Digital Transformation and Technology Dynamics

Journal Homepage: www.techdynamicsjournal.com | ARTICLE NO. DTTD-2021004 | VOL. 1 ISSUE 2

ICT for Sustainable Development: Assessing the Carbon Footprint of National Communication Networks

Rashadul Islam Samrat[1]*, Md Rasel Ul Alam[2], Kanita Haider[3],

[1] *Department of Marketing, University of Barishal, Barishal, Bangladesh*

[2] *Department of Computer and Information Sciences, University of the Cumberlands, Kentucky, USA.*

[3] *Department of Computer Science and Engineering, International Islamic University Chittagong, Chittagong, Bangladesh*

**Corresponding author: samrat.meazi1@gmail.com*

Received 19 August 2021; Revised 12 September 2021; Accepted 30 October2021; Published: 29 November 2021

KEYWORDS

ICT carbon footprint;
Telecommunications networks;
Energy consumption;
Greenhouse gas emissions;
Sustainable development;
Life-cycle assessment;
National communication infrastructure;
Green ICT policy

Abstract

Information and communication technology (ICT) is widely promoted as an enabler of low-carbon development, yet the networks that deliver connectivity are themselves a growing source of electricity consumption and greenhouse gas (GHG) emissions. Global estimates place the ICT sector's life-cycle carbon footprint at roughly 1.5-4% of worldwide emissions, but country-level evidence remains sparse: only a small number of national telecommunications regulators or operators publish emissions data with sufficient granularity to support policy decisions. This gap is particularly acute for developing and emerging economies, where network densification, generation upgrades (2G to 5G), and continued reliance on diesel back-up power at off-grid sites can move national ICT footprints in directions not captured by global averages. This paper addresses that gap by proposing a tiered, bottom-up methodological framework for assessing the carbon footprint of a national communication network, combining network inventory data, segment-level energy modelling, national grid emission factors, and equipment life-cycle data, in line with ITU-T Recommendations L.1410, L.1420, and L.1450. The paper reviews the theoretical and empirical literature on ICT energy and emissions, develops a mathematical formulation for use-stage and embodied emissions and a companion scenario module for renewable-energy and efficiency pathways to 2030, and presents an illustrative application demonstrating the framework's outputs using synthetic, clearly labelled data rather than measured results, since no primary national dataset was available for this study. The discussion interprets what such a framework can and cannot show, situates the results relative to international benchmarks, and considers governance, data-availability, and equity implications for policymakers and regulators. The paper concludes that a standardised, transparent, tier-based national assessment methodology is a necessary precondition for evidence-based ICT decarbonisation policy, and it sets out a concrete agenda—centred on regulator-mandated disclosure, primary energy metering, and cross-country validation—for turning the proposed framework into an empirically grounded research programme.

1. Introduction

1.1 Background

Digital connectivity is central to the United Nations Sustainable Development Goals, most directly Goal 9 (industry, innovation and infrastructure) and Goal 13 (climate action), and national governments increasingly treat broadband expansion as both an economic and a climate priority (Oughton et al., 2023). At the same time, delivering that connectivity requires an expanding physical infrastructure of radio access network (RAN) sites, core and transport networks, data centres, and customer premises equipment, all of which consume electricity and embody carbon in their manufacture. Global assessments converge on a life-cycle ICT sector footprint of roughly 1.5 to 4 percent of world greenhouse gas emissions, depending on scope and year (Andrae & Edler, 2015; Belkhir & Elmeligi, 2018; Malmodin & Lundén, 2018), a range comparable to that of civil aviation. Within the ICT sector, telecommunications networks occupy a distinctive position. Unlike user devices, whose footprint is dispersed across billions of individually owned products, and unlike data centres, which are increasingly concentrated among a small number of hyperscale operators, national communication networks are operated by a limited number of licensed entities, are subject to national regulation, and are geographically bound to a single country's electricity grid and climate policy. This makes the national network a natural unit of analysis for climate accounting and policy intervention (International Telecommunication Union & World Bank, 2024).

1.2 Problem Statement

Despite this natural fit, systematic, standardised assessment of national ICT network carbon footprints remains rare. The joint International Telecommunication Union (ITU) and World Bank review of the thirty highest-emitting countries for telecommunications found that France is, at present, the only country where the sector regulator itself compiles telecom emissions and energy data as a matter of course (International Telecommunication Union & World Bank, 2024). Elsewhere, assessment depends on voluntary corporate sustainability disclosure, academic reconstruction from public data, or global top-down apportionment, each of which has known limitations for country-specific policy use.

1.3 Research Gap

Three gaps recur across the literature reviewed in Section 2. First, most rigorous, primary-data-based footprint studies are geographically concentrated in Europe and a small number of high-income countries, most visibly through the European Telecommunications Network Operators' Association (ETNO) and Global e-Sustainability Initiative (GeSI) data collections underlying Lundén et al. (2022) and Malmodin and Lundén (2018); comparable primary datasets for national networks in South Asia, Sub-Saharan Africa, and Latin America are scarce. Second, existing national or regional case studies (for example, on France's radio access network, Belgium's 4G/5G projections, or off-grid towers in East Africa) tend to model a single network layer—commonly the RAN—rather than the full stack of RAN, core, transport, data-centre, and embodied emissions in a single, internally consistent accounting boundary. Third, where developing-country evidence does exist, it emphasises operational cost and energy access more than standardised GHG accounting, so results are difficult to compare with ITU-T L.1420/L.1450-aligned assessments used elsewhere (GSMA, 2024).

1.4 Motivation

Closing these gaps matters for two connected reasons. Academically, a transparent, reproducible national assessment framework allows researchers to compare countries on a common basis, to attribute footprint differences to identifiable causes (technology generation mix, grid emission factor, network topology, traffic growth), and to test decarbonisation levers before they are deployed at scale. Practically, national telecom regulators, energy ministries, and operators cannot manage what they do not measure: without a country-level baseline and a defensible method for projecting it forward, commitments to net-zero or science-based targets in the sector risk remaining aspirational rather than accountable (International Telecommunication Union & World Bank, 2024).

1.5 Research Objectives

i. To synthesise the theoretical and empirical literature on ICT and telecommunications network energy consumption and carbon emissions, distinguishing use-stage from embodied contributions.

ii. To develop a tiered, mathematically explicit methodology for estimating the carbon footprint of a national communication network from network inventory, energy, grid-emission-factor, and life-cycle data.

iii. To design a companion scenario and sensitivity module capable of projecting national network footprints under alternative traffic-growth, efficiency, and renewable-energy assumptions.

iv. To demonstrate the framework's output structure using clearly labelled illustrative data, and to identify the primary data sources a country would need to operationalise it with real measurements.

v. To discuss the governance, policy, and equity implications of national ICT carbon accounting, and to set out a research agenda for empirical validation.

1.6 Research Questions

i. RQ1: What network, energy, and emissions data are required to estimate a national ICT communication network's carbon footprint in a manner consistent with ITU-T L.1410/L.1420/L.1450 and comparable across countries?

ii. RQ2: How can use-stage and embodied emissions be combined into a single, mathematically explicit national footprint model that remains tractable with data typically available to regulators and operators?

iii. RQ3: How sensitive is a projected national network footprint to plausible variation in traffic growth, technology efficiency gains, and renewable electricity share, and which lever offers the greatest illustrative leverage?

iv. RQ4: What governance and disclosure arrangements would be needed to move from an illustrative application of the framework to an empirically validated national assessment?

1.7 Research Contributions

This paper contributes: (i) a thematic, critical synthesis of the ICT and telecommunications carbon footprint literature organised around global sector estimates, network-layer life-cycle assessment, and national/operator-level primary studies; (ii) a tiered mathematical framework linking network inventory, energy modelling, grid emission factors, and embodied emissions into a single national footprint estimate, together with an explicit scenario-projection formulation; (iii) an illustrative, transparently labelled application of the framework's output structure that can be repopulated with real national data; and (iv) a discussion of the data-governance conditions under which such a framework could be operationalised for policy use, including in low- and middle-income countries currently underrepresented in the empirical literature.

1.8 Paper Organisation

Section 2 reviews the literature thematically, covering global ICT footprint estimates, network life-cycle assessment, national and operator-level studies, and the ITU-T assessment standards, and presents a comparative summary table. Section 3 develops the theoretical and conceptual framework. Section 4 presents the mathematical model. Section 5 sets out the proposed methodology, including recommended data sources. Section 6 presents the proposed assessment framework and its illustrative output. Section 7 discusses the results and their implications. Section 8 addresses ethics, governance, and policy. Section 9 states the limitations. Section 10 identifies future research directions, and Section 11 concludes.

2. Literature Review

The literature on ICT and telecommunications carbon accounting can be organised into four broad, overlapping themes: (a) global, top-down sector estimates; (b) network- and equipment-level life-cycle assessment; (c) national or operator-level primary-data studies; and (d) standardisation and methodology efforts, principally through the ITU-T L.14xx series. Each is reviewed critically below, followed by a comparative summary in Table 1.

2.1 Global Sector-Level Estimates

Early prospective modelling by Andrae and Edler (2015) projected that, under a worst-case scenario, communication technology could account for as much as half of global electricity use by 2030, a figure frequently cited but also frequently misunderstood as a central estimate rather than an upper bound; the same study's best-case scenario shows electricity use roughly stable. Belkhir and Elmeligi (2018) similarly extrapolated device- and network-level trends to suggest ICT's share of global emissions could approach 14 percent by 2040 absent substantial efficiency gains. These scenario-based studies are valuable for bounding the problem but, as Malmodin and Lundén (2018) argue, they can diverge substantially from measured outcomes: their own primary-data-based reconstruction found the global ICT and entertainment and media sector's footprint in 2015 to be roughly stable relative to 2010 despite a large increase in data traffic, because efficiency gains and infrastructure consolidation offset traffic growth over that period. This tension between scenario-based projection and primary-data reconstruction is a recurring methodological fault line in the field, and it motivates the tiered, data-source-explicit approach adopted in Section 4.

2.2 Network- and Equipment-Level Life-Cycle Assessment

A second stream examines specific network layers rather than the sector as a whole. Williams et al. (2022), in a systematic review of 5G network energy literature, find that operational-only estimates routinely understate total impact by excluding embodied energy from equipment manufacture and indirect effects from induced traffic and device turnover; they call for consistent system boundaries across studies, a recommendation this paper adopts explicitly in Section 4. Complementary radio access network (RAN) power modelling—most visibly the linear, traffic-dependent power model refined for 4G and 5G base stations and validated against on-site measurements shows that base-station power draw combines a large traffic-independent (static) component with a smaller traffic-proportional component, a structure carried into the mathematical model developed in Section 4 (Mytton et al., 2024). At the level of individual sites, industry technical guidance indicates that radio access networks account for the large majority of an operator's energy consumption, with core network and data-centre operations a distinctly smaller share (Nokia, 2024), a distribution that motivates the segment-level disaggregation used in the illustrative results in Section 6.

2.3 National and Operator-Level Primary-Data Studies

A smaller but methodologically important body of research moves beyond equipment-level specifications and engineering assumptions by using primary, named-operator data to quantify the actual electricity use and operational emissions of telecommunications networks. This distinction is important because specification-based approaches generally describe the rated or expected energy performance of individual network components, whereas operator-level datasets capture the aggregate effect of network architecture, traffic demand, equipment utilisation, geographic deployment, cooling and auxiliary loads, power-management practices, and electricity procurement. Consequently, operator-level evidence provides a more realistic empirical basis for developing national or sector-wide energy and emissions estimates.

Lundén et al. (2022) provide one of the clearest examples of this approach. Using electricity, subscription, traffic, and emissions data reported by identified members of the European Telecommunications Network Operators' Association (ETNO), the authors construct a multi-year empirical dataset covering 2015–2018, complemented by earlier observations for 2010–2015. The dataset represents approximately 36% of European subscriptions and 8% of global subscriptions, providing substantially greater granularity than estimates based solely on equipment specifications or generic ICT-sector assumptions. Their findings reveal a particularly important decoupling between network traffic growth and electricity consumption. Between 2015 and 2018, electricity consumption among the reporting operators increased by only approximately 1%, while data traffic increased by a factor of three. Across the longer 2010–2018 period, data traffic increased approximately twelvefold, whereas electricity consumption increased by only about 9%.

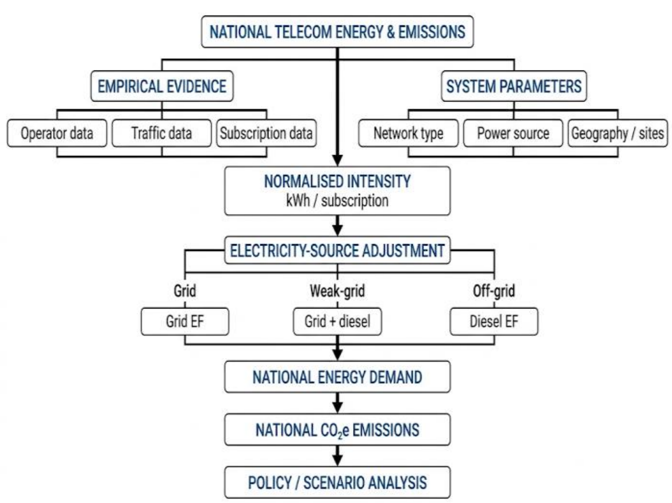

Figure 1: Proposed evidence hierarchy for national telecommunications energy and emissions estimation

This result demonstrates why traffic growth cannot be translated directly into proportional growth in network electricity consumption. Improvements in network equipment efficiency, capacity utilisation, technology transitions, and power-management practices can allow operators to accommodate substantially greater volumes of traffic without a corresponding increase in electricity demand. The finding is particularly relevant for forward-looking national assessments because a static energy-per-unit-of-traffic assumption may substantially overestimate future electricity requirements if technological efficiency improvements are ignored.

Lundén et al. (2022) also provide a useful normalisation framework through electricity consumption per subscription. For the ETNO Total dataset, electricity intensity including overhead was 24 kWh/subscription in both 2015 and 2016 and 26 kWh/subscription in both 2017 and 2018. In 2018, the corresponding network-type values were substantially different: approximately 62 kWh/subscription for fixed networks and 17 kWh/subscription for mobile networks. For the Europe-only dataset, the total intensity was higher, reaching approximately 39 kWh/subscription in 2018. These differences indicate that network composition, geography, operating conditions, and the treatment of overhead can materially affect measured intensity.

Accordingly, the kWh-per-subscription metric is adopted in Section 4 as the principal normalised comparability indicator, while absolute electricity consumption remains the basis for estimating national energy requirements. The indicator is particularly useful because subscription counts are more consistently available across countries than detailed operator-level electricity inventories. Nevertheless, subscription intensity should not be interpreted as a universal technological constant. Differences between mobile and fixed networks, network maturity, traffic patterns, geographical coverage, legacy infrastructure, and off-grid power requirements can produce substantial variation. It is therefore used as a normalisation measure rather than as a standalone forecasting coefficient.

The importance of operator-level evidence is reinforced by Malmodin and Lundén (2018), who extend the analysis to the global ICT and entertainment-and-media sectors. Their work demonstrates the value of combining bottom-up sectoral activity data with electricity and carbon-intensity assumptions when estimating the environmental footprint of digital infrastructure. Together, these studies establish an important methodological progression: equipment-level specifications can provide engineering inputs, but empirical operator data are required to validate aggregate energy-use patterns and to identify the extent to which technological efficiency offsets rapid growth in digital demand.

A related strand of research operates at the national infrastructure-planning level. Oughton and colleagues develop techno-economic and environmental simulation frameworks capable of evaluating alternative broadband deployment strategies, including different 4G/5G architectures, technology choices, geographic deployment requirements, energy demand, emissions, infrastructure sharing, and investment costs. This literature is particularly relevant to developing and emerging economies because it moves the analysis from retrospective sector accounting toward forward-looking infrastructure scenarios. Oughton's 2025 analysis, for example, estimates that universal 4G delivery at 20 GB/month per user using wireless backhaul could generate approximately 88.9 Mt of operational CO_2-equivalent emissions annually across the developing-Asia cases considered. Importantly, infrastructure-sharing strategies were estimated to reduce energy consumption and emissions by approximately 9–19%, while reducing required investment by 15–49%.

This body of work represents the closest existing methodological analogue to a national-scale, policy-facing assessment. However, its principal objective is comparative strategy evaluation, rather than the construction of a standardised national telecommunications emissions inventory. The distinction creates an opportunity for the present framework to combine the strengths of both approaches: empirical operator-level observations can provide calibration and validation, while techno-economic simulation can support scenario analysis and policy evaluation.

The limitations of applying high-income-country operator averages become particularly important when telecommunications networks contain substantial off-grid and weak-grid segments. In regions where grid reliability is low, telecom operators frequently depend on diesel generators, battery systems, hybrid systems, or other distributed power solutions to maintain network availability. The resulting emissions profile can differ materially from that of a grid-connected network powered predominantly by relatively low-carbon electricity.

GSMA evidence from African mobile-network operations illustrates the magnitude of this difference. A single-tenant telecom tower site operating continuously on a diesel generator can consume approximately 28,000 litres of diesel per year, while diesel-generated electricity is reported to produce around 60% more CO_2 than average grid-based electricity in Africa. In Nigeria, mobile operators and tower companies have reportedly purchased and transported more than 40 million litres of diesel per month for tower operations because of recurrent grid outages and inadequate energy access.

These observations have two methodological implications. First, a national telecom emissions inventory cannot simply multiply total electricity demand by a single national grid-emission factor if a significant proportion of network sites operate on diesel or hybrid power. Second, the framework should distinguish between grid-connected, weak-grid, and off-grid network segments, because the same quantity of electricity can have substantially different carbon consequences depending on its source.

The issue is also economically significant. GSMA reports that diesel generation in parts of Sub-Saharan Africa can cost approximately three to four times as much as grid electricity, meaning that unreliable electricity supply simultaneously increases both the financial and environmental burden of network operation. Consequently, energy-source composition should be treated not merely as an emissions-factor adjustment but as a structural variable affecting network operating costs, resilience, and sustainability.

Taken together, the literature suggests that a robust national telecommunications energy-and-emissions framework should combine four layers of evidence: (1) empirical operator-level electricity and subscription data for calibration; (2) technology- and network-type-specific intensity indicators; (3) national infrastructure and deployment characteristics; and (4) differentiated electricity-source emission factors for grid, weak-grid, hybrid, and diesel-powered sites. Such a layered approach reduces the risk of transferring averages from mature, highly electrified telecommunications markets directly into countries where network architecture, electricity reliability, and energy sources differ substantially.

The methodological contribution of the present framework therefore lies not in assuming a single universal telecom energy intensity, but in constructing a normalised yet context-sensitive estimation architecture. Operator-level kWh/subscription values provide the empirical benchmark, while network composition, traffic growth, infrastructure deployment, electricity-source mix, and off-grid dependence provide the adjustment dimensions required to translate that benchmark into a national-scale assessment.

2.4 Standardisation and Assessment Methodology

The ITU-T L.14xx series provides the closest approximation to an internationally agreed methodology for this domain. ITU-T

Recommendation L.1410 sets out a life-cycle assessment methodology for ICT goods, networks and services; L.1420 extends this to organisational energy and GHG accounting; and the most recent L.1450 (2025) revision introduces a tiered approach—from screening-level Tier-3 estimates using secondary or proxy data through to detailed, primary-data Tier-1 assessments—explicitly designed to accommodate varying data availability across countries and organisations (International Telecommunication Union, 2012, 2014, 2025). The joint ITU and World Bank (2024) review operationalises this guidance at country scale, compiling emissions data for the thirty highest-emitting countries in telecommunications and concluding that standardised national reporting remains the exception rather than the rule. This paper's methodology (Section 5) is designed to be interoperable with the ITU-T L.1450 tier structure, so that a country beginning with only secondary data can progress toward a Tier-1 assessment as primary data becomes available.

2.5 Synthesis and Positioning of the Present Study

Read together, the literature suggests three things relevant to this paper's positioning. First, global and scenario-based estimates, while useful for framing the scale of the issue, are not a substitute for country-specific measurement, and can diverge from measured outcomes in either direction (Andrae & Edler, 2015; Malmodin & Lundén, 2018). Second, the primary-data studies that do exist are concentrated in Europe, leaving the applicability of their intensity benchmarks (for example, kWh per subscription) to other regions, grid mixes, and network topologies as an open empirical question (Lundén et al., 2022). Third, the ITU-T L.14xx standards provide a tiered methodological scaffold that has not, to this paper's knowledge, been widely operationalised and reported for national telecommunications networks outside a small number of jurisdictions (International Telecommunication Union & World Bank, 2024). This paper responds directly to this positioning by adapting the ITU-T tier structure into an explicit mathematical model (Section 4) and a reusable methodology (Section 5), applied illustratively in Section 6.

Table 1: Chronological Mapping of Empirical and Theoretical Research on Global Telecom Sustainability (2015–2024)

Study	Year	Method	Context	Key Finding	Limitation / Gap
Andrae & Edler	2015	Scenario modelling	Global ICT electricity, 2010-2030	Worst case: ICT could reach ~51% of global electricity by 2030; best case near-stable	Wide scenario range; no national resolution
Malmodin & Lundén	2018	Bottom-up LCA, primary data	Global ICT & E&M, 2010-2015	Footprint ~730 Mt CO2e in 2015, stable despite traffic growth	Global/regional aggregation only
Belkhir & Elmeligi	2018	Trend extrapolation	Global ICT emissions to 2040	Could reach ~14% of global emissions without efficiency gains	Extrapolation-based; needs recalibration
Lundén, Malmodin, Bergmark & Lövehagen	2022	Primary ETNO operator data	European telecom operators, 2015-2018	Electricity/subscription stable (~30 kWh) despite 3x traffic growth	Europe-centric primary dataset
Williams, Sovacool & Foxon	2022	Systematic review	Global 5G network energy studies	Operational-only estimates understate embodied/indirect effects	Review-based; heterogeneous scope across sources
Oughton, Oh, Ballan & Kusuma	2023	Techno-economic + environmental simulation	Global, 4G vs 5G universal broadband	5G with efficient backhaul can lower per-user emissions vs 4G	Ex-ante simulation, not measured outcomes
GSMA / Mobile for Development	2024	Industry data synthesis	Off-grid towers, Sub-Saharan Africa	Diesel towers emit ~60% more CO2 than average grid electricity	Practitioner report; limited academic modelling
ITU & World Bank	2024	Cross-country data compilation	30 highest-emitting countries	France is the only country with regulator-level telecom emissions reporting	Standardised national reporting largely absent

3. Theoretical and Conceptual Framework

The framework draws on two complementary theoretical traditions. The first is environmental life-cycle assessment (LCA) theory, as codified for ICT in ITU-T L.1410 and ISO 14064-1, which defines a system boundary (use-stage versus embodied, first-order versus second- and third-order effects) and requires impacts to be attributed to a defined functional unit—here, the provision of national communication service over a defined period (International Telecommunication Union, 2014). The second is the techno-economic network-modelling tradition exemplified by Oughton et al. (2021, 2023), which represents a national network as an assembly of discrete infrastructure elements (sites, links, technology generations) whose technical and economic parameters can be varied to explore policy-relevant scenarios.

Four constructs link these traditions in the present framework: (1) network topology and technology mix, the physical inventory of RAN, core, transport, and data-centre elements and their generation (2G-5G, fixed and mobile); (2) energy intensity, the electricity drawn by each element as a function of its static baseline and traffic-dependent load (Mytton et al., 2024); (3) the grid emission factor, which converts electricity into carbon and is itself a function of the national energy mix and its trajectory toward renewables; and (4) embodied carbon, the emissions associated with manufacturing, transporting, and disposing of network equipment, amortised over its service life. The framework treats traffic growth, technology efficiency improvement, and renewable energy share as the principal moderating variables connecting network topology to the eventual footprint, consistent with the sensitivity analysis literature reviewed in Section 2. A key assumption, following ITU-T L.1450's tiered approach, is that a national assessment need not start with full Tier-1 primary data; it can begin at Tier-3 (secondary/proxy data) and be progressively refined, provided the boundary and functional unit are held constant across iterations (International Telecommunication Union, 2025).

4. Mathematical Modelling

This section formalises the constructs in Section 3. All symbols are defined at first use; time is indexed by year t.

4.1 Segment-Level Energy Model

$$E_i(t) = P_static, i \times N_i(t) \times 8760 + \beta_i \times D_i(t)(1)$$

where E_i(t) is the annual electricity consumption (kWh) of network segment i (i ∈ {RAN, core/transport, data centres, CPE}) in year t; P_static,i is the average static (traffic-independent) power draw per unit of segment i, in kW; N_i(t) is the number of installed units of segment i; 8760 converts kW to annual kWh; β_i is the marginal energy cost per unit of data traffic for segment i (kWh/GB); and D_i(t) is the annual data traffic carried by segment i (GB). This linear static-plus-traffic-dependent structure follows the power-model approach validated against operator measurements by Mytton et al. (2024) and is consistent with the RAN-dominant energy shares reported for operational mobile networks (Nokia, 2024).

4.2 Use-Stage Carbon Footprint

$$F_use(t) = \Sigma_i E_i(t) \times GEF(t)(2)$$

where F_use(t) is the annual use-stage carbon footprint (kg CO2e) and GEF(t) is the national grid emission factor (kg CO2e/kWh) in year t. Where a material share of sites operate off-grid on diesel generation, GEF(t) should be disaggregated into a grid-connected term and a diesel/hybrid term weighted by the share of electricity drawn from each source, since diesel-based generation carries a substantially higher emission factor than typical grid electricity (GSMA, 2024).

4.3 Embodied Carbon Footprint

$$F_embodied(t) = \Sigma iNit/Li \times Ci3$$

where L_i is the average service life (years) of equipment in segment i and C_i is the embodied carbon per unit (kg CO2e) across its manufacture, transport, and end-of-life stages, drawn from equipment life-cycle inventory data or manufacturer environmental product declarations.

4.4 Total National Network Footprint and Intensity

$$F_total(t) = F_use(t) + F_embodied(t)(4)I(t)$$
$$= F_total(t)/S(t)(5)$$

where S(t) is the number of active subscriptions in year t, so that I(t) expresses the footprint as an intensity metric (kg CO2e per subscription per year) comparable across countries and over time, following the kWh-per-subscription normalisation used by Lundén et al. (2022).

4.5 Scenario and Sensitivity Formulation

$$F_total(t) = F_total(t0) \times (1+g)^{(t-t0)} \times (1-\eta)^{(t-t0)}$$
$$\times \left[\big(1-\rho(t)\big) + \rho(t) \cdot \kappa\right](6)$$

where g is the annual growth rate of data traffic and subscriptions, η is the annual rate of technology efficiency improvement (energy per GB or per subscriber), ρ(t) is the renewable share of grid electricity in year t, and κ is the residual emission factor of renewable generation relative to the baseline grid mix (κ → 0 for near-zero-carbon sources, but strictly positive once the embodied emissions of renewable infrastructure are included). Equation (6) is the basis for the illustrative scenario comparison in Section 6.3: business-as-usual ($g > 0$, $\eta \approx 0$, ρ(t) fixed), moderate decarbonisation ($\eta > 0$, ρ(t) rising moderately), and accelerated decarbonisation (higher η and faster-rising ρ(t)).

Statistical treatment of uncertainty follows standard sensitivity-analysis practice: each parameter (P_static,i, β_i, GEF(t), L_i, C_i, g, η, ρ(t)) should be assigned a plausible range informed by the data-quality tier from which it was drawn (Section 5.9), and F_total(t) recomputed across the Cartesian product or a Monte Carlo sample of these ranges to report a central estimate with an interquartile or 90 percent interval, consistent with the uncertainty ranges reported in comparable base-station life-cycle studies.

5. Proposed Methodology

Because no primary national network dataset was available for this study, the methodology below is presented as a proposed, reusable research design rather than as an account of experiments actually performed. Where illustrative figures are used in Section 6 to demonstrate the framework's output structure, they are explicitly labelled as synthetic.

5.1 Research Design

A mixed quantitative design is proposed, combining (a) a bottom-up engineering-economic inventory model of the national network (Section 4.1) with (b) scenario-based sensitivity analysis (Section 4.5) and (c) cross-validation against publicly available international benchmarks (for example, the kWh-per-subscription intensity reported by Lundén et al., 2022, or the sector-wide estimates in International Telecommunication Union & World Bank, 2024). This triangulation strengthens the credibility of the proposed estimates by assessing their robustness against alternative assumptions and established international evidence.

5.2 Recommended Data Sources

Table 2 sets out the primary data sources a national implementation would require, explicitly labelled as proposed/recommended rather than data actually collected for this paper.

Table 2: Proposed / Recommended Data Sources for National Implementation

Data Source	Provider	Variables Supplied	Framework Tier	Rationale
Regulator technical filings/spectrum & licensing records	National telecom regulator	Site counts, technology generation, spectrum holdings	Tier 1 (inventory)	Ground-truth for N_i(t) in Eq. (1)
Operator sustainability / ESG disclosures	Individual operators; GSMA aggregation	Electricity use, renewable share, Scope 1-3 emissions	Tier 1-2 (energy)	Validates modelled E_i(t)
National grid emission-factor registry	Energy ministry / national communications to UNFCCC	Annual kg CO2e/kWh, generation mix, diesel share	Tier 2-3 (grid)	Required to compute GEF(t) in Eq. (2)
Equipment life-cycle inventories / EPDs	Manufacturer environmental product declarations	Embodied carbon per unit, service life	Tier 4 (embodied)	Required for C_i, L_i in Eq. (3)
ITU-T / GSMA global benchmark datasets	ITU-T L.1450; GSMA Mobile Net Zero	Cross-country ratios (kWh/subscriber, kWh/GB)	Validation	External benchmark for Section 6 comparison

5.3 Data Preprocessing and Boundary Definition

Consistent with ITU-T L.1410, the assessment boundary should be fixed prior to data collection: geographic scope (national territory), temporal scope (calendar year), network scope (fixed and mobile RAN, core, transport, and data-centre/central-office segments operated to deliver public communication services), and life-cycle scope (use-stage plus embodied; excluding, unless otherwise stated, end-user device manufacture and use, which the literature treats as a separate ICT sub-sector; Malmodin & Lundén, 2018).

5.4 Segment and Technology Disaggregation

Network inventory should be disaggregated at minimum by segment (RAN, core/transport, data centres, CPE) and, within RAN, by technology generation (2G, 3G, 4G, 5G) and site power source (grid-connected, diesel, hybrid, renewable), since these are the dimensions shown in Section 2 to drive the largest variation in energy intensity and emission factor.

5.5 Model Calibration and Validation

Where operator-reported electricity or emissions totals are available, model parameters (P_static,i, β_i) should be calibrated so that Σ E_i(t) reproduces the reported total within a stated tolerance, following the calibration-against-measurement approach used by Mytton et al. (2024) and Lundén et al. (2022). Where no operator data are available, parameters should be drawn from published benchmarks with the tier of the source data explicitly recorded.

5.6 Scenario and Sensitivity Analysis

At minimum, three scenarios should be run using Equation (6): business-as-usual, moderate decarbonisation, and accelerated decarbonisation, with parameter ranges for g, η, and ρ(t) drawn from national policy targets where available (for example, national renewable-energy or net-zero plans) and from the international literature otherwise (Andrae & Edler, 2015; International Telecommunication Union & World Bank, 2024).

5.7 Ablation Design

To isolate the contribution of each mechanism in Equation (6), a proposed ablation design would sequentially hold η and ρ(t) at baseline (2024) levels while varying g alone, then release η while holding ρ(t) fixed, then release ρ(t), reporting F_total(2030) at each step; this design would show, for a given country, how much of any projected footprint reduction is attributable to efficiency versus to renewable electricity, information directly relevant to policy sequencing (Section 8).

5.8 Reproducibility

All equation parameters, their data sources, and their assigned data-quality tier (Tier 1-3, following International Telecommunication Union, 2025) should be published alongside any national application of this framework, together with the boundary definition (Section 5.3) and the version of grid emission-factor data used, to allow independent replication and year-on-year comparison. This transparency also strengthens accountability, reproducibility, and methodological consistency across jurisdictions and reporting periods.

5.9 Data-Quality Tiers and Uncertainty

Following ITU-T L.1450, three data-quality tiers are recommended: Tier 1 (primary, operator-measured data for E_i(t) and N_i(t)); Tier 2 (a mix of primary and secondary/benchmark data); and Tier 3 (screening-level estimates from secondary or proxy data only). Countries beginning implementation should report which tier applies to each parameter, and treat Tier 3 outputs as indicative screening estimates rather than audit-grade figures (International Telecommunication Union, 2025).

6. Proposed Framework and Illustrative Application

Figure 1 presents the proposed assessment framework as an architecture: four inventory/data tiers feed an aggregation engine implementing Equations (1)-(4); the engine's output (segment-level and total footprint) feeds a scenario and sensitivity module implementing Equation (6); and an explainability and uncertainty layer records the data-quality tier and sensitivity range behind every reported figure, so that policy users can see not only the estimate but its evidentiary basis.

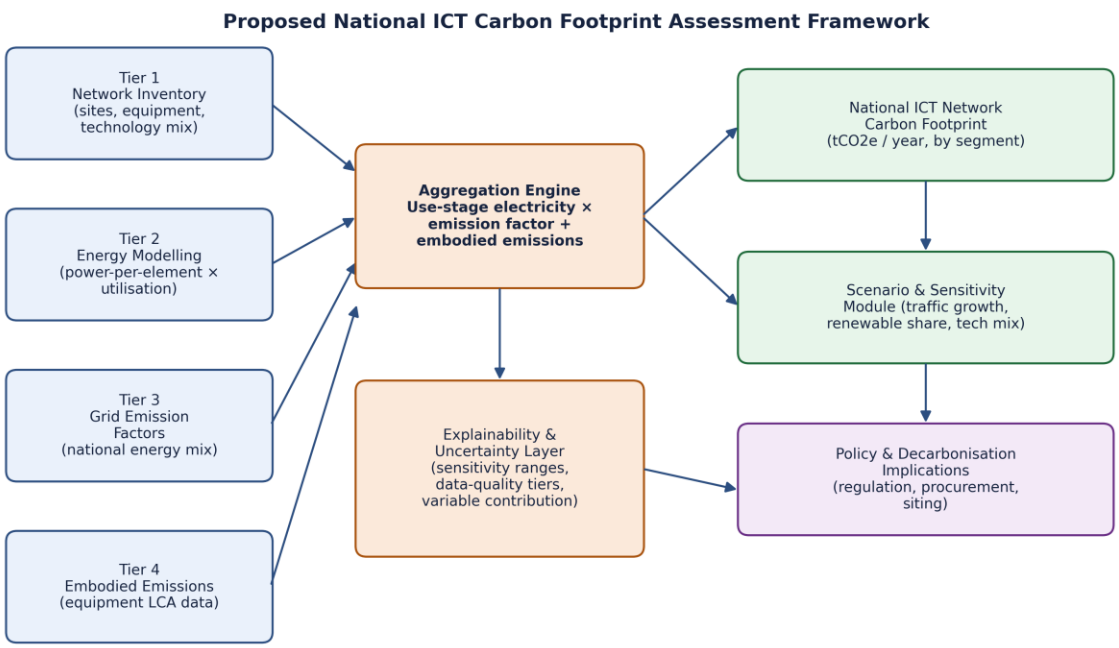

Figure 2: Proposed national ICT network carbon footprint assessment framework.

6.1 Illustrative Segment Composition

Figure 2 illustrates the output structure the framework would produce once populated with real national data. The values shown are synthetic and were constructed to be directionally consistent with the RAN-dominant energy shares reported in the operator-level literature (Nokia, 2024; Williams et al., 2022) rather than measured for any specific country; they are presented solely to demonstrate what the framework's output looks like and must not be read as an empirical result. Taken together, these synthetic outputs illustrate the directional validity of the framework, aligning with operator-level benchmarks while avoiding claims of empirical precision. They demonstrate how the model can be scaled to national datasets, enabling comparative analysis across diverse energy economies once real data are integrated.

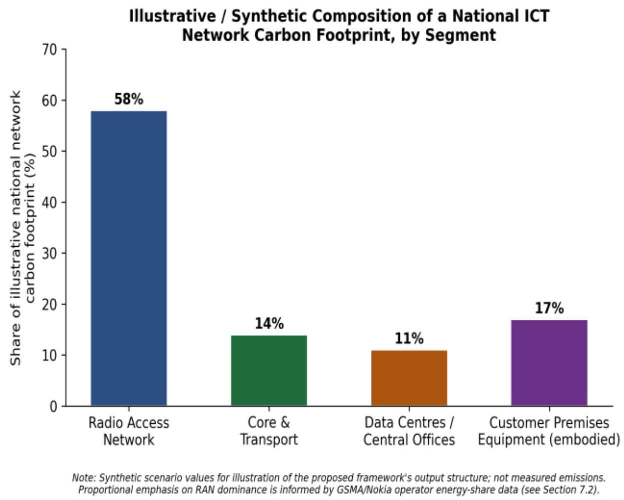

Figure 3: Illustrative/synthetic composition of a national ICT network carbon footprint, by segment. Synthetic values for demonstration only.

6.2 Illustrative Scenario Assumptions

Table 3 lists the synthetic parameter assumptions used to generate the three illustrative scenarios plotted in Figure 3 via Equation (6). These are placeholder values chosen for demonstration and internal consistency, not calibrated forecasts for any real network. These assumptions are intentionally simplified to isolate the relationships represented in Equation (6). They provide a transparent basis for interpreting the relative differences among the scenarios. The resulting values should therefore be viewed as illustrative outputs rather than empirical evidence. Future applications should replace these assumptions with validated, context-specific parameters derived from observed network data.

Table 3: Illustrative Scenario Assumptions (Synthetic, for Demonstration Only)

Scenario	Traffic growth, g	Efficiency gain, η (annual)	Renewable share, ρ(2030)	Residual factor, κ
Business-as-usual	7% / yr	0%	unchanged from 2024 baseline	n/a
Moderate decarbonization	7% / yr	3% / yr	rising to ~45%	0.05
Accelerated decarbonization	7% / yr	6% / yr	rising to ~75%	0.05

6.3 Illustrative Scenario Projection

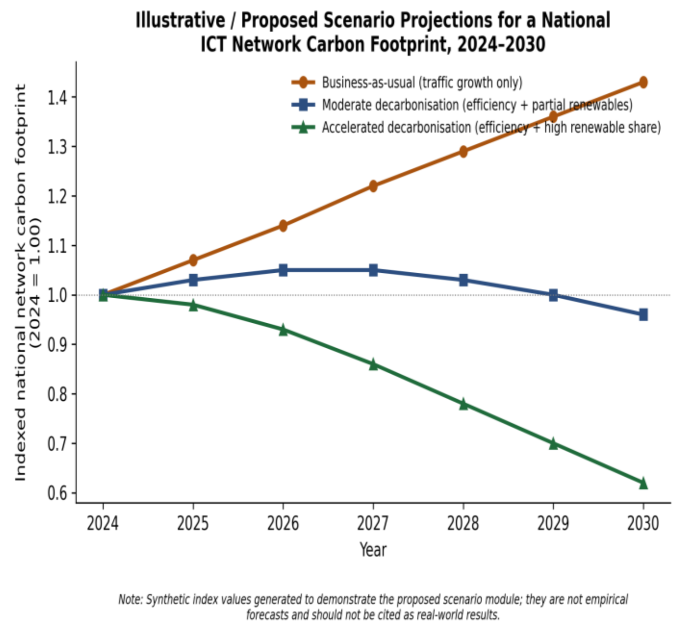

Figure 4: Illustrative / proposed scenario projections, 2024-2030 (indexed, 2024 = 1.00). Synthetic values, not empirical forecasts.

Under the synthetic business-as-usual assumptions, the indexed footprint rises by roughly 43 percent by 2030, driven entirely by traffic growth with no offsetting efficiency or renewable-energy effect. Under moderate decarbonisation, efficiency gains and a rising renewable share are sufficient to roughly offset traffic-driven growth, leaving the indexed footprint close to its 2024 level by 2030. Under accelerated decarbonisation, the indexed footprint falls by roughly 38 percent over the same period. Because these figures are generated from illustrative parameters rather than a calibrated national model, they should be interpreted only as a demonstration of the scenario module's behaviour under Equation (6), not as a projection for any real country; Section 9 returns to this limitation.

7. Discussion

7.1 Interpreting the Illustrative Results

The illustrative results in Section 6 are best read as a proof of concept for the framework's structure rather than as findings about any national network. Two qualitative patterns nonetheless track the literature closely enough to be worth drawing out. First, the RAN-dominant segment composition in Figure 2 is consistent with independent operator-reported energy-share data showing the radio access network accounting for the large majority of mobile network energy consumption (Nokia, 2024), which suggests that national decarbonisation strategies should prioritise RAN-level interventions—site consolidation, sleep-mode and traffic-adaptive power scaling, and antenna/technology upgrades—over, for example, core-network measures alone.

Second, the scenario spread in Figure 3 illustrates a point implicit in Equation (6): traffic growth alone does not determine whether a national footprint rises or falls; the outcome depends on whether efficiency and renewable-electricity gains, η and $\rho(t)$, grow at least as fast as traffic. This mirrors the empirical finding that European operator electricity use and subscriptions remained close to flat between 2015 and 2018 despite a threefold increase in data traffic, evidently because efficiency gains kept pace with demand over that period (Lundén et al., 2022). Whether the same holds for a given developing-country network—where technology-generation upgrades, from 2G/3G toward 4G/5G, can themselves be a major source of efficiency gain, but where diesel back-up power can also push the effective grid emission factor upward—is precisely the empirical question the proposed framework is designed to answer once populated with real data (GSMA, 2024).

7.2 Comparison with International Benchmarks

The framework's normalised intensity metric, I(t) in Equation (5), is designed to be directly comparable with the roughly 30 kWh-per-subscription benchmark reported for European operators (Lundén et al., 2022) and with global sector-level ratios reported in International Telecommunication Union and World Bank (2024). A national implementation reporting an intensity substantially above such benchmarks would flag either genuinely higher network energy intensity (for example, due to a higher share of off-grid diesel sites, lower site density relative to subscriber dispersion, or an older technology mix) or a data or boundary inconsistency requiring review before the figure is used for policy purposes.

7.3 Trade-offs and Practical Implications

Three trade-offs are worth flagging for implementing countries. First, there is a data-availability/accuracy trade-off: a Tier-3 screening assessment can be produced quickly from secondary data but carries wide uncertainty, whereas a Tier-1 assessment requires sustained operator cooperation and disclosure, which several studies note is currently the exception rather than the norm outside a handful of jurisdictions (International Telecommunication Union & World Bank, 2024). Second, there is a coverage/emissions trade-off specific to universal-access policy: extending service to remote, currently unconnected populations, a stated national priority in many countries, will tend to increase off-grid or weak-grid site counts and therefore, absent a parallel renewable-energy push, increase the effective grid emission factor term in Equation (2) even as it advances connectivity and development goals (GSMA, 2024; Oughton et al., 2023). Third, there is a timing trade-off between efficiency and renewable-energy investment: the ablation design in Section 5.7 is intended to help a given country identify, from its own data, which lever offers the larger near-term footprint reduction, since the answer need not be the same in every country or grid context.

7.4 Deployment Considerations

Operationalising the framework inside a regulator or ministry would likely require: a legal or regulatory basis for mandatory operator disclosure of the Tier-1 variables in Table 2; a designated data custodian (plausibly the telecom regulator, following the French precedent noted in International Telecommunication Union & World Bank, 2024); and a recurring (at minimum annual) reporting cycle aligned with the ITU-T L.1450 tier structure so that data quality can improve incrementally rather than requiring a single, resource-intensive baseline study.

8. Ethics, Governance, and Policy Implications

Several governance considerations follow directly from the framework. Operator-level disclosure of energy and emissions data can raise commercial-confidentiality concerns, which is why Lundén et al. (2022) report aggregated rather than operator-attributed figures even where the underlying primary data are operator-specific; a national implementation should similarly define, in advance, which figures are published at the aggregate-national level and which (if any) at the operator level, and under what confidentiality safeguards.

Equity considerations arise from the coverage/emissions trade-off noted in Section 7.3: because universal-access policy inherently expands service into higher-cost, often off-grid or weak-grid areas, a naive emissions-only evaluation of network expansion could inadvertently penalise the connectivity gains most valuable for underserved and rural populations. The framework therefore recommends reporting the intensity metric I(t) (Equation 5) alongside, not instead of, absolute connectivity and coverage indicators, so that decarbonisation and universal-access objectives can be weighed together rather than treated as a single undifferentiated target (GSMA, 2024; Oughton et al., 2023).

Finally, regulatory accountability depends on methodological transparency: because Section 2 shows that scenario-based global projections can diverge substantially from measured national outcomes, any policy target set using this framework should specify which data tier (Section 5.9) underlies it, and should commit to revising the target as the tier improves, rather than treating an initial Tier-3 screening estimate as a fixed baseline (International Telecommunication Union, 2025).

9. Limitations

i. No primary national network dataset was collected or analysed for this paper; the results in Section 6 are explicitly synthetic and illustrate the framework's output structure, not a measured or forecast national footprint.

ii. The mathematical model (Section 4) assumes a linear static-plus-traffic-dependent power relationship at segment level; this is well supported for radio access network base stations (Mytton et al., 2024) but may require adaptation for other segments, such as software-defined core network functions, where power-traffic relationships can be non-linear.

iii. The framework treats the national grid emission factor as an exogenous, nationally uniform input (subject to the grid/diesel disaggregation noted in Section 4.2); sub-national variation in grid mix and time-of-day emission-factor variability are not modelled.

iv. Embodied-emissions parameters (C_i, L_i in Equation 3) depend on manufacturer life-cycle inventory data of variable public availability and quality; where such data are unavailable, Tier-3 proxy values must be used and clearly flagged as such.

v. The literature review, while covering primary academic sources, ITU-T standards, and major industry reports, is not an exhaustive systematic review; a full national implementation would benefit from a broader, country-specific grey-literature search, including national statistical office and energy-ministry publications.

vi. Second- and third-order effects of ICT (for example, emissions avoided elsewhere in the economy through digital substitution) are outside the system boundary defined in Section 5.3 and are not estimated here, consistent with the paper's focus on the network's own footprint rather than its net societal climate effect.

10. Future Research

i. Pilot implementation of the framework in one or more low- or middle-income countries currently underrepresented in the primary-data literature, using regulator-mandated Tier-1/Tier-2 data, to test whether the European kWh-per-subscription intensity benchmark (Lundén et al., 2022) holds outside high-income, predominantly grid-connected network contexts.

ii. Extension of the segment-level power model (Equation 1) to core-network functions increasingly delivered via virtualised, cloud-native infrastructure, where power-traffic relationships may differ from the base-station-derived model used here.

iii. Longitudinal validation of the scenario module (Equation 6) by comparing multi-year projections against subsequently measured national outcomes, in the spirit of the retrospective validation Malmodin and Lundén (2018) perform against earlier scenario-based projections.

iv. Integration of off-grid and hybrid-power site data at finer geographic resolution, potentially combining regulator site registries with remote-sensing-based settlement and grid-coverage data, extending the techno-economic siting approach of Oughton et al. (2021, 2023) to the emissions domain.

v. Cross-country comparative research applying the framework consistently across a sample of countries with differing grid mixes and network topologies, to test which structural factors (grid emission factor, technology generation mix, off-grid site share, population density) best explain observed variation in the intensity metric I(t).

vi. Human-centred and institutional research on the disclosure and governance arrangements (Section 8) that would make sustained Tier-1 data collection feasible, including regulator capacity, operator incentives, and confidentiality-preserving aggregation and reporting mechanisms.

11. Conclusion

This paper set out to address a specific, policy-relevant gap: the scarcity of standardised, country-level assessments of the carbon footprint of national communication networks, notwithstanding a substantial and growing global-sector literature. Building on a thematic review of that literature—spanning global scenario estimates (Andrae & Edler, 2015; Belkhir & Elmeligi, 2018), primary-data operator studies (Lundén et al., 2022; Malmodin & Lundén, 2018), network-layer life-cycle assessment (Williams et al., 2022), techno-economic national modelling (Oughton et al., 2021, 2023), and the ITU-T L.14xx methodological standards (International Telecommunication Union, 2012, 2014, 2025)—the paper developed a tiered mathematical framework (Section 4) linking network inventory, segment-level energy use, national grid emission factors, and embodied equipment emissions into a single, internally consistent national footprint estimate, together with a companion scenario module for projecting that footprint under alternative traffic, efficiency, and renewable-energy assumptions.

Because no primary national dataset was available, the paper demonstrated the framework's output structure using transparently labelled synthetic data (Section 6) rather than claiming empirical findings, in keeping with the research-integrity standards this paper has sought to observe throughout. The illustrative application nonetheless reproduces two qualitative patterns consistent with the wider literature: radio-access-network dominance of the energy footprint, and the central role of the relative pace of traffic growth versus efficiency and renewable-energy gains in determining whether a national footprint rises or falls. The paper's research questions are answered at the level the available evidence permits: RQ1 and RQ2 are addressed through the data-source mapping (Table 2) and mathematical model (Section 4); RQ3 is addressed illustratively through the scenario module (Section 6.3), pending empirical calibration; and RQ4 is addressed through the governance discussion in Section 8. The central practical implication is that a tiered, ITU-T-aligned national assessment methodology, of the kind proposed here, is a necessary but not yet sufficient condition for evidence-based ICT decarbonisation policy: sufficiency requires the sustained regulator-operator data disclosure and cross-country validation set out in the future research agenda (Section 10). Extending this work from a proposed framework to an empirically populated, peer-validated national assessment—beginning with the pilot implementation recommended in Section 10—is the logical next step for this research programme.

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