GSMA

May 2023

# Spectrum: the Climate Connection

## Spectrum policy and carbon emissions

## Appendix

## GSMA

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www.gsmaintelligence.com

info@gsmaintelligence.com

**Authors:**
Jakub Zagdanski, Senior Economist
Pau Castells, Head of Economic Analysis
**Contributors:**
Carol Sosa Leguizamón
Ross Bateson

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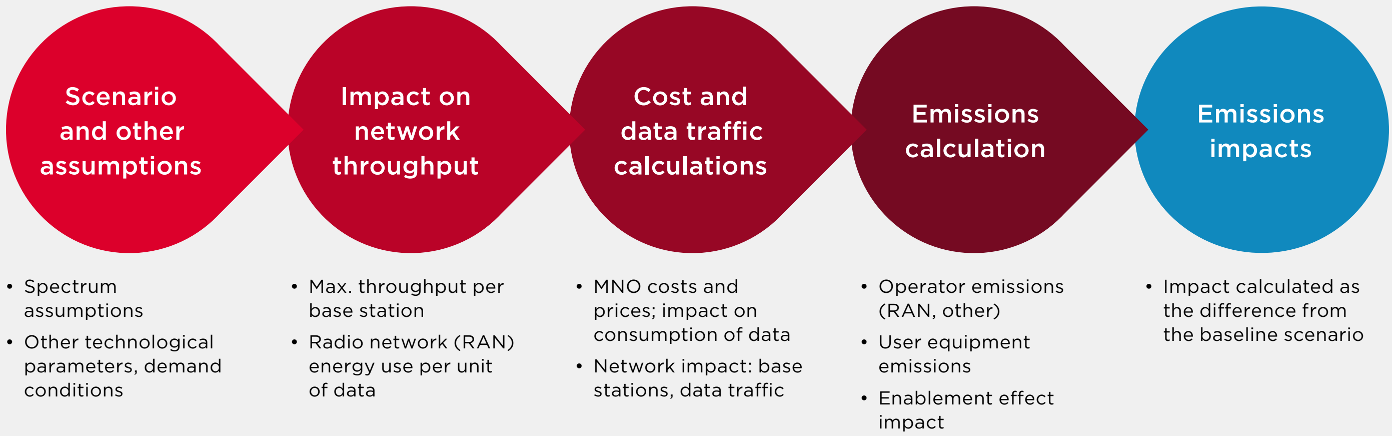
# Appendix A1: Quantitative modelling

## Introduction

To assess the carbon impact of different spectrum policies, we developed 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/IoT devices.

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




Source: GSMA Intelligence

As shown in Figure 1, the calculation comprises four steps. First, we enter into the model the assumptions of the baseline spectrum policy, as well as four alternative scenarios with different, sub-optimal spectrum policy choices. Each set of spectrum assumptions represents the impact of a particular spectrum policy aspect. 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 element in this calculation is the 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 previous intermediate outputs 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 in terms of the mobile traffic demand in GB 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.

## Scenarios and countries considered in the quantitative assessment

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 Figure 2. The reference scenario (Baseline) is used as a comparator versus four different scenarios, each highlighting a separate aspect of spectrum 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.

**Figure 2**
**Spectrum policy assumptions used in the modelled scenarios**

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

Source: GSMA Intelligence

We consider the effects of these different spectrum policy choices on two hypothetical countries. As shown in Figure 3 (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.[1] 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 emissions impacts, we estimate the current total carbon emissions of the low-income country at about 160 megatonnes of CO2 equivalent (MtCO2e) versus 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 rapid economic growth and some growth in population. In contrast, the high-income country aims to reduce its emissions by about a half.

## Figure 3
## Comparison of hypothetical countries used in modelling

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

Notes: All figures are approximate. Targets are based on Paris Climate Agreement targets for benchmark countries. GDP per capita quoted in purchasing power parity terms (2021 international USD).
Source: GSMA Intelligence

1 GSMA (2022) "Mobile Industry position paper Access to renewable electricity". https://www.gsma.com/betterfuture/wp-content/uploads/2022/11/Mobile_Industry_Position_Paper_Access_to_Renewable_Electricity_Nov22.pdf

## Scenario-related and other assumptions

The model performs calculations based on a range of assumptions, which can be divided into two types:

1. Spectrum policy assumptions for the baseline and alternative scenarios.

2. Technical parameters that do not change across scenarios. These include assumptions on baseline demand for mobile data and number of subscribers, technical parameters on the spectral efficiency and energy efficiency of mobile networks, assumptions on operator costs, and others.

### Spectrum policy assumptions (vary across scenarios)

The spectrum policy assumptions include two aspects of spectrum assignments:

- The amount of spectrum assigned to mobile operators and its use by generation for each year of calculation. In the model, we aggregate spectrum holdings at a country level to estimate overall capacity across all mobile networks.
- The level of fragmentation of 5G spectrum. 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).

### 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 4).

**Figure 4**

**Estimating total demand for data and required peak-hour network throughput**

**Projected number of smartphone subscribers** →

- GSMA Intelligence projections

**Demand for data per user, per month** →

- Based on representative use projections

**Required peak-hour network throughput**

- Intermediate calculation based on the peak throughput rate parameter

Source: GSMA Intelligence

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. The projected number of smartphone subscribers is multiplied by the assumed demand for mobile data per subscriber. The assumptions are based on current and projected growth in consumption of mobile data for regions corresponding to our representative countries: Southeast Asia for the low-income country and Western Europe for the high-income country.[2] The two assumptions are used in an intermediate calculation to obtain the annual amount of mobile traffic in gigabytes.

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%, 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).[3] Hence the required peak-hour throughput to serve the given annual demand is calculated as follows:

$$\textit{Peak hour throughput (bytes per second)} = \frac{\textit{Annual data traffic}}{365} * \textit{Peak hour rate}$$

## Impact on network throughput

We use additional calculations to estimate the maximum throughput per base station, 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 (Figure 5).

We develop estimates of maximum throughput per base station for two sizes of base station:

- macro base station, with three sectors of operation permitting higher throughput
- micro base station, with a single sector of operation.

Among these, we distinguish between 5G-enabled and legacy sites. 5G-enabled sites can utilise all 5G spectrum holdings, boosting their throughput. In contrast, legacy site throughput is limited to throughput offered by spectrum assigned to 2G, 3G and 4G networks.

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

$$\begin{aligned}&\textit{Maximum throughput per base station}\\&\quad = \textit{Allocated spectrum} \times (\textit{Spectral efficiency DL} * \textit{DL ratio}\\&\quad + \textit{Spectral efficiency UL} * \textit{(1-DL ratio)}) \times \textit{Sectors}\end{aligned}$$

Downlink (DL) ratio is the assumed share of downlink data in the total mobile traffic, at 75%. Using the calculated maximum throughput per base station and additional assumptions on the share of each type of site allows us to calculate the share of each generation in the total traffic handled by each type of base station. This is assumed to be proportional to the throughput offered by each network generation, given the spectrum allocated to it.

2 Ericsson (2022) "Mobile data traffic outlook". https://www.ericsson.com/en/reports-and-papers/mobility-report/dataforecasts/mobile-traffic-forecast
3 Adapted by GSMA from Nokia Siemens Networks (2010) "Mobile broadband with HSPA and LTE – capacity and cost aspects". https://fcc.report/ELS/Nokia-House/0249-EX-ML-2011/121259.pdf

**Figure 5**
## Spectral efficiency parameters used in modelling

| Downlink/uplink | Generation | Spectral efficiency (bit/s/MHz) | Source | Notes |
|---|---|---|---|---|
| Downlink | 2G | 0.30 | Rysavy Research, 2014 | Based on EDGE |
| | 3G | 0.90 | Rysavy Research, 2014 | Based on HSDPA |
| | 4G | 1.70 | Rysavy Research, 2014 | Based on MIMO 4×2 |
| | 5G | Between 1.80 (low bands) and 6.00 (high bands) | Coleago (2021) | |
| Uplink | 2G | 0.09 | Rysavy Research, 2014 | Based on 1/3 of HSUPA, as for DL |
| | 3G | 0.26 | Rysavy Research, 2014 | Based on HSUPA |
| | 4G | 1.30 | Rysavy Research, 2014 | Based on MU-MIMO 4×2 |
| | 5G | Between 1.80 (low bands) and 4.10 (high bands) | Coleago (2021) | |

In the same step, we calculate the average energy consumption per unit of data, given the available spectrum. The energy efficiency of networks is measured in Watt hours per megabyte of transmitted data (Wh/MB). According to the surveyed estimates (Figure 6), the energy efficiency of networks varies significantly across different generations. In addition, it is expected that the energy efficiency of 5G networks will continuously improve.

To estimate combined network energy efficiency, we weight the energy efficiencies of different network generations by their share in network throughput.

**Figure 6**

**Energy efficiency of networks – assumptions on energy use per unit of data**

| Generation | Band | Downlink/uplink | Energy use (Wh/MB) | Source | Notes |
|---|---|---|---|---|---|
| **2G** | All bands | Same for both uplink and downlink traffic | 37.00 | Malmodin (2018) | |
| **3G** | | | 2.90 | Malmodin (2018) | |
| **4G** | | | 0.10 | Pihkola et al. (2018) | Based on the projected efficiency for 2020 |
| **5G** | | | Linearly decreasing from 0.05 in 2022 to 0.005 in 2031 | Adapted by GSMA from Orange (2020) | Assuming initially twice as efficient as 4G in 2021, later improving efficiency in line with Orange (2020) projections. |

# Cost and data traffic calculations

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

## Baseline costs and network variables

We use a stock-flow model to estimate the composition of types of base station and their number required to meet the data traffic. For the baseline scenario, we calculate this according to the following steps:

1. We estimate the throughput of existing base stations based on the spectrum holdings in a given year. Based on a 10-year lifespan of a base station, we assume that 10% of the existing stock of base stations needs to be replaced with new equipment each year. If 5G spectrum has been available to the operators in that year, the operators replace them with 5G-enabled base stations. Otherwise, these will be replaced with legacy-type base stations (unable to use 5G spectrum). This step allows us to calculate the network throughput gap for the existing stock of base stations, after any upgrades. The throughput gap is calculated as the difference between the throughput required to serve demand and the throughput offered by existing base stations.
2. Using the estimated network throughput gap, we calculate the number of additional base stations needed to meet the throughput gap. In a similar way to the previous step, we assume that the newly added base stations will be 5G-enabled if 5G spectrum is available to operators, or legacy-type if 5G spectrum has not yet been assigned.

In steps 1 and 2, to accurately represent multiple network operators, we multiply the estimated number of base stations by three, assuming that the sites and equipment need to be set up separately for each operator. We effectively assume three operators, which is the typical number of large operators in medium-sized countries. We use additional assumptions to account for imperfect utilisation of base stations in the peak hour. To account for this, we further scale the estimated number of base stations three-fold. This adjustment is supported by evidence showing that, even in busy networks, resources are not utilised 75–90% of the time.[4]

Steps 1 and 2 provide us with the number of base stations and their type. Combined with the throughput per base station parameters, these figures allow us to estimate the share of each network generation in total network traffic.

In further steps, we focus calculations on costs. For the baseline scenario:

- we use additional parameters on the setup and annual running cost per base station (these assumptions are outlined in Figure 7)
- we estimate the energy cost as a component of total network cost based on assumptions in Figure 7.

In the last step, we sum the costs to estimate the baseline network cost and network cost per unit of data.

**Figure 7**
**Cost calculation parameters used in modelling**

| Parameter | Value | Source |
|---|---|---|
| **Capex per base station** | Macro: $135,000<br>Micro: $17,000 | Illustrative assumptions based on 5G NORMA |
| **Opex per base station, per annum** | Macro: $45,000<br>Micro: $5,667 | Assumed at approximately 30% of capex, based on the evidence on 5G networks[5] |
| **Share of energy costs in opex** | 21% | Based on the evidence on 5G networks.[6] In the baseline scenario is assumed constant throughout the modelled period |

4 RCRWIrelessNews (2022) "The green credentials of 5G and IoT". https://f.hubspotusercontent40.net/hubfs/8928696/20220208%20Green%20Credentials%20IoT%20Editorial%20Report.pdf
5 Analysys Mason (2019) "What are key considerations for 5G sites?". https://www.analysysmason.com/globalassets/x_migrated-media/media/analysys_mason_5g_key_considerations_white_paper_oct20192.pdf
6 Ibid.

## Alternative scenario costs and network variables

In the calculation of alternative scenarios, we dynamically model the relationship between the key network variables (number of base stations, 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, we use the alternative spectrum assignment assumptions to estimate the throughput of existing base stations, and the throughput gap to meet demand for data.

As with the baseline, this allows us to estimate the alternative capital costs, based on the stock of base stations, which determines the number of base stations to be replaced (at 10% of the stock, in line with the depreciation rate) and the number of new base stations to be added.

Similarly, we calculate operational costs, including the energy cost component. The energy cost component is estimated by adjusting the baseline energy cost according to the change in the combined network's energy efficiency per unit of data estimated in the earlier steps. For example, if the energy consumption of the network decreased 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.

In the next step, we sum all the costs to obtain the total network cost in the alternative scenario. We compare this estimate to the baseline scenario data traffic and costs to 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. To do this, we use further assumptions on the share of network costs in total operator costs and cost pass-through ratio. We use the following formula to estimate the impact on consumer prices:

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

### Figure 8
### Cost calculation parameters used in modelling

| Parameter | Value | Source |
|---|---|---|
| **Cost pass-through ratio** | 80% | Illustrative assumptions based on pass-through of mobile taxation[7] |
| **RAN cost as a share of total MNO costs** | 29% | Baseline scenario assumption based on European network data[8] |
| **Price elasticity of demand** | –0.9 | Based on the estimate of ownership elasticity with respect to the cost of services for low-income countries[9] |

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. This step marks the end of one iteration in the process of dynamic estimation of demand and costs for a single year of estimation. 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.

As a result of modelling the demand for mobile services as responsive to costs and prices, our modelling accounts for rebound effects.[10] In our modelling, lower energy efficiency of the network and higher number of base stations translate into a cost impact, which is partly passed onto consumers, who adjust their demand for mobile services.

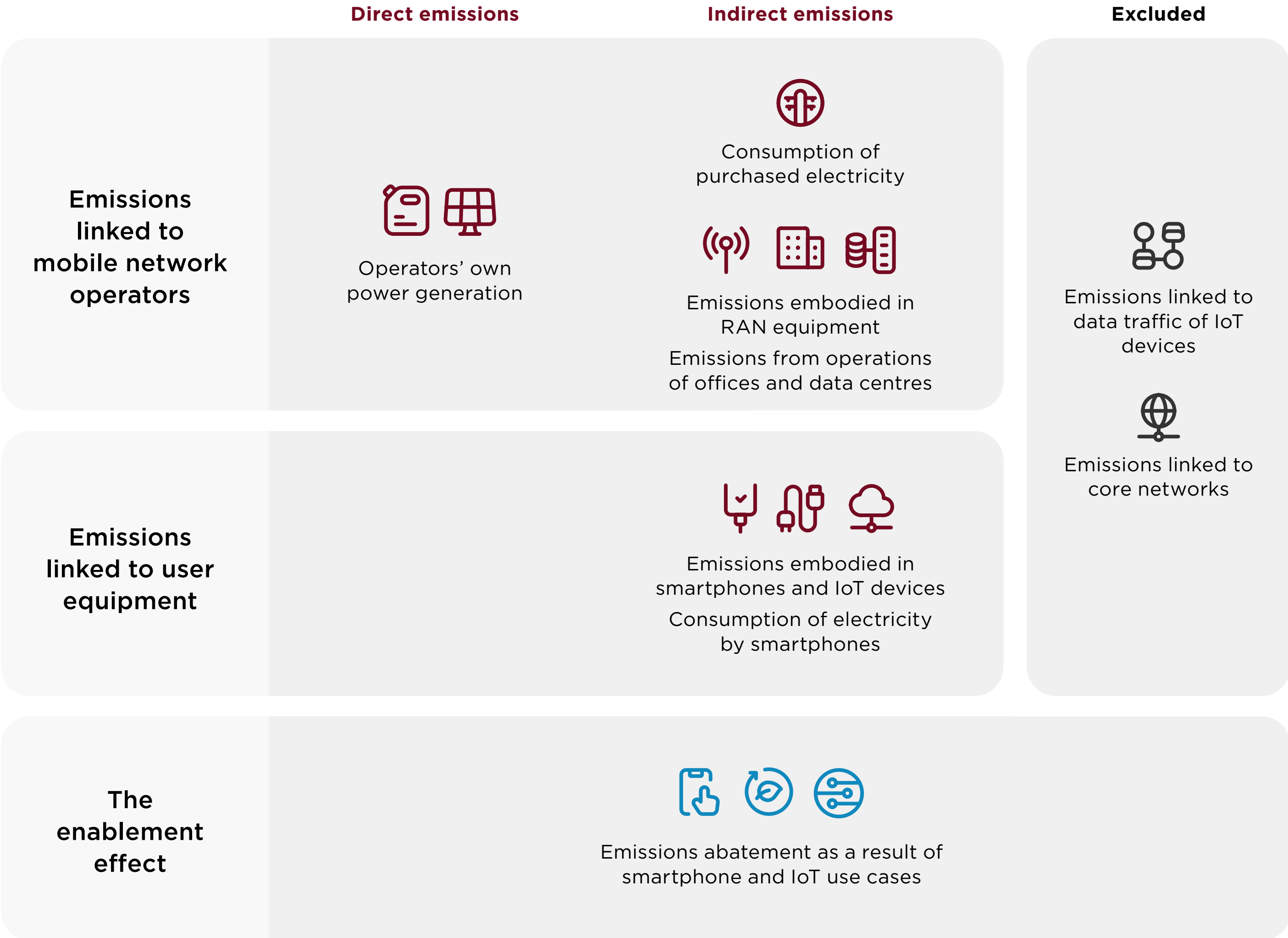
An additional important feature of model design is that the past outcomes can have an impact on future outcomes.

7 GSMA (2020) "Mobile taxation studies Methodology documentation". https://www.gsma.com/publicpolicy/wp-content/uploads/2020/04/Mobile_taxation_studies_Methodology_documentation.pdf
8 GSMA (2012) "Comparison of fixed and mobile cost structures". https://www.gsma.com/publicpolicy/wp-content/uploads/2012/09/Tax-Comparison-of-fixed-and-mobile-cost-structures.pdf
9 GSMA (2020) "Mobile taxation studies: Methodology documentation". https://www.gsma.com/publicpolicy/wp-content/uploads/2020/04/Mobile_taxation_studies_Methodology_documentation.pdf
10 Gillingham et al. (2015) "The Rebound Effect and Energy Efficiency Policy". https://resources.environment.yale.edu/gillingham/GillinghamRapsonWagner_Rebound.pdf

## 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 9.

**Figure 9**
**Emissions within and out of scope of modelling**




Source: GSMA Intelligence

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 base stations).

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.[11] 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.[12]

11 James Brehm & Associates (n.d.) "State of the Network: An Introduction to the Sunset". https://www.business.att.com/content/dam/attbusiness/briefs/state-of-the-network-whitepaper.pdf
12 Ficher et al. (2021) "Assessing the carbon footprint of the data transmission on a backbone network". https://hal.science/hal-03196527/document

## Emissions of the 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 Figure 10.

For example, to calculate emissions embodied in base stations each year, we multiply the number of refurbished and newly added base stations by their respective emissions intensities.

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 base stations, as outlined in Figure 10.

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.

**Figure 10**

**Parameters used in calculation of carbon impacts**

| Parameter | Low-income country | High-income country |
|---|---|---|
| **Electricity supply mix of the network** | **Macro base stations:**<br>Purchased electricity: 94%<br>Own diesel generation: 3%<br>Own solar: 3%<br>**Small sites:**<br>Purchased electricity: 100% | Purchased electricity: 100% |
| **Share of purchased grid electricity by type** | Regular grid electricity: 95%<br>Renewables-only electricity: 5%[13] | Regular grid electricity: 29%<br>Renewables-only electricity: 71%[14] |
| **Emissions intensity of regular grid electricity** | 2022: 425 gCO2e/kWh<br>2031: 333 gCO2e/kWh<br>Linearly interpolated between the years | 2022: 322 gCO2e/kWh<br>2031: 197 gCO2e/kWh<br>Linearly interpolated between the years |
| **Grid share of renewables** | 25% | 36% |

13 Based on South-East Asia estimates from GSMA (2022) "Mobile Industry position paper Access to renewable electricity" https://www.gsma.com/betterfuture/wp-content/uploads/2022/11/Mobile_Industry_Position_Paper_Access_to_Renewable_Electricity_Nov22.pdf

14 Based on Europe estimates from GSMA (2022) "Mobile Industry position paper Access to renewable electricity" https://www.gsma.com/betterfuture/wp-content/uploads/2022/11/Mobile_Industry_Position_Paper_Access_to_Renewable_Electricity_Nov22.pdf

| Parameter | Low-income country | High-income country |
|---|---|---|
| **Emissions intensity of renewables-only grid electricity** | 53 gCO2e/kWh[15] | |
| **Carbon intensity of operators' own electricity generation** | Diesel: 987 gCO2e/kWh[16]<br>Solar: 53 gCO2e/kWh[17] | |
| **Share of offices and data centres in total operator emissions** | 43%, based on a representative operator[18] | |
| **Carbon embodied in base stations** | Figures adapted from estimates for 5G networks in China[19], at:<br>128 tCO2e per macro base station<br>42 tCO2e per micro base station | |
| **Emissions embodied in smartphone devices** | Figures[20] adapted and annualised assuming a three-year lifespan: 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[21] | |
| **Smartphone network module energy consumption** | GSMA Intelligence calculations based on evidence on power consumption in carrier aggregation scenarios[22] and a representative use case of video calling<br>**Without carrier aggregation:**<br>2022: 0.0010 kWh/GB<br>2031: 0.00015 kWh/GB<br>With carrier aggregation:<br>2022: 0.0011 kWh/GB<br>2031: 0.00017 kWh/GB | |

15 Based on the mid-point of estimates for of Poly-SI PV, roof mounted from UNECE (2021) "Life Cycle Assessment of Electricity Generation Options" https://unece.org/sites/default/files/2021-10/LCA-2.pdf

16 GSMA calculations based on carbon emissions per one litre of diesel from UK Department for Business, Energy & Industrial Strategy (2022). "Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal" https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal and diesel generator specific fuel consumption (L/kWh) from Shakya et al. (2022) "Estimation of air pollutant emissions from captive diesel generators and its mitigation potential through microgrid and solar energy" https://www.sciencedirect.com/science/article/pii/S2352484722003316

17 Based on the mid-point of estimates for of Poly-SI PV, roof mounted from UNECE (2021) "Life Cycle Assessment of Electricity Generation Options" https://unece.org/sites/default/files/2021-10/LCA-2.pdf

18 Elisa (2014) "Annual Report 2014". https://corporate.elisa.com/attachment/content/Elisa_Annual_Report_2014.pdf

19 Figures assuming 10-year life span per base station and including emissions embodied in manufacturing, construction and transport of base stations. Adapted by GSMA Intelligence from Ding et al. (2022) "Carbon emissions and mitigation potentials of 5G base station in China". https://www.sciencedirect.com/science/article/abs/pii/S092134492200177X?via%3Dihub

20 Ericsson (n.d.) "Life cycle environmental impacts of a smartphone". https://www.ericsson.com/en/reports-and-papers/research-papers/life-cycle-assessment-of-a-smartphone

21 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 could increase. Adapted from Ericsson (n.d.) "Life cycle environmental impacts of a smartphone". https://www.ericsson.com/en/reports-and-papers/research-papers/life-cycle-assessment-of-a-smartphone

22 Adopted from Santos et al (n.d.) "LTE-A UE Power Consumption for Carrier Aggregation Scenario" https://www.sbrt.org.br/sbrt2020/papers/1570661121.pdf and Yan et al. (2019) "Modelling the Total Energy Consumption of Mobile Network Services and Applications" https://www.mdpi.com/1996-1073/12/1/184/htm

# Emissions impact through the mobile enablement effect

## Baseline projection

To estimate the impact through mobile enablement, we rely on previous GSMA analysis on the size of the enablement effect.[23 24]

**Figure 11**

**Approach to modelling the impact of spectrum policy through the enablement effect**

**Abatement factors**

- For each use case, we rely on abatement factors: estimates of avoided emissions per connection per year.
- We adjust these estimates for the projected changes in emissions intensity – for example, to reflect that in the future electricity production or transport will become greener.

**Baseline projection of connections**

- We develop baseline projections of the number of connections of each type (smartphones and IoT) for each modelled country.
- These projections are adapted from previous studies estimating future global IoT connections.

**Alternative projection of connections**

- For each scenario, we adjust the baseline projections of the number of connections to obtain a counterfactual projection.
- This adjustment is based on the estimated change in prices and the demand for mobile data under a given spectrum policy variant.

**Emissions impact**

- For each scenario, we multiply the projected number of connections by the abatement factors to obtain the estimate of the mobile enablement effect.
- To obtain the estimate of the impact of spectrum policy, we compare the size of the enablement effect with the baseline spectrum policy scenario.

Source: GSMA Intelligence

To estimate the size of the mobile enablement effect, we develop baseline estimates of the number of smartphones and IoT connections (Figures 12 and 13). The baseline projections of the number of IoT connections are regional projections developed by GSMA Intelligence that were scaled down at country level based on each country's implied GDP share of the corresponding region's GDP.

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 – for example, avoided kg/CO2 per connection). These estimates are presented in Figure 14 and Figure 15.[25] We adapted the figures for the corresponding regions (Asia for the low-income country and Europe for the high-income country) and

23 GSMA (2019) "The Enablement Effect" https://www.gsma.com/betterfuture/wp-content/uploads/2019/12/GSMA_Enablement_Effect.pdf

24 GSMA (2021) "The Enablement Effect 2021 Mobile Net Zero How can mobile tech help us reach Net Zero faster, easier, and cheaper?" https://www.gsma.com/betterfuture/wp-content/uploads/2022/04/The-Enablement-Effect-2021.pdf

25 Ibid.

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 average for Asia, 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.

In our assessment, the estimated impacts through the enablement effect are generally less reliable than the estimates on the sector's own emissions. This is for the following reasons:

— There is a large degree of uncertainty about avoided emissions per use case, especially for later years of projection when carbon intensity of the economy might evolve differently compared to our assumptions.

— Other emission-saving use cases exist that we did not include in the modelling due to lack of data. Moreover, new emission-saving use cases may emerge in the near future.

— Rebound effects could affect the abatement factors because improved usability or economic growth generated by the mobile connectivity can increase the demand for certain emission-saving activities.[26]

— There is a large degree of uncertainty about the number of IoT devices supporting emission-saving use cases and how responsive the demand for these is with respect to the cost of mobile data. At least some of these use cases could also be supported by alternative networks, mitigating some of the emissions impacts.

We therefore advise caution and careful consideration of assumptions underpinning the calculated size of the impacts through the mobile enablement effect.

## Alternative scenario estimate

To estimate the size of the mobile enablement effect under alternative spectrum policy scenarios, we adjust the baseline effect according to the estimated change in uptake of emission-saving use cases in response to changing prices of mobile data. We use the following assumptions:

— Uptake of smartphone emission-saving use cases reduces proportionally to changes in demand for mobile data.

— For IoT connection use cases, we assume a very low elasticity of uptake with respect to data prices, at –0.2. This means that a 1% increase in prices of data results in the uptake of IoT use cases declining by only 0.2%. This assumption reflects that a vast majority of IoT connections typically use less than a few megabytes of data per month, so uptake is likely to respond to price of data only very modestly.

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

26 GSMA (2019) "The Enablement Effect". https://www.gsma.com/betterfuture/wp-content/uploads/2019/12/GSMA_Enablement_Effect.pdf

**Figure 12**
## Smartphone and IoT connections relying on mobile networks (millions) – baseline assumption in low-income country

| | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 |
|---|---|---|---|---|---|---|---|---|---|---|
| Smartphones | 46 | 50 | 55 | 59 | 63 | 68 | 72 | 77 | 82 | 87 |
| Crop management | 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) | 0.185 | 0.228 | 0.282 | 0.349 | 0.382 | 0.415 | 0.449 | 0.482 | 0.516 | 0.552 |
| Building energy management systems (gas commercial) | 0.016 | 0.020 | 0.025 | 0.031 | 0.034 | 0.037 | 0.040 | 0.043 | 0.046 | 0.049 |
| HVAC control – commercial buildings | 0.069 | 0.085 | 0.105 | 0.130 | 0.142 | 0.155 | 0.167 | 0.180 | 0.192 | 0.206 |
| Smart meters (electricity residential) | 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 | 0.002 | 0.002 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.004 | 0.004 |
| Micro generation (solar) | 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 | 0.003 | 0.003 | 0.004 | 0.004 | 0.005 | 0.005 | 0.006 | 0.006 | 0.006 |
| Smart grids – electric network management | 0.082 | 0.102 | 0.126 | 0.155 | 0.170 | 0.185 | 0.200 | 0.215 | 0.230 | 0.246 |
| Inventory management | 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 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| Fleet vehicle driver behaviour improvement | 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 | 0.002 | 0.002 | 0.002 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.004 |
| Smart logistics – efficient routing and fleet management | 0.567 | 0.699 | 0.864 | 1.069 | 1.172 | 1.274 | 1.377 | 1.480 | 1.582 | 1.692 |
| Smart logistics – loading optimisation | 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 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.003 | 0.003 |
| Traffic congestion monitoring (road signs and traffic lights) | 0.002 | 0.002 | 0.003 | 0.003 | 0.004 | 0.004 | 0.004 | 0.005 | 0.005 | 0.006 |
| Usage-based car insurance | 0.326 | 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) "The Enablement Effect".https://www.gsma.com/betterfuture/wp-content/uploads/2019/12/GSMA_Enablement_Effect.pdf and GSMA (2021) "The Enablement Effect 2021 How can mobile tech help us reach Net Zero faster, easier, and cheaper?" https://www.gsma.com/betterfuture/wp-content/uploads/2022/04/The-Enablement-Effect-2021.pdf

**Figure 13**

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

| | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 |
|---|---|---|---|---|---|---|---|---|---|---|
| Smartphones | 98 | 101 | 102 | 104 | 106 | 108 | 111 | 114 | 116 | 119 |
| Crop management | 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) | 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) | 0.105 | 0.124 | 0.146 | 0.171 | 0.183 | 0.196 | 0.208 | 0.220 | 0.233 | 0.246 |
| HVAC control – commercial buildings | 0.446 | 0.526 | 0.619 | 0.724 | 0.776 | 0.828 | 0.881 | 0.933 | 0.986 | 1.041 |
| Smart meters (electricity residential) | 25.304 | 29.865 | 35.106 | 41.053 | 44.026 | 46.999 | 49.972 | 52.945 | 55.918 | 59.058 |
| Electric vehicle connection | 0.010 | 0.011 | 0.013 | 0.015 | 0.017 | 0.018 | 0.019 | 0.020 | 0.021 | 0.022 |
| Micro generation (solar) | 0.014 | 0.016 | 0.019 | 0.022 | 0.024 | 0.026 | 0.027 | 0.029 | 0.031 | 0.032 |
| Micro generation (wind business) | 0.020 | 0.023 | 0.027 | 0.032 | 0.034 | 0.037 | 0.039 | 0.041 | 0.044 | 0.046 |
| Smart grids – electric network management | 0.459 | 0.541 | 0.637 | 0.744 | 0.798 | 0.852 | 0.906 | 0.960 | 1.014 | 1.071 |
| Inventory management | 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 | 0.006 | 0.006 | 0.006 | 0.006 | 0.006 | 0.007 | 0.007 | 0.007 |
| Fleet vehicle driver behaviour improvement | 3.310 | 3.906 | 4.592 | 5.370 | 5.759 | 6.148 | 6.537 | 6.925 | 7.314 | 7.725 |
| Sea fleet – efficient routing | 0.007 | 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 | 3.308 | 3.905 | 4.590 | 5.367 | 5.756 | 6.145 | 6.534 | 6.922 | 7.311 | 7.722 |
| Smart logistics – loading optimisation | 3.309 | 3.905 | 4.590 | 5.368 | 5.757 | 6.145 | 6.534 | 6.923 | 7.312 | 7.722 |
| Traffic congestion management | 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) | 0.010 | 0.012 | 0.014 | 0.016 | 0.017 | 0.018 | 0.020 | 0.021 | 0.022 | 0.023 |
| Usage-based car insurance | 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) "The Enablement Effect".https://www.gsma.com/betterfuture/wp-content/uploads/2019/12/GSMA_Enablement_Effect.pdf and GSMA (2021) "The Enablement Effect 2021 How can mobile tech help us reach Net Zero faster, easier, and cheaper?" https://www.gsma.com/betterfuture/wp-content/uploads/2022/04/The-Enablement-Effect-2021.pdf

**Figure 14**

## 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) "The Enablement Effect".https://www.gsma.com/betterfuture/wp-content/uploads/2019/12/GSMA_Enablement_Effect.pdf and GSMA (2021) "The Enablement Effect 2021 How can mobile tech help us reach Net Zero faster, easier, and cheaper?" https://www.gsma.com/betterfuture/wp-content/uploads/2022/04/The-Enablement-Effect-2021.pdf

## Figure 15
**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: GSMA Intelligence analysis based on: GSMA (2019) "The Enablement Effect".https://www.gsma.com/betterfuture/wp-content/uploads/2019/12/GSMA_Enablement_Effect.pdf and GSMA (2021) "The Enablement Effect 2021 How can mobile tech help us reach Net Zero faster, easier, and cheaper?" https://www.gsma.com/betterfuture/wp-content/uploads/2022/04/The-Enablement-Effect-2021.pdf

# Appendix A2:
# Detailed modelling results

**Figure 16**
**Emissions impacts in low-income country: detailed estimates**

MtCO2e

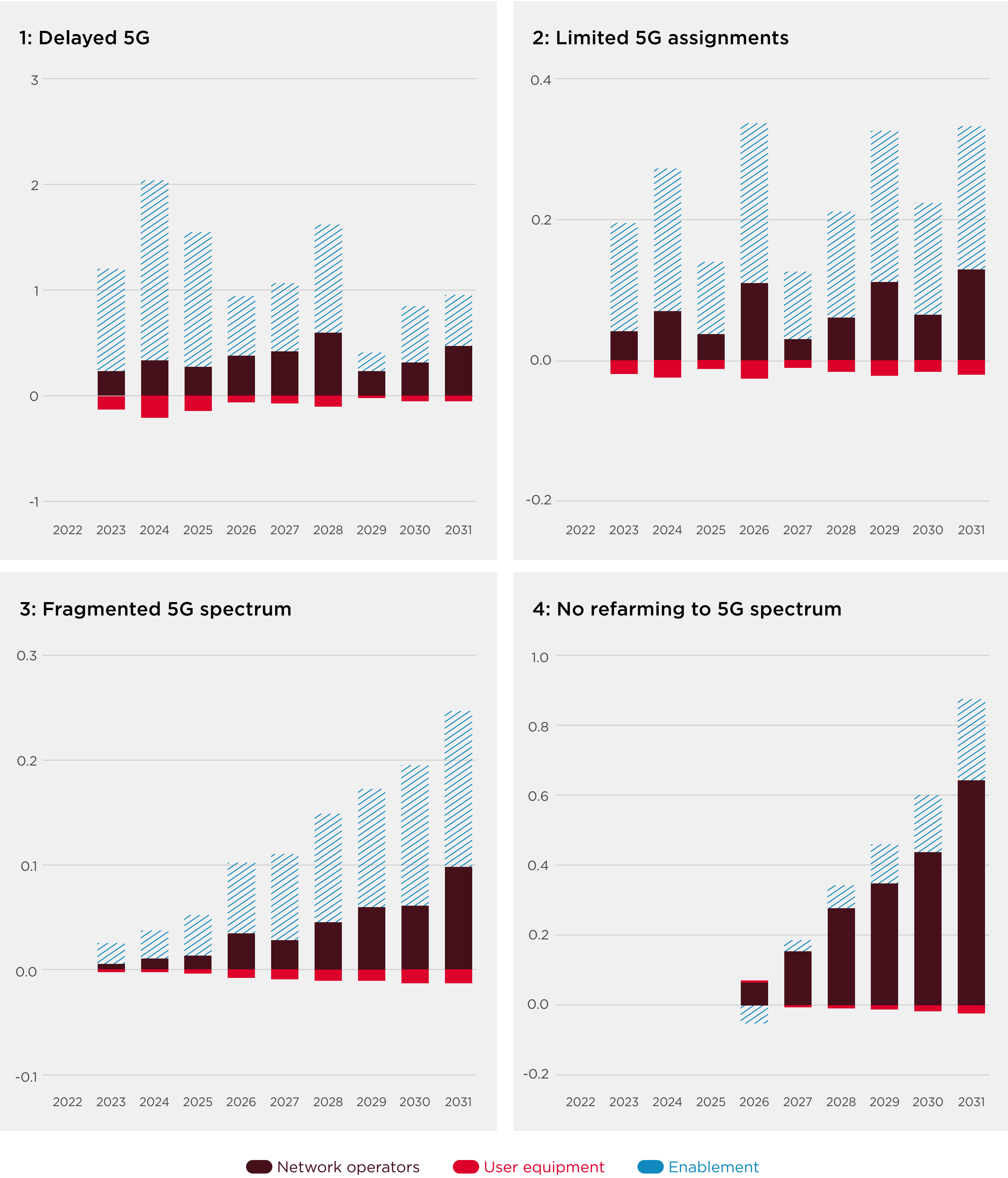
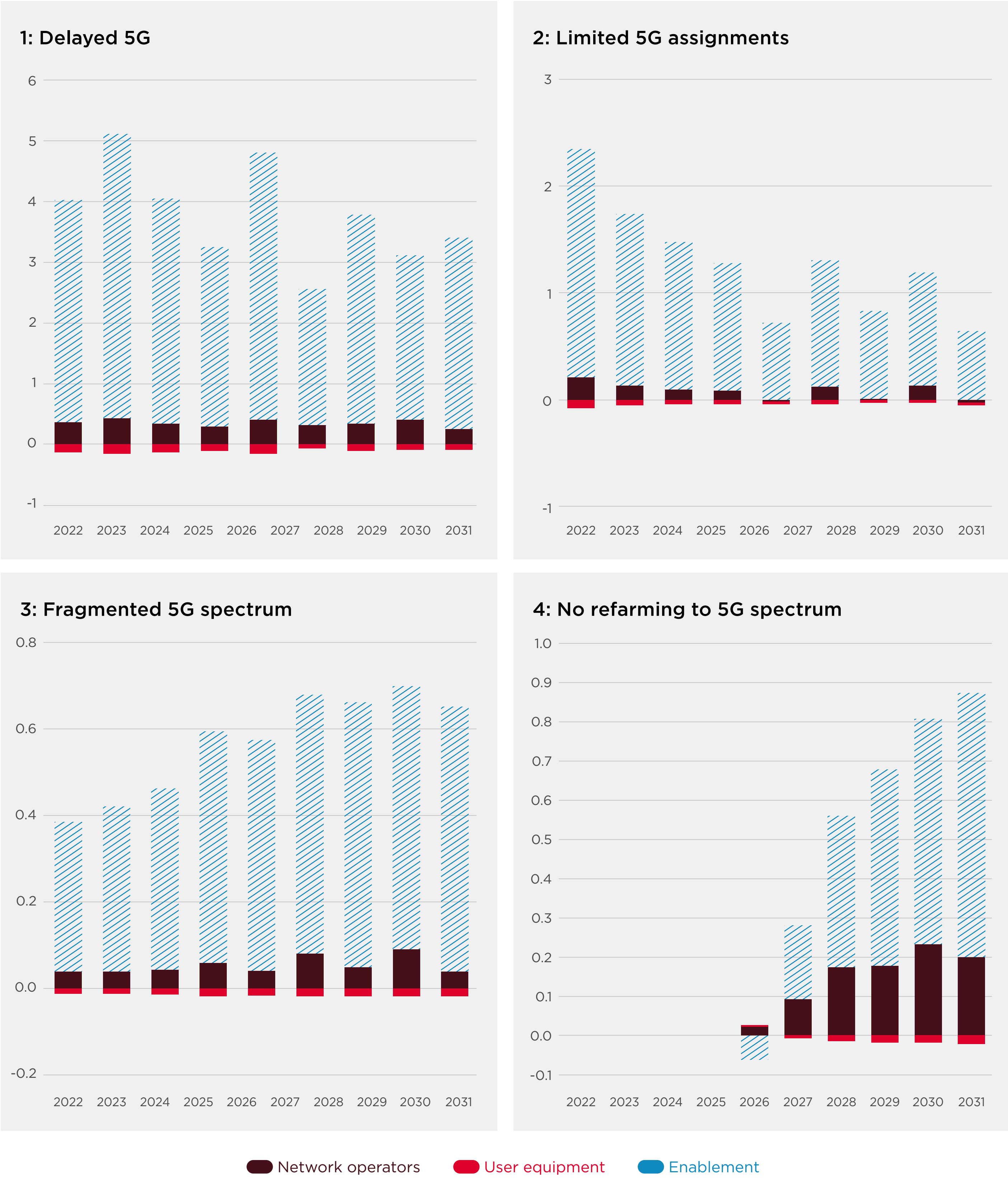


**Figure 17**

## Emissions impacts in high-income country: detailed estimates

MtCO2e



**GSMA Head Office**
1 Angel Lane
London
EC4R 3AB
United Kingdom
Tel: +44 (0)20 7356 0600
Fax: +44 (0)20 7356 0601