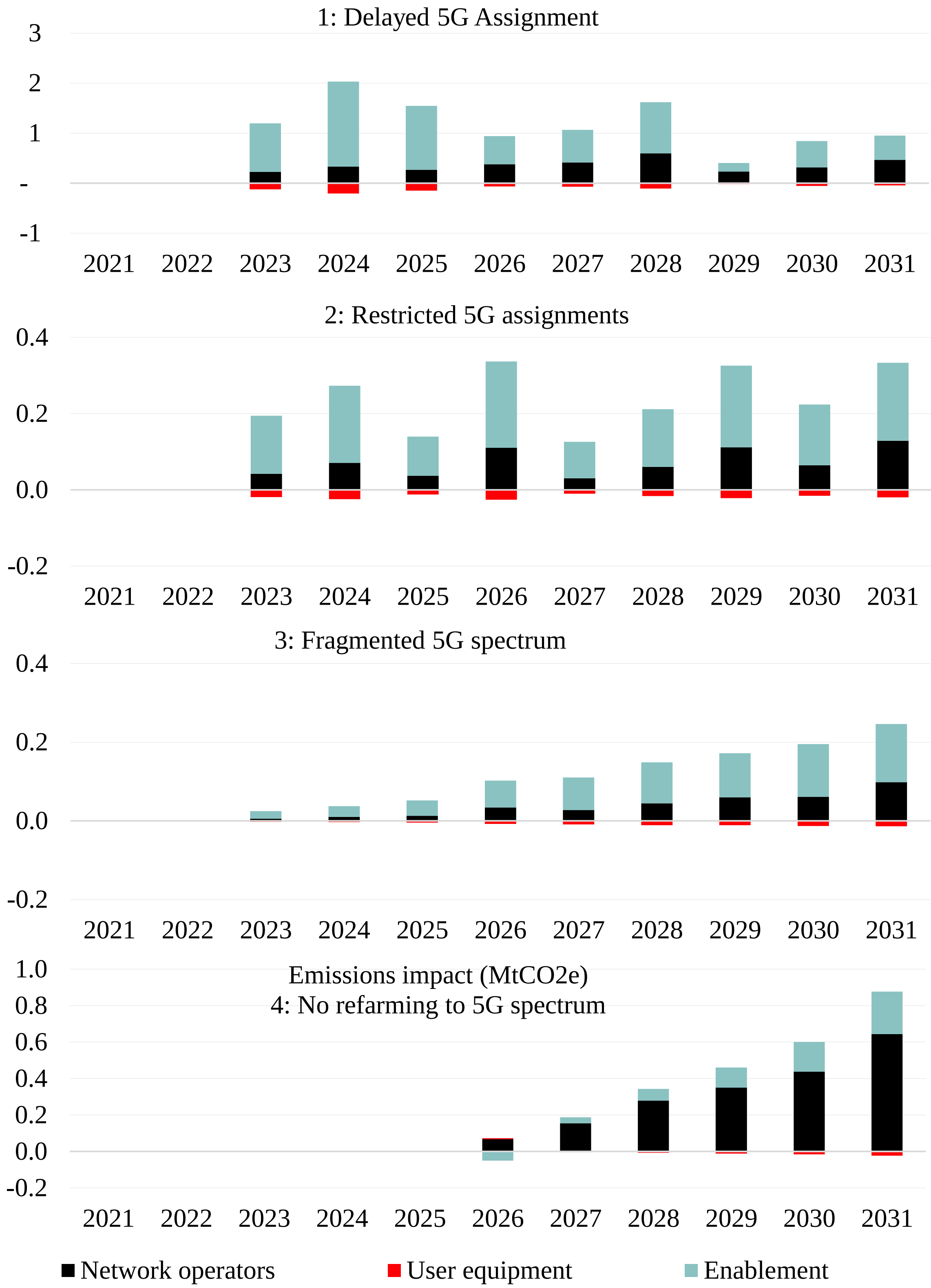
Table A-11 Spectrum availability assumptions by scenario, network generation and band (MHz): high-income country

Gen	Band	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Baseline												
2G	**Low (<1GHz)**	10	10	10	10	10	10	10	10	10	10	10
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	10	10	10	10	10	10	5	5	5	5	5
	Lower mid (1GHz-2.6GHz)	10	10	10	10	10	10	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	250	250	250	250	250	200	200	150	120	100	100
	Lower mid (1GHz-2.6GHz)	300	300	300	300	300	250	250	175	150	150	100
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0

Gen	Band	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
5G	**Low (<1GHz)**	0	0	0	0	0	50	55	105	135	155	155
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	50	55	130	155	155	205
	Upper mid(3.5GHz-6GHz)	150	150	200	250	300	350	450	450	450	450	500
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	100	100	200
1: Delayed 5G												
2G	**Low (<1GHz)**	10	10	10	10	10	10	10	10	10	10	10
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	10	10	10	10	10	10	10	10	5	5	5
	Lower mid (1GHz-2.6GHz)	10	10	10	10	10	10	10	10	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	250	250	250	250	250	250	250	200	200	150	120
	Lower mid (1GHz-2.6GHz)	300	300	300	300	300	300	300	250	250	175	150
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
5G	**Low (<1GHz)**	0	0	0	0	0	0	0	50	55	105	135
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	0	0	50	55	130	155
	Upper mid(3.5GHz-6GHz)	0	0	150	150	200	250	300	350	400	400	400
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	100
2: Restricted 5G assignments												
2G	**Low (<1GHz)**	10	10	10	10	10	10	10	10	10	10	10
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	10	10	10	10	10	10	5	5	5	5	5
	Lower mid (1GHz-2.6GHz)	10	10	10	10	10	10	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	250	250	250	250	250	200	200	150	120	100	100
	Lower mid (1GHz-2.6GHz)	300	300	300	300	300	250	250	175	150	150	100
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
5G	**Low (<1GHz)**	0	0	0	0	0	50	55	105	135	155	155
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	50	55	130	155	155	205
	Upper mid(3.5GHz-6GHz)	50	50	100	150	200	250	350	350	350	350	400

Gen	Band	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	100	100	200
3: Fragmented 5G spectrum												
2G	**Low (<1GHz)**	10	10	10	10	10	10	10	10	10	10	10
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	10	10	10	10	10	10	5	5	5	5	5
	Lower mid (1GHz-2.6GHz)	10	10	10	10	10	10	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	250	250	250	250	250	200	200	150	120	100	100
	Lower mid (1GHz-2.6GHz)	300	300	300	300	300	250	250	175	150	150	100
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
5G	**Low (<1GHz)**	0	0	0	0	0	50	55	105	135	155	155
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	50	55	130	155	155	205
	Upper mid(3.5GHz-6GHz)	150	150	200	250	300	350	450	450	450	450	500
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	100	100	200
4: No refarming to 5G												
2G	**Low (<1GHz)**	10	10	10	10	10	10	10	10	10	10	10
	Lower mid (1GHz-2.6GHz)	5	5	5	5	5	5	5	5	5	5	5
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
3G	**Low (<1GHz)**	10	10	10	10	10	10	10	10	10	10	10
	Lower mid (1GHz-2.6GHz)	10	10	10	10	10	10	10	10	10	10	10
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
4G	**Low (<1GHz)**	250	250	250	250	250	250	250	250	250	250	250
	Lower mid (1GHz-2.6GHz)	300	300	300	300	300	300	300	300	300	300	300
	Upper mid(3.5GHz-6GHz)	0	0	0	0	0	0	0	0	0	0	0
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	0	0	0
5G	**Low (<1GHz)**	0	0	0	0	0	0	0	0	0	0	0
	Lower mid (1GHz-2.6GHz)	0	0	0	0	0	0	0	0	0	0	0
	Upper mid(3.5GHz-6GHz)	150	150	200	250	300	350	450	450	450	450	500
	High (24GHz-40GHz)	0	0	0	0	0	0	0	0	100	100	200

Figure A-5 Emissions impacts in low-income country: detailed impact breakdowns (MtCO2e)

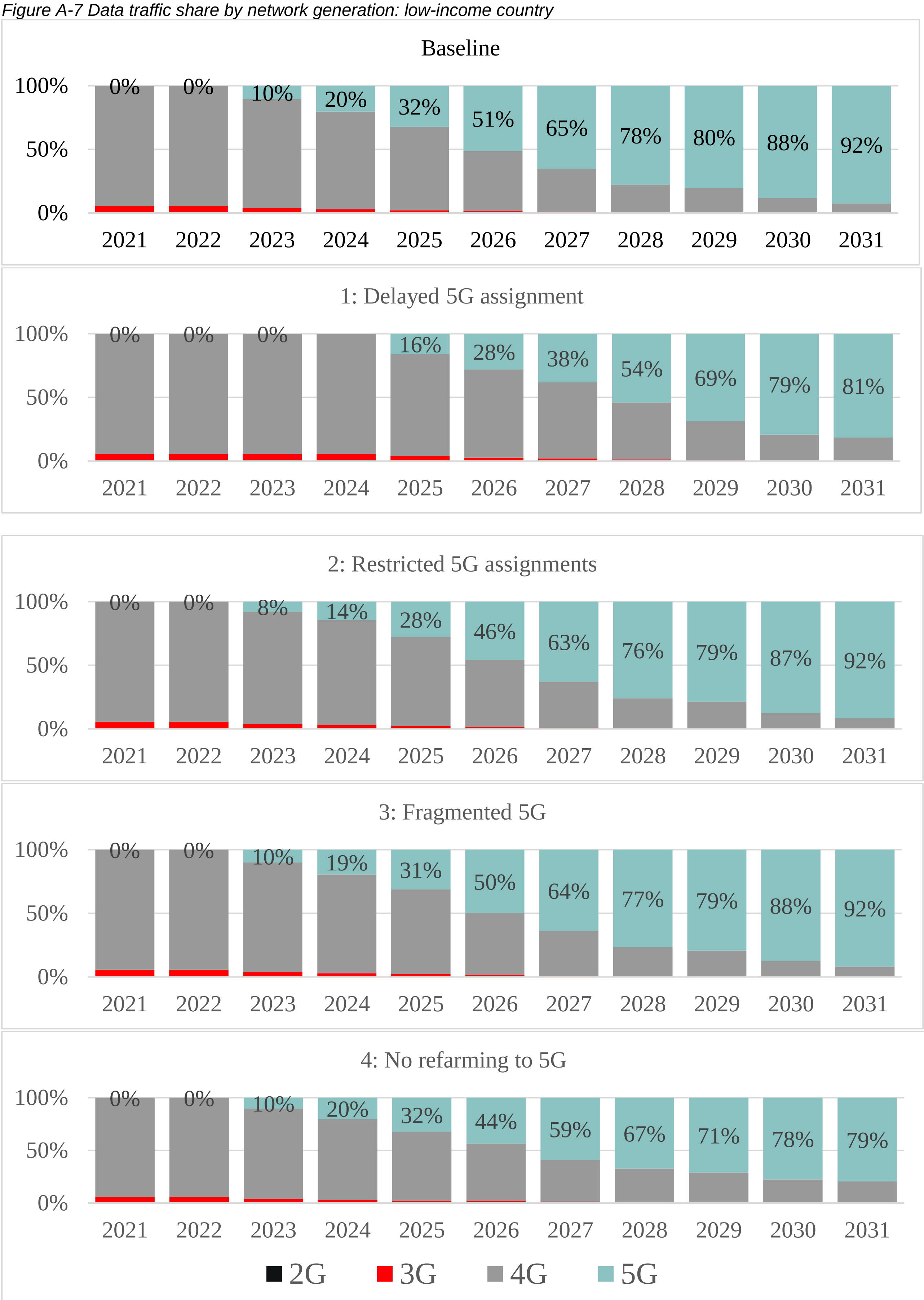


Source: Authors' analysis based on (GSMA, 2019) (GSMA, 2021).

Figure A-6 Emissions impacts in high-income country: detailed impact breakdowns (MtCO2e)

Source: Authors' analysis based on (GSMA, 2019) (GSMA, 2021).

Figure A-7 Data traffic share by network generation: low-income country



Source: Authors' analysis based on (GSMA, 2019) (GSMA, 2021).

Figure A-8 Data traffic share by network generation: high-income country

Source: Authors' analysis based on (GSMA, 2019) (GSMA, 2021).