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A Framework to Incentivise Green Networks and Infrastructure in the 6G Mobile Ecosystem

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Abstract

The transition to greener energy sources and the reduction of greenhouse gas (GHG) emissions are essential to mitigating climate change and ensuring a sustainable future. Although the ICT sector currently accounts for a modest share of global emissions, its contribution is expected to soar due to the rapid growth in data and computing demand in all industry verticals, driven by the deployment of 6G that will enable AI-driven services by providing ultra-reliable, low-latency, and high-capacity connectivity across the cloud–edge continuum.

Initiatives like 6Green are developing technical capabilities to measure and expose information on GHG emissions associated with 6G network services throughout the value chain. However, such technical enablers are not sufficient to incentivise investment in sustainable infrastructures and the adoption of green services.

This paper introduces a techno-economic framework to evaluate policy mechanisms for promoting greener network and infrastructure in the 6G ecosystem. The model captures interactions between stakeholders under varying market conditions, integrates sustainability key performance indicators (KPIs), such as carbon emissions, and operationalises the concept of Decarbonisation Level Agreements (DLAs) as an extension of traditional Service Level Agreements (SLAs).

Four policy options are compared: laissez-faire, infrastructure subsidisation, uniform DLA enforcement, and a tiered DLAs allowing for green premium services. Results show that while strict DLAs and subsidies can reduce emissions, they may also introduce cost and capacity constraints unless carefully designed. Tiered approaches, which combine regulation with market-driven incentives and user awareness, offer a more balanced and scalable path toward sustainability.

Keywords: Mobile networks, 6G, economics, sustainability

1 Introduction

Addressing climate change through a global reduction in carbon emissions and a transition to greener energy sources is essential to meet the Sustainable Development Goals (SDGs) of the United Nations and ultimately to protect our planet and ensure a livable future for generations to come. Although the ICT sector is responsible for barely 2–3% of global energy consumption and 1% of greenhouse gas (GHG) emissions [1], this contribution is expected to grow due to soaring data and computing power demanded by Artificial Intelligence (AI) and Machine Learning (ML) applications and services in many industry verticals. The future generation of mobile networks, 6G, must address the challenge of controlling energy consumption and carbon emissions, particularly those of radio access networks (RAN) and edge computing nodes [2].

5G technologies defined an ecosystem that supports vertical applications and the distribution of virtualised network functions (VNFs) across the network through slicing. Network slicing allows for the coexistence of multiple virtual networks with different requirements on a single physical infrastructure.

The GSMA has developed a Generic Slice Template (GST) for slice orders that includes green parameters such as resource utilisation, energy consumption, and efficiency [3], as well as others that state Service Level Agreements (SLAs) between slice providers and their customers. Researchers have proposed to improve this framework with Decarbonisation Level Agreements (DLAs) to incorporate sustainability parameters [4], such as carbon emissions and renewable energy usage, and data analytics functions to monitor and optimise them [5].

The mere existence of technical capabilities to enable and measure sustainability indicators in network slices does not, on its own, ensure the adoption of greener services. Stakeholders such as Infrastructure Providers (IPs) and Network Platform Providers (NPPs), who orchestrate slice orders, play distinct roles within the ecosystem and operate under different objectives and constraints. As we will demonstrate, these differing incentives may lead to suboptimal outcomes from a sustainability perspective, with the system favouring cost or performance over environmental issues. Therefore, effective mechanisms (both technical and economic) are needed to incentivise the deployment and selection of lower-emission network slices. Without such measures, the ecosystem is unlikely to achieve its sustainability targets.

This paper explores mechanisms to incentivise stakeholders for the greener and more efficient deployment and operation of networks and services in 6G, and defines a techno-economic framework to model the dynamics of flexible vertical application deployment over 6G network slices. Building on existing literature, we propose a techno-economic framework based on Mixed Integer Linear Programming (MILP) to evaluate a range of policy options aimed at promoting the adoption of lower-emission services. We examine the case of a Network Platform Provider (NPP) that can request network slices on demand from multiple Infrastructure Providers (IPs), with realistic power-consumption and carbon-emission profiles based on existing studies [6]. Without loss of generality, the framework can also be applied to alternative configurations, such as a single IP managing multiple types of infrastructure or energy sources with differing carbon profiles.

Specifically, we address the following research questions:

- Under what conditions are sustainability policies necessary to incentivise the adoption of greener 6G services and infrastructure?
- To what extent can subsidies drive the deployment of lower-emission services in a competitive 6G market?
- What role can DLAs and regulatory decarbonisation glide paths play in promoting greener infrastructure adoption within the 6G ecosystem?
- Can sustainability awareness and tiered service models that distinguish between standard and green premium services provide a scalable mechanism for internalising sustainability costs?

To the best of our knowledge, this is the first paper that includes criteria related to key performance indicators (KPIs) related to sustainability in the orchestration and implementation of 5/6G network slices. Our contributions include:

- Formulating the optimisation problem from the perspective of an NPP.
- Developing a techno-economic model that accounts for sustainability based on a MILP approach.
- Identifying potential ICT policies towards sustainability.
- Proposing and testing policy options by applying the framework to a practical case.

Section 2 provides the background to our study. Next, Section 3 presents related works. Section 4 presents the techno-economic framework, including the detailed formulation of a MILP problem to optimise the orchestration of 5G/6G network slices under sustainability constraints. In Section 5, we define the policy options tested and analyse the results in multiple demand scenarios. Finally, Section 6 concludes the paper and points to future research.

2 Background

This section provides the background to our study. Section 2.1 introduces technical enablers for a framework to incentivise sustainable 5/6G infrastructure and services, notably slicing, DLAs, their monitoring and reporting. In Section 2.2, we explain the ecosystem of 5/6G service and network infrastructure and point to market failures that may hinder investment, which justifies the need for policy intervention and for this framework. Finally, Section 2.3 reviews existing policy initiatives that seek to incentivise sustainability in the EU, and Section 2.4 summarises sustainability policies in the ICT sector.

2.1 Technical Enablers

To enable a framework that incorporates the sustainability of ICT networks and services into their operation, several key components are required. First, we need mechanisms to partition 5G/6G infrastructure in order to support networks and services with diverse requirements. Second, there must be a way to integrate sustainability-related KPIs, such as carbon emissions or reliance on renewable energy sources, into

those service requirements. Third, we require mechanisms to propagate this information throughout the network and across all stakeholders in the value chain. These needs are addressed through: (i) 5G/6G network slicing, (ii) the extension of Service Level Agreements (SLAs) via Decarbonisation Level Agreements (DLAs), and (iii) a data analytics system integrated with the Business Support System (BSS) to enable end-to-end monitoring. We present these enabling technologies and refer to relevant literature in the following sections.

2.1.1 5/6G Network Slicing

Network slicing allows the creation of multiple virtual networks on a single physical 5/6G infrastructure, each tailored to specific needs, such as ultra-low latency, high throughput, or massive Machine-Type Communications. From a technical point of view, network slicing allows services that require very different capabilities in the network to co-exist on top of a single infrastructure. Therefore, it creates economies of scale and additional levers to optimise network resources, and increase the efficiency of 5/6G networks and services. From a business perspective, this differentiation enables the provisioning of customised corporate virtual networks and services.

The GSMA has defined a Generic Slice Template (GST) that specifies the attributes and parameters a slice order can contain, which characterise the area of service or the functionality of the slice (e.g., includes positioning), and specify QoS parameters relevant for scaling the slice such as throughput, latency or the maximum number of users or sessions, among others [3]. Moreover, the GSMA provides sample Network Slice Templates (NESTs) for typical network slices requesting ultra-reliable low-latency communications (urLLC), enhanced mobile broadband services (eMBB), public safety or massive IoT services, among others.

GSMA GST defines parameters to configure and monitor the operation of 5/6G slices and their Service Level Agreements (SLAs), which include key KPIs related to sustainability such as resource utilisation, energy consumption and efficiency. However, GSMA templates lack sustainability KPIs related to carbon emissions, which hence cannot be considered in scheduling, monitoring and managing network slices.

2.1.2 Decarbonisation Level Agreements

The Decarbonisation Level Agreement (DLA) is a formal framework that incorporates energy and carbon footprint considerations as part of the business arrangements between network stakeholders, complementing traditional Service Level Agreements (SLAs) [4, 7]. DLAs are designed to enable the explicit negotiation and enforcement of sustainability objectives—such as energy consumption, carbon emissions, and the use of renewable energy—within the service definition and delivery process. This approach allows customers and providers to jointly define and pursue green targets, ensuring that sustainability becomes a measurable and enforceable part of network service agreements.

A DLA is structured across three main dimensions: decarbonisation, level, and agreement [4, 7]. The decarbonisation dimension focuses on identifying relevant terms and targets for carbon reduction, as well as describing the consequences for not meeting these goals. The level dimension defines how sustainability objectives are measured

and evaluated, including the mechanisms for retrieving key performance indicators (KPIs) and the specification of consistent and meaningful metrics. The agreement dimension addresses the processes for negotiating, committing to, and enforcing the DLA, ensuring dynamic interaction and governance between customer and provider.

The concept of DLAs paves the way for agreements between stakeholders of the ecosystem that include energy and carbon footprint. 3GPP and GSMA standards for the operation of 5/6G networks lack information beyond the standard KPIs of the GST, which are useful to ensure the SLAs of 5G network slices, but do not include any sustainability indicator. To address this issue, some authors have proposed DLAs as an extension of the classical SLAs established between customers and providers to guide the execution and compliance of services agreed among them. DLAs include sustainability KPIs such as carbon emissions, percentage of energy used generated through renewable sources, etc [4] and were based on a related report by the Body of European Regulators of Electronic Communications (BEREC) [7].

To integrate DLAs into actual agreements, 6Green service-based architecture has defined the Business Support System Function (BSSF). The BSSF interfaces the customer for receiving slice requests, defines intents for operational components to take into account SLAs and DLAs, and reports back to the customer metrics associated to the requested network slice. The interaction with the 6Green system will be based on declarative interfaces using intents, with syntax compatible with the 3GPP TS 28.312 specification. These components are still under development within 6Green.

2.1.3 Tools to monitor carbon emissions in 6G networks

Assurance of sustainable networks and services requires awareness. Consequently, a framework to incentivise sustainable 5/6G services requires making stakeholders in the ecosystem aware of their power and energy consumption and their carbon emissions. This requires a monitoring platform covering the whole ecosystem, adequate KPIs, and network functions able to introduce sustainability factors into the operation of mobile networks, core and edge computing nodes, and the cloud.

3GPP has defined an architecture for a network analytics service in 5G standards [8], and key equipment vendors have developed NetWork Data Analytics Functions (NWDAF) for 5G networks. Some authors have developed open-source frameworks to monitor the edge and the cloud and produce KPIs in real time, and to produce aggregate statistics [5]. Thanks to DLAs, such indicators could include sustainability KPIs like carbon emissions or utilisation of renewable energy.

Therefore, measuring and reporting sustainability KPIs of telecom infrastructures and services will be key to ensuring this system is effective. Especially when end customers cannot make such measurements and must rely on service providers to report them using the built-in monitoring system and the BSSF. The EU is working to identify common indicators and methodology to measure the environmental footprint of electronic communications networks for the provision of electronic communications services [9], and on Codes of Conduct for sustainable telecom networks. In this paper, we will assume that NPPs and IPs are able to measure power consumption and carbon emissions and transparently report them to their customers.

2.2 6G Ecosystem and Stakeholders

The transition to 6G introduces a complex ecosystem involving multiple stakeholders with distinct roles, objectives, and constraints. Unlike previous generations, 6G networks will operate over a highly virtualised infrastructure, leveraging the cloud-edge continuum to support flexible and scalable deployment of services tailored to vertical application needs. Within this context, three primary stakeholder groups emerge: Infrastructure, Network Platform, and Vertical Application Providers.

- Infrastructure Providers (IPs) are responsible for the long-term investment in and operation of physical ICT infrastructure, including data centres, edge nodes, and access network components. They typically offer wholesale services through Infrastructure-as-a-Service models. IPs aim to maximise the return on investment, which can discourage them from investing in greener technology without a clear economic reward or unavoidable regulatory pressure.
- Network Platform Providers (NPPs) operate on top of the infrastructure provided by IPs. They manage and orchestrate virtualised network resources—processing, storage, connectivity, and Virtual Network Functions (VNFs)—to deliver tailored network slices in response to service demands. As intermediaries, NPPs must balance cost, performance, and sustainability requirements when accepting slice orders and allocating resources to competing IPs.
- Vertical Application Providers (VAPs) interface with the end users. They design and deploy applications across various industry sectors (e.g. healthcare, gaming, manufacturing), defining specific Service Level Agreements (SLAs) and requesting slices to NPPs. VAPs may be motivated to offer environmentally friendly services if they can capture “green premiums” from sustainability-conscious users; however, their decisions are often constrained by price sensitivity, performance targets, and information asymmetries.

These stakeholders interact in a market-driven environment, yet their independent optimisation strategies may not converge towards environmentally optimal outcomes. For instance, IPs might avoid greener investments if competition erodes profit margins, while VAPs may deprioritise sustainable choices if green performance metrics are not transparently communicated or economically incentivised. Consequently, the 6G ecosystem risks under-delivering on its potential for sustainability, unless appropriate incentive mechanisms or regulations are introduced to realign stakeholder objectives.

This analysis underscores the necessity of a techno-economic framework capable of modelling stakeholder behaviour under different policy and market conditions. Such a framework must account for the interplay between cost structures, SLAs, DLAs, and pricing strategies, enabling a systematic evaluation of incentive mechanisms that promote energy-efficient and sustainable 6G deployments.

2.3 Policies towards sustainability in the EU

Policy-making has been active in promoting sustainability in industry verticals. The EU issued the European Green Deal and set the strategic priority of becoming a climate-neutral, resource-efficient competitive economy by 2050 [10], setting interim goals to reduce energy consumption and increase the share of renewables by 2030 (see Directives EU/2023/1791 and EU/2023/2413). Moreover, following the Paris Agreement at COP21, the EU established an internal Emissions Trading System (ETS) for countries to trade excess GHG emissions over yearly revisable lowering targets.

Recently, a growing concern about boosting the competitiveness of the European industry and the need for self-sufficiency led to the Clean Industry Deal [11]. The Deal included a plan to make energy more affordable in the EU, measures to promote demand of clean energy, funds for R&D&i and renewable energy rollouts, and measures to unify actions to secure supply chains and purchase and secure raw materials, among other initiatives. In addition to these cross-industry initiatives, specific industries and countries took other measures to achieve the EU sustainability objectives. These include measures targeting the demand and supply sides.

Automotive. The automotive sector has set increasingly restrictive regulations to specify sustainability targets for new vehicles sold in the EU, such as maximum emissions or minimum battery life [12]. To accelerate fleet modernisation, national governments resorted to direct aid to consumers purchasing low-emission vehicles (GE, FR, IT, SP) supported by environmental labels that classify vehicles depending on their energy efficiency and emissions, and by bonus/malus systems that reward owners of clean vehicles (e.g., free public parking) and/or penalise older more polluting cars [13]. On the supply side, they established different types of subsidies and funding for clean vehicle manufacturing (GE, FR, IT, SP), and penalties for non-compliance with target emissions [14, 15].

Energy. The energy sector subsidises specific projects to transition to a net-zero economy (e.g., through direct subsidies or tax reductions), and its regulations promote investment in renewable energy through wholesale tender processes resulting in financial support to greener generation technologies, *feed-in tariffs*¹ securing long-term access to the grid at cost-based regulated prices to otherwise unprofitable green energy providers, or *feed-in premiums*² that overpay for green energy generation [16]. On the demand side, some governments support consumers who invest in more efficient housing or greener heating systems [17]. Similar to cars, dwellings carry an eco label, which is required when landlords rent or sell them.

Chemicals. We find similar policies in the chemical industry or agriculture, which add challenges regarding the control of the supply chain, the circular management of materials to foster reuse, and the control of potentially harmful ingredients, production factors or processes that may affect the health of end consumers. On the supply side, we also find subsidies to promote investment in greener and healthier production plants and methods [18]. To promote demand, nutritional or eco labels increase the awareness of end consumers and highlight products that fully comply with EU regulations [19].

¹Policy instrument designed to incentivise renewable energy production by offering guaranteed payments to renewable energy generators for the electricity they feed into the grid

²Policy mechanism designed to support investment in renewable energy, allowing renewable energy producers to sell to the electricity market and receive a premium in addition to the market price.

A key aspect of implementing this strategy is monitoring [20]. Should the EU propose targets, incentives for greener telecom networks, and penalties for less efficient and less sustainable network infrastructure, it will require supervised, reliable mechanisms to measure energy efficiency and carbon emissions (see Sect 2.1.3). In the next section we summarise policies towards sustainability in the ICT industry.

2.4 Towards Sustainable ICT Networks and Services

Despite not considered a top environmentally impactful vertical, carbon emissions from ICT infrastructures and services are dramatically increasing due to sustained growth in connected devices of end users, the proliferation of large processing data centers, and the increasing digitalisation of the economy. Emission projections vary. Whereas some studies suggest that emissions from the ICT sector will remain largely stable around 2-4% global emissions and that the ICT sector will contribute positively to the greening of the economy, others suggest that ICT could account for 14-24% global emissions by 2030/40 and become a potential obstacle to achieving Europe's climate neutrality and environmental targets [21].

Determining a breakdown of carbon emissions in the ICT industry is far from straightforward. Several studies and research have published information on this relevant topic. Most works agree that around 60% of emissions are due to the production and use of terminal equipment especially large screens (TVs and computers). whereas ICT networks account for 25% of ICT industry emissions, that is, 0.5-1% of the total global GHG emissions [21].

Although the ICT sector and digitalisation are largely considered net contributors to the greening of other sectors of the economy, some voices have raised the concern that growth in terminal equipment and ICT infrastructure may outweigh these benefits. Therefore, policies towards sustainable ICT are responsible for harnessing the potential benefits of the ICT sector and digitalisation in greening the economy. Demand-side ICT policies aim to stimulate the demand for sustainable services, and supply-side policies aim to create positive incentives for stakeholders involved in the value chain to invest in more sustainable and efficient ICT networks and services. In particular, we have identified the following types of policies [22].

Environmental, Social and Governance (ESG) policies integrate sustainable practices, such as minimizing environmental harm, into business operations by addressing environmental impact, social responsibility and governance standards. Large corporations, not only those related to ICT, and publicly traded companies are subject to ESG obligations, which typically include environmental responsibilities such as reducing carbon emissions and managing climate risks, implementing sustainable resource management (energy, water, waste), or complying with environmental regulations and reporting standards. ESG policies require the disclosure of environmental information for monitoring [23].

Non-compliance leads to at least reputational damage, but also to fines and sanctions. Institutional investors are increasingly demanding ESG reporting, as well. As a result, market leaders have set their own sustainability goals, targeting net-zero carbon emissions by 2040 [24], and neutralizing residual emissions through the purchase of carbon removal credits [25].

Policies aimed to increase investment incentives in sustainable ICT infrastructure are common not only in ICT but also in other industries. These incentives may include targeted tax exemptions [26] and financing for specific ICT initiatives. In that direction, key telcos have been actively using green bonds to raise funds for projects with positive environmental or climate benefits [27].

Specific sustainability regulations that focus on the sustainability of digital technology and end user devices [28], which drive most of the environmental impact of ICT, and on ecodesign [29] rather than on infrastructure. Despite sustainability regulations often falling outside the mandate of ICT national regulatory authorities (NRA), some of them actively engage in discussions and some of them collect and publish information related to this topic [30].

Policies aimed to increase the awareness of the industry are a more passive yet effective policy to move towards sustainability in the ICT sector. This is accomplished by different instruments such as the publication of standards by standardisation bodies [31–34], and the promotion and publication of research and reports by governments and NRAs [7, 35].

Policies aimed to increase end user awareness, such as certification programmes and labelling schemes, which send a signals to consumers about which ICT brands meet certain environmental standards [36]. Such schemes are an effective way of recognising achievements in areas such as energy efficiency, waste reduction and emissions reduction, and usually target data centres and energy-consuming products, and offer public recognition as a reward to companies for their sustainability efforts.

3 Related Works

5G admission control and resource allocation have long been active research lines within the field of 5G network operations. Researchers have resorted to various approaches to decide on the acceptance of incoming network slices and resource allocation in core and edge nodes, which include heuristics [37], linear programming and, more recently, reinforcement learning [38, 39], which has become very popular also in dynamic management of radio access network resources. They all have formulated and solved optimisation problems targeting network performance metrics like latency and throughput, operational metrics like acceptance ratio, or even financial metrics like revenues or profit of 5G service providers. Some works have focused on network resilience [40], whereas others have introduced slice overbooking [41] and VNF migration to maximise revenues [42]. They all have focused on dynamic management of network in operational timeslots in the range of an hour or even shorter. However, they have not considered energy consumption or sustainability metrics.

In parallel, several works have addressed the topic of 5G slicing from a techno-economic perspective, for example addressing the problem of cost allocation to 5G slices and measuring the savings in the 5G core network thanks to slicing [43]. Other works have already identified players in the ecosystem and have extended the slice admission and resource allocation algorithms to minimise the cost of NPPs [44]. Some

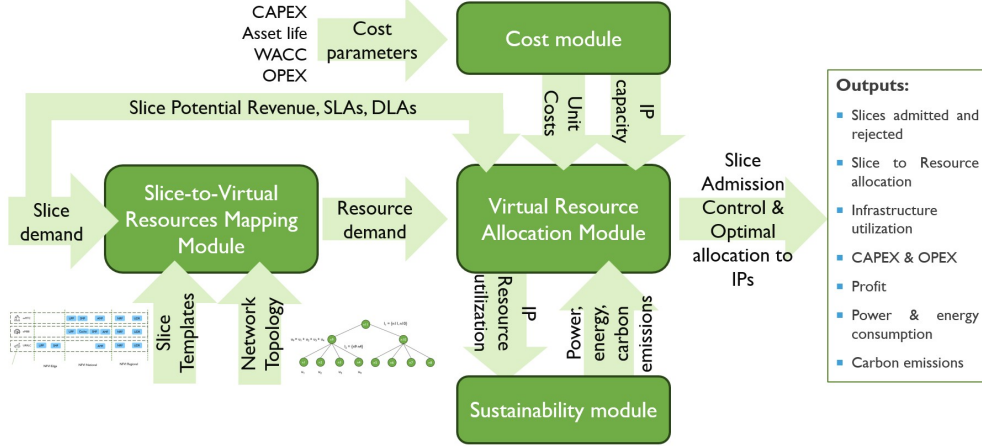


Fig. 1 Techno-economic framework block diagram

authors have applied game theory and studied the role of economic regulation in decision making and ultimately user welfare [45]. Finally, 5G slicing has sparked interest from the perspective of network neutrality in policy-related journals [46, 47].

Our work is, to the best of our knowledge, the first techno-economic paper that considers sustainability in the operation of 5/6G network slices. Building on technical enablers of the 6Green Project [48], we formulate a profit optimisation problem that integrates sustainability metrics slice admission control and resource allocation.

4 Techno-Economic Framework

The ecosystem described in Section 2 enables the exposure of sustainability KPIs of network infrastructure and services, and sustainability-aware interaction between all the stakeholders involved in the provision of vertical applications and services on top of 5/6G network slices. Moreover, we have identified often conflicting incentives from these parties that can hinder investment in greener 6G infrastructure.

In this work, we focus on modelling the techno-economic perspective of the NPP to illustrate how these perverse incentives influence the dynamics of the ecosystem. An NPP receives slice orders from VAPs, orchestrates virtual resources required to fulfil them, and allocates network resources from multiple IPs to host those virtual resources. IPs can be separate entities offering infrastructure services to the NPP, or different network infrastructures owned by a vertically integrated NPP.

Figure 1 summarises the architecture of the framework. For a series of slice orders submitted to the NPP, the model returns whether each slice is accepted or rejected, an optimal allocation of virtual resources of accepted slices to IPs, infrastructure utilisation, the operational profit for the NPP, and the estimated environmental footprint. This is achieved in two steps:

- Step 1 involves *mapping slice orders to virtual resources* and returns the demand for virtual resources needed to fulfil the required slice orders.

- Step 2 performs an *optimal allocation of virtual resources to available infrastructure* supplied by IPs, considering their cost, their environmental footprint, and the constraints imposed by SLAs and DLAs. To solve the resource allocation problem described above, we resort to Mixed Integer Linear Programming (MILP).

This section describes our techno-economic model in detail. First, Section 4.1 introduces MILP. Next, Section 4.2 defines terms, notation and variables used in the modelling and describes all the modules in detail. Finally, Section 4.3 summarises the formulation, the constraints and restrictions of the framework.

4.1 Mixed Integer Linear Programming

MILP models are well suited for this scenario because they allow for the joint optimisation of binary decisions (slice admission) and continuous variables (resource allocation), subject to a set of linear constraints representing capacity, environmental, and operational service requirements. This approach guarantees optimal solutions for moderate problem sizes and provides a flexible framework to incorporate additional business or technical constraints as needed.

The MILP model is implemented in Python using the PuLP library, which provides a user-friendly interface to define decision variables, constraints, and objective functions and supports a range of commercial and open source solvers. Data preprocessing and scenario management are handled with `pandas`, while power and emissions calculations are modularised for clarity and reusability. The overall workflow-reading input data, defining the MILP, solving and extracting results-enables reproducible and extensible experimentation with different network, demand, and sustainability scenarios.

4.2 Model Description

This section thoroughly describes the techno-economic framework. We start with introducing some general terms and notation about slicing and resources, and then we delve into the details of each module.

4.2.1 Slicing and virtual resources

Network slices refer to purely virtual 5/6G networks, a collection of VNFs running on top of a network of VNF infrastructure (VNFI) nodes, $n \in N$, interconnected by bidirectional links $l = \{n_1, n_2\} \mid n_1, n_2 \in N$ connecting VNFs running on n_1 and n_2 . We will denote by L the set of all network links and by $T = \{N, L\}$ the undirected connected graph that defines the topology of the network. We will generally refer to nodes and links as ‘*network resources*’ $r \in R = N \cup L$ (VNFI nodes and links).

5G networks are hierarchical, with edge nodes close to end users that concentrate their traffic in several levels, up to data centres that provide nationwide or regional services to end users. Slice templates define the virtual resources (VNFs and links) required by a slice (VR_s) required at each network level to comply with the SLAs of the slice. such as minimum/average throughput, maximum latency, etc.

For each virtual resource, the slice demand parameters and the slice coverage determine the demand for physical resources ($d_r(\cdot)$). The unit in which this demand is

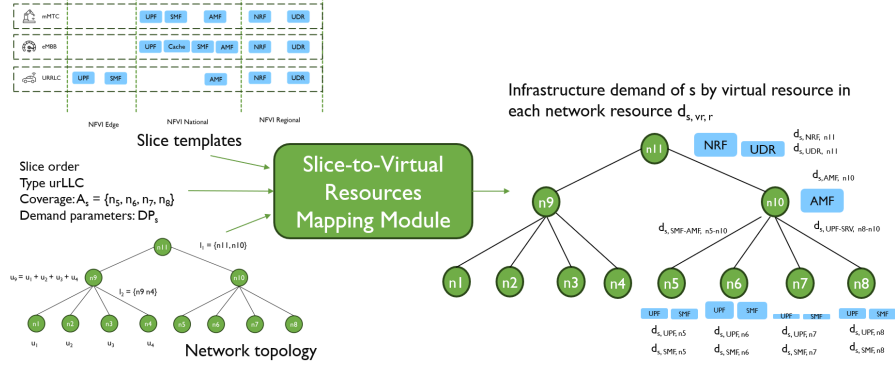


Fig. 2 Slice orders and slice resource mapping

measured depends on the type of resource, typically the number of vCPU (normalised virtual CPUs) for VNFI, GB for memory usage, TB for storage, or Gbps for network links. Demand drivers also differ between types of resources, and some papers have measured how virtual resources consume physical resources depending on different demand parameters [49]. For example, User-Part Functions (UPFs) for urLLC slices and servers providing these services consume resources according to the average number of users and their average throughput, whereas 5G mobile CORE platforms dealing with signalling consume resources depending just on the number of users.

4.2.2 Slice-to-Virtual Resources Mapping Module

The first step of the model takes as input the slice orders received by the NPP, including their parameters, SLAs and DLAs. Based on the type of slice, the model lists virtual resources required to fulfil SLAs, maps them to the network topology, and dimensions the demand for physical resources. Figure 2 graphically describes the process of mapping slices to resources in a network topology.

A network slice order s belongs to a template and must specify its geographic coverage as a list of nodes $N_s \subseteq N$, the arrival time t_s , the holding time ht_s , its potential income I_s in this period, and a set of demand parameters $DP_{s, vr}$ to dimension virtual resources (nodes or links) required to fulfil the order (e.g., unit bandwidth consumption per user at different levels in eMBB templates). We assume that I_s represents net revenues (i.e., returns, allowances, sales costs and discounts should be removed), and that SLAs are secured by scheduling all virtual resource, hence we neglect penalties for non-compliance with SLAs.

Slice templates determine which virtual resources are required at different network levels and can also specify usage parameters applicable to all slices of that type (e.g., unit processing per user required in the 5G mobile core). Thus, given a network slice order, we can map the required virtual resources according to the template to specific VNFs and connectivity demands in the network topology to comply with the target coverage and SLAs of the slice. We will denote the matrix that binds the demand for virtual resources to that for network resources of a slice s by $\mathbf{D}_s = \{d_{s, vr, r}(u_r, DP_{s, vr})\}_{vr \in VR_s, r \in R}$. By aggregating the demand for virtual

resources in a network resource, we obtain the demand for a network resource due to the slice s , $d_{s,r}$. By aggregating the demand for all slices in a network resource, we obtain the total demand for such resource d_r .

4.2.3 Virtual Resource Allocation Module

NPPs must select between competing infrastructure resources capable of hosting virtual resources demanded by network slices. This process is known as Virtual resource allocation. Without loss of generality, we will assume that IPs offer overlapping resources and extend the notation for network resources r to r, o , where $o \in O$ denotes the IP providing resource r , up to maximum capacity $C_{r,o}$. The output of this process is the virtual resource demand allocated to each IP, denoted as $da_{s,vr,r,o}$.

The resource allocation matrix maps slice virtual resource demands to available network resources provided by IPs, and specifies the percentage of demand of a virtual resource vr allocated to IP resource r, o . It is denoted by $a_{s,vr,r,o} \in [0, 1]$, $vr \in VR_s, r \in R, o \in O$. The demand for a resource r allocated to IP o is given by $da_{s,r,o} = \sum_{vr \in VR_s} a_{s,vr,r,o} \cdot d_{s,vr,r}$.

In heavy demand scenarios, NPPs may decide to relocate virtual resources from congested nodes to alternative nodes with excess capacity-which may have an impact on QoS (e.g., more latency if relocated to upper nodes in the hierarchy) and on SLAs-or even to reject the slice order. In this paper, we do not allow relocations and NPPs must make the decision y_s about whether to accept the slice ($y_s = 1$), and obtain income from it at the cost of allocating all its demands for network resources, or reject it ($y_s = 0$) and give up its potential revenue.

Among all possible allocations of resources to IPs, a rational NPP would choose those maximising its profit, given by the income of the accepted slices $y_s \cdot I_s$ minus the cost of resources needed to implement them according to the cost module (see Section 4.2.4). For this purpose, we define and solve a MILP problem, which will need to take into consideration the following constraints.

- The demand allocated to a IP's resource cannot exceed its maximum capacity. We call it the *Maximum capacity constraint*.
- Slices cannot be partially allocated, we call this the *Slice fulfillment condition*.
- Slice allocation must satisfy its SLAs, which we assume granted if it is accepted.
- Slice allocation must satisfy its DLAs, according to the KPI estimates returned by the sustainability module (see Section 4.2.5).

Maximum capacity constraint. Eventually, the demand allocated to a resource must be less than its available maximum capacity, that is, $\forall r \in R, o \in O, da_{r,o} \leq C_r$.

Slice fulfilment condition. Since the NPP cannot relocate demands to different network resources, slices must be fully allocated if accepted, which means that all demand must be allocated to IPs, that is, $y_s = 1 \implies \forall r, \sum_{o \in O} da_{s,vr,r,o} = d_{s,vr,r}$ or alternatively, $\sum_{o \in O} a_{s,vr,r,o} = 1$. If rejected ($y_s = 0$), then $da_{s,vr,r,o} = a_{s,vr,r,o} = 0$.

In the next section, we provide some details about how we model the cost of network resources. Finally, we will also assume that the allocation of network resources respects the DLAs. Section 4.2.5 delves into the details of the sustainability metrics supported by the model.

4.2.4 Cost Module

We assume that IPs charge NPPs on a cost-plus basis. This hypothesis is realistic for regulated oligopolistic infrastructure markets, but eventually this pricing will depend on the level of competition at the level of infrastructures and network service and on the market power of IPs and NPPs.

To calculate the CAPEX of network computing resources, we resort to market-based prices for a reference server architecture, and we calculate its capacity based on its specifications [49]. We annualised CAPEX using financial annuity and adding a cost of capital equal to twice the weighted average cost of capital (WACC) defined by NRAs in Spain [50]. OPEX is added by using a reference mark-up to network CAPEX, based on references of bottom-up models to set cost-based charges for wholesale services.

Regarding the capacity of network resources, we consider these an input in the current version of the model. In future versions, we will include functionality to allow IPs to adapt and grow their infrastructure according to the demand, and cost-volume curves to estimate cost as a function of demand.

4.2.5 Sustainability Module

Network resources consume power and energy. IPs may provide an energy-efficient infrastructure that can be more or less sustainable, and the sustainability module is responsible for informing the *Virtual resource allocation module* about the power and energy consumption and carbon emissions of resources for the latter to optimise resource allocation for compliance with the slices DLAs.

The *power consumption* of a network resource will be a function of i) the nominal maximum power consumption of a network resource when fully used ($PC_{max,r,o}[kW]$), ii) the *power consumption profile* that relates resource utilisation and power consumption ($PC_{p,r,o}(\cdot)$), and iii) its actual utilisation $Ru_{r,o}$.

We define *resource utilisation* of resource r of IP o as $Ru_{r,o} = da_{r,o}/C_{r,o} \in [0, 1]$. The power consumption profile is subadditive, its domain is $[0, 1]$ (none to full utilisation) and its range is $[0, 1]$ (none to nominal power consumption). Hence, the power consumption will be calculated as $PC_{r,o}[kW] = PC_{max,r,o} \cdot PC_{p,r,o}(Ru_{r,o})$. In the model, we will use an empirical power consumption profile for active equipment that considers fixed power consumption and saturates to the maximum nominal power for high utilisation above 80% [51][Figure 4].

Energy consumption reflects power consumption over time. It can be easily estimated for a resource r, o in a certain period Δt as $EC_{r,o}[kWh] = PC_{r,o} \cdot \Delta t$.

Depending on the amount of energy produced by renewable energies, power consumption can translate into the emission of GHG. To capture this, we define the *carbon emissions* of a resource as $CE_{r,o} = CI_{p,r,o}(PC_{r,o}) \cdot \Delta t$, where CI_p refers to the *carbon intensity profile* that relates the carbon intensity, measured in GHG/s, and the power consumption of that resource.

Figure 3 shows different examples of carbon intensity profiles. Subfigure (a) shows an ideal purely green infrastructure (e.g., powered only by solar cells and batteries) that does not emit GHG to the atmosphere, i.e. $CI(PC_n) = 0$. If a node is powered by the grid, we can assume that carbon emissions will be proportional to power

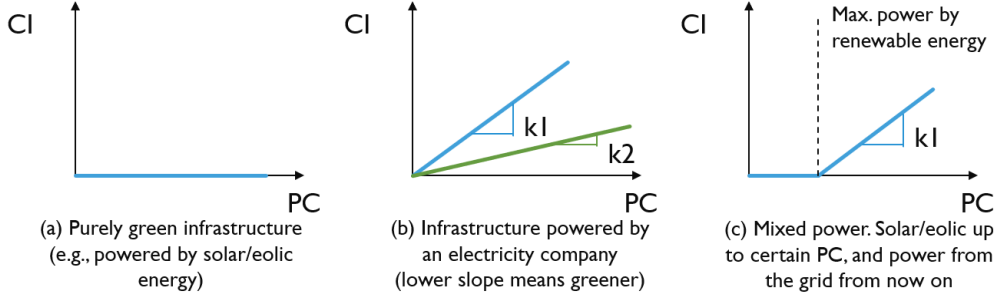


Fig. 3 Carbon intensity (CI) profiles as a function of infrastructure power consumption (PC)

consumption, that is, $CI = k \cdot PC$, as shown in Subfigure (b). The slope of the CI profile will depend on the mix of generation sources employed by the electricity company. There can also be mixed solutions, where IPs own self-powered infrastructure is capable of providing GHG-emission-free power up to a maximum threshold PC_t , and resort to the grid to accommodate additional power consumption. In this case, $CI = 0$ if $PC < PC_t$, $CI = k \cdot (PC - PC_t)$ if $PC \geq PC_t$, as shown in Subfigure (c).

In this paper, we consider the DLA restrictions for *maximum power consumption* and *maximum carbon emissions* of a slice. However, the definition of DLAs allows future restrictions to ensure a minimum percentage of renewable energy consumption, minimum energy, or carbon emissions efficiency.

4.3 Problem formulation

The NPP optimisation problem can be expressed as follows:

$$\max_{\substack{a_{s,vr,r,o} \\ y_s}} \left(\sum_{s \in S} \left[y_s \cdot I_s - \sum_{r \in R} \sum_{o \in O} c_{r,o} \cdot \sum_{vr \in VR_s} a_{s,vr,r,o} \cdot d_{s,vr,r} \right] \right) \quad (1)$$

Subject to:

Maximum capacity:

$$\sum_{s \in S} da_{s,r,o} \leq C_{r,o}, \quad \forall r \in R, \forall o \in O \quad (2)$$

Maximum power consumption:

$$\sum_{r \in R, o \in O} \left(PC_{r,o} \cdot \frac{da_{s,r,o}}{\sum_{s \in S} da_{s,r,o}} \right) \leq PC_s^{\max}, \quad \forall s \in S \quad (3)$$

Maximum carbon emissions:

$$\sum_{r \in R, o \in O} \left(CE_{r,o} \cdot \frac{da_{s,r,o}}{\sum_{s \in S} da_{s,r,o}} \right) \leq CE_s^{\max}, \quad \forall s \in S \quad (4)$$

Slice fulfilment condition:

$$\sum_{o \in O} a_{s, vr, r, o} = y_s, \quad \forall s \in S, \forall r \in R, \forall vr \in VR_s \quad (5)$$

Where:

$y_s \in \{0, 1\}$: binary decision variable, 1 if slice s is accepted, 0 otherwise.
 $a_{s, vr, r, o} \in [0, 1]$: continuous decision variable, fraction of the demand of virtual resource vr of slice s for resource r of IP o .
 $I_s \in \mathbb{R}, I_s \geq 0$: parameter, income for slice s .
 $d_{s, vr, r} \in \mathbb{R}, d_{s, vr, r} \geq 0$: parameter, demand for resource r by v. resource vr of slice s .
 $da_{s, r, o} = \sum_{vr \in VR_s} a_{s, vr, r, o} \cdot d_{s, vr, r}$. Demand for resource r of IP o by slice s
 $c_{r, o} \in \mathbb{R}, c_{r, o} \geq 0$: parameter, unit cost of resource r of IP o .
 $C_{r, o} \in \mathbb{R}, C_{r, o} \geq 0$: parameter, maximum capacity of resource r of IP o .
 $PC_{r, o} \in \mathbb{R}, PC_{r, o} \geq 0$: parameter, nominal power consumption of resource r of IP o .
 $PC_s^{\max} \in \mathbb{R}, PC_s^{\max} \geq 0$: parameter, maximum power allowed for slice s .
 $CE_{r, o} \in \mathbb{R}, CE_{r, o} \geq 0$: parameter, nominal carbon emissions of resource r of IP o .
 $CE_s^{\max} \in \mathbb{R}, CE_s^{\max} \geq 0$: parameter, maximum carbon emissions for slice s .
 S : set of all service slices.
 VR_s : set of all virtual resources required by slice s
 R : set of all resources.
 O : set of infrastructure providers.

5 Policy Options Assessment

To illustrate how sustainability policies can incentivise investment in greener infrastructure, we model scenarios where an NPP orchestrates and delivers a range of advanced 5G services to its end users and corporate clients. The NPP does not own physical infrastructure, but must select between two competing IPs to fulfil the resource and connectivity needs required for its service portfolio. The NPP offers three service categories, belonging in different slice types:

1. *eMBB (enhanced Mobile Broadband) 5G Services*. The NPP delivers high-speed, high-capacity broadband connectivity to users within a targeted geographic area. eMBB slices are designed to support data-intensive applications such as seamless HD video streaming, mobile cloud computing, and connected smart offices, meeting the high throughput and reliability expectations of both consumers and enterprises.
2. *uRLLC (Ultra-Reliable Low Latency Communications)* for corporate clients in the manufacturing sector. Tailored to support factories with robotised production lines and automated warehouse logistics, where real-time control, ultra-low latency, and high reliability are essential for continuous yet moderate data throughput, uRLLC slices enable efficient and safe operation of industrial robots and logistics systems, minimising downtime and operational risks.

3. *MTC (Massive Machine-Type Communications)* to real estate companies that manage highly automated buildings. These clients require reliable connectivity for a large number of sensors and actuators, enabling advanced domotics and IoT-driven services for both business tenants and residential users. The MTC slice is optimised for massive device connectivity with low individual throughput requirements, supporting the digital transformation of smart buildings.

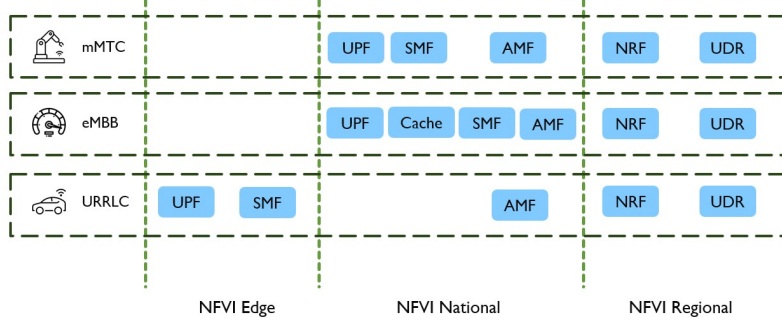


Fig. 4 Slice templates and virtual resources by network level

Figure 4 depicts virtual resources required by the slice templates of each service category. 6G slicing enables the NPP to dynamically adapt to varying user and enterprise requirements, efficiently allocate resources, and maintain differentiated service levels. Moreover, DLAs allow the NPP to consider sustainability issues when selecting a suitable provider to meet the requirements of network slices. Bottom-up awareness of operational and sustainability KPIs allows the NPP and end customers to monitor SLAs and DLAs, and enables guaranteed green services and applications.

5.1 Baseline Hypotheses

To systematically assess the interplay between sustainability incentives, economic levers, and regulatory constraints, all scenarios are defined based on a common experimental baseline. This approach ensures comparability and isolates the effects of each variable under study. This section summarises key hypotheses used in all scenarios, and Table 1 summarises the inputs of the model and the references used to feed them.

Network topology. Without loss of generality, we can assume a hierarchical 5/6G network where nodes are arranged in three levels:

1. Level 1 refers to nodes at the *regional* level, points of presence (PoPs) shared by many operators and over-the-top (OTT) players from different jurisdictions.
2. Level 2 refers to *national* service centres of telcos in their national core networks.
3. Level 3 (local) refers to the edge of the network, and includes nodes next to centralised units (CUs) of the RAN that can run processing tasks close to end users.

In a certain time frame, a network node n provides service to u end users in the vicinity of that node, an input that reflects the geography and the expected demand.

Each node in a level connected to at least one node in the upper level, and nodes in the upper layer fully meshed. Therefore, the number of users that rely on the upper network nodes can be calculated bottom-up as the sum of the users of the adjacent nodes in the lower level. The number of users depending on a link will be the number of users depending on the lowest level node it connects.

Table 1 Summary of Model Inputs

Input	Current Data / Assumption	Reference
Server Typology and Computation		
Core VNFI Basic Physical Server	HPE DL380 Gen11, 2x Xeon 6760P, 512GB DDR5, 2x NVMe 3.84TB, 2x Nvidia ConnectX-6	[49]
vCPUs per Physical Server	128 physical cores → 256 vCPUs	[49]
vCPUs Allocated for Virtualisation	10% reserved for HA cluster	[49]
CAPEX VNFI Basic Physical Server	27,600€/per server, ~230 vCPUs allocatable	Vendor/Market, [49]
VNFI Lifecycle	7 years	Bottom-up models
WACC	11%	[50]
OPEX Mark-up	10% of CAPEX	Bottom-up models
Energy and Environmental		
Carbon Emissions per kWh	30 (NO), 174 (ES), 662 (PL) gCO ₂ e/kWh	[52]
Energy OPEX	0.29€/kWh avg. (EU), 0.11–0.37€/kWh range	[53]
Power Consumption vs Utilisation	Non-linear, abrupt growth >70%	[49]
GHG emission profiles	Typical theoretical curves	Assumption
Network Topology and Traffic		
Network Topology	8 hierarchical nodes (synthetic)	–
Users per EDGE node	100,000–400,000	Assumption
Users per Slice	800,000–1,000,000	Assumption
Unit Throughput for Slices	URLLC: 0.022, mMTC: 0.007, eMBB: 7.78 Mbps/user	[54]
Resource units and drivers for link type	Mbps, based on slice traffic and users	[49]
5G Slicing and Templates		
5G Network Slice VNF replica capacity	Per VNF: users/traffic/replicas	[49], [3]
5G Network Slice VNF resource consumption	Estimated vCPU usage per VNF	[49], [3]
SLA requirements per slice	GSMA definitions (throughput, latency)	[3]
GSMA NESTs	uRLLC, eMBB, mMTC templates	[3]
Temporal Granularity	1 hour	[49]
Slice order unit revenue	Cost + 30% margin	Assumption
Slice requests (DLA, SLA)	May include max. energy/carbon	Assumption
Max VNFI capacity per level	Edge < National < Regional	[55]

IP Competition. Each scenario features two IPs with identical technical portfolios (e.g., vCPUs, bandwidth, coverage), establishing a neutral baseline for competition. Any differentiation between IPs arises solely from their cost structures, energy sourcing, or sustainability-related constraints as defined in each specific case.

Demand Scaling. The model explores a wide range of operating conditions by scaling the demand for each slice type from 10% to 300% of the baseline in Table 1. This allows analysis of behaviour under typical and stress test conditions, revealing how allocation strategies and provider selection may change as demand intensifies.

Resource Capacity Adjustment. Resource capacities for each IP are initially dimensioned so that either provider, operating alone, can satisfy the entire baseline demand at the most constrained node. To further minimise the influence of capacity bottlenecks and focus the analysis on economic and sustainability-driven decisions, this baseline is then doubled in the model. However, it is important to note that at the highest demand scaling (e.g., 300%), even this augmented capacity may not suffice for a single IP to serve all demand alone, thus realistically reflecting the need for cooperation or load balancing at extreme loads.

KPI Monitoring: Key performance indicators—including total cost, energy consumption, carbon emissions, and resource allocation per IP—are systematically measured for each scenario and presented as results. This comprehensive monitoring supports a robust evaluation of the efficiency, sustainability, and economic trade-offs in different experimental cases.

5.2 Policy Options Description

In this section, we apply the proposed techno-economic framework to evaluate how several policy interventions affect the allocation of vertical service demand between two competing Infrastructure Providers (IP1 and IP2). Based on the common inputs and hypotheses defined above, we have set a **baseline scenario** where the two IPs are equivalent and operate with similar cost, energy efficiency and carbon intensity. This resembles a common situation in mature competitive telecom markets, where concurrent IPs are unaware or unable to exploit sustainability as a competitive advantage. Then, we run the model with varying situations to test the policies. In all of them:

- IP1 will represent in all cases a conventional “grey” provider with baseline costs and higher carbon emissions.
- IP2 will become “green” by investing in sustainable telecom infrastructure at a 20% higher cost relative to IP1 in exchange for operating at zero emissions.

We estimate the resources allocated, costs, energy consumption and carbon emissions of IP1 and IP2 in four additional scenarios that reflect different policy options to incentivise greener networks, inspired by our preliminary policy review in Sections 2.3 and 2.4, and compare to the baseline. The policy options analysed are as follows.

Policy Option 1: *Laissez-faire*. Policy makers do not apply any incentive policy. IP2 cost increases 20%, which translates into 20% higher infrastructure wholesale prices. This scenario reflects a plausible situation where IPs test green investment seeking to differentiate or to meet their ESG objectives.

Policy Option 2: Subsidisation of Green Infrastructure. Investment in net-zero-emitting telecom infrastructures is actively subsidised through direct subsidies or tax exemptions. As a result, subsidies compensate for the cost increase of IP2 due to the investment in greener energy sources, and the wholesale charges of both IPs are balanced. Direct subsidisation of green investment projects has been actively used in other industries and hence could be a policy option in the telecommunications market.

Policy Option 3: Introduction of uniform DLAs. Policy makers impose a *glide path* on maximum carbon emissions through the use of DLAs applied to network slices, requiring NPPs to reduce emissions associated with their network services by 25%, primarily by contracting green infrastructure for slice deployment. Progressive tightening of environmental and energy consumption limits has long been a feature of greening policies, and glide paths have been effectively used by telecommunication NRAs in various countries to steadily advance policy objectives, such as reducing interconnection charges, while avoiding abrupt industry disruptions and providing stakeholders with time to adapt to regulatory changes.

Policy Option 4: Tiered DLAs for premium services. Consumers demonstrate willingness to pay a price premium for greener services, which incentivises VAPs to offer sustainable services with stricter carbon requirements enforced through DLAs. In particular, green VAP slice requests that include net-zero emission DLAs are treated as premium services and receive a 30% revenue uplift, reflecting the higher value placed on sustainability by end users.

Table 2 Summary of scenarios

Scenario	Green slice premium?	IP1 vs. IP2 costs	IP1 vs IP2 GHG Emis-sions	DLA limits
Baseline	No	Equal	Equal	No
PO1: <i>Laissez-faire</i>	No	IP2 + 20%	IP2 = 0	No
PO2: Subsidisation	No	Equal(subsid.)	IP2 = 0	No
PO3: Introducing DLAs	No	IP2 + 20%	IP2 = 0	Yes
PO4: DLA + Green Prem.	Yes	IP2 + 20%	IP2 = 0	Yes

Table 2 summarises the definitions and parameters of the different scenarios. To evaluate policy options, we assess the behaviour of stakeholders and the outcomes of the resource allocation process, illustrating the dynamics and trade-offs that emerge in a multi-actor 6G ecosystem. For each scenario, we test different levels of demand, ranging from 10 % to 300 % of the baseline demand. For each demand level, we plot and compare to the baseline the following KPIs: the vCPUs scheduled by each IP, the cost incurred by the NPP (in €), the energy consumption (in kWh) and the resulting carbon emissions (in kg CO_2).

5.3 Policy Option 1: Laissez-faire

In this setting, no policy instruments are in place, such as sustainability constraints or financial incentives. In this purely cost-driven context, NPPs prioritise minimising operational expenditure when orchestrating network slices. As a result, demand is overwhelmingly allocated to IP1 due to its lower cost, and despite its higher carbon emissions, as shown in Figure 5.

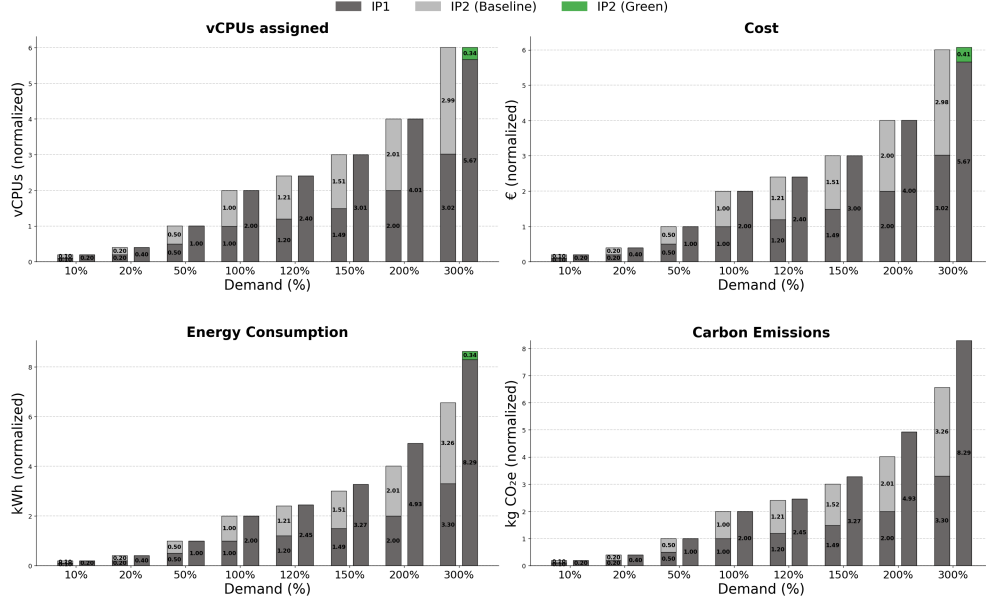


Fig. 5 PO1. *Laissez-faire* vs baseline

Despite offering a greener infrastructure, IP2 is 20% more expensive and therefore NPP prioritises IP1 until it reaches its capacity limit. Only when demand exceeds IP1’s capacity is the excess allocated to IP2. This allocation pattern reflects a clear market failure: environmental performance is not factored into service provisioning decisions unless cost or capacity constraints force a deviation from the baseline.

We show the resulting KPIs for different demand levels in Figure 5. At low demand levels, energy consumption remains close to the baseline, despite all demand is served by IP1. However, as demand increases and IP1 approaches saturation, energy consumption rises sharply due to the shape of the consumption curves, which raises steeply for utilizations above 60%. Energy use reaches approximately 127% of the baseline at 200% demand and up to 140% at 300% demand. At peak demand, IP1 becomes fully saturated, and a portion of the demand is subsequently redirected to IP2.

This pronounced increase in energy use also leads to a significant rise in carbon emissions. Since IP1—the highest-emitting provider—operates at full capacity and becomes less energy efficient at high utilisation, total emissions increase by up to 130%

compared to baseline at peak demand. However, this increase in emissions is slightly lower than the corresponding rise in energy consumption, as a portion of the demand is reallocated to IP2, which does not contribute to carbon emissions.

In summary, the *laissez-faire* scenario results in minimal use of green infrastructure and maximum reliance on high-emission providers. Green providers are only used when high-emission providers, such as IP1, can no longer meet demand due to capacity limitations. The system naturally converges towards configurations that are economically efficient but environmentally suboptimal, highlighting the need for policy interventions to internalise sustainability considerations within the 6G value chain.

5.4 Policy Option 2: Subsidisation of Green Infrastructure

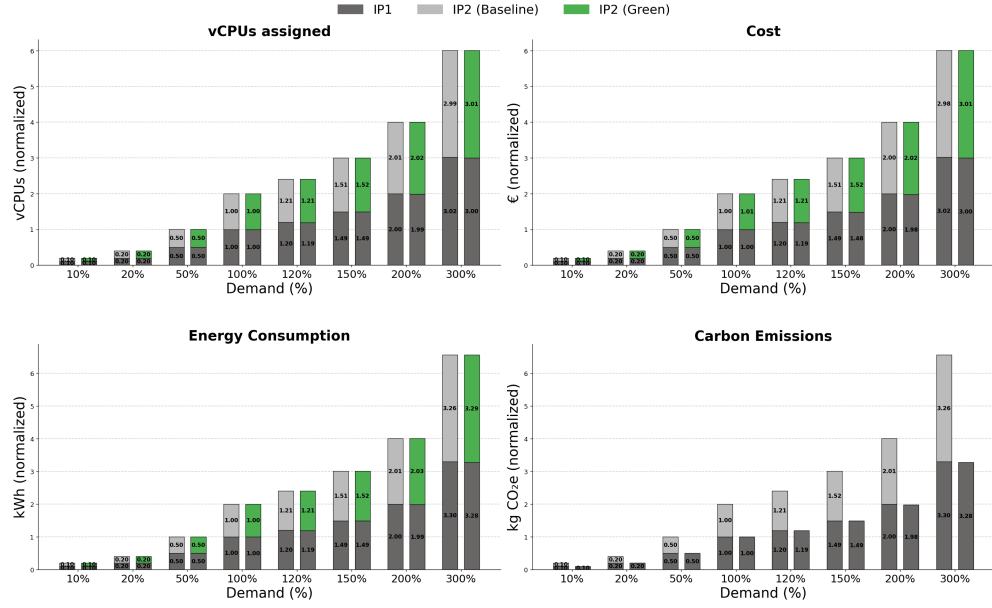


Fig. 6 Subsidisation of Green Infrastructure vs. Baseline

In this policy option, we examine the impact of financial support mechanisms designed to correct the cost disadvantage of greener infrastructure. Specifically, we introduce a subsidy that fully offsets the 20% cost premium associated with IP2, the low-emission provider. The goal is to evaluate whether equalising the cost of green and grey infrastructure—without imposing direct regulatory constraints—can lead to more sustainable allocation outcomes driven by market forces.

By neutralising the price difference between IP1 and IP2, this setting allows NPPs to make allocation decisions without being biased towards the cheaper, higher-emission

provider. Since both IPs now appear economically equivalent, the NPP faces no economic disincentive to select IP2, leading to an even distribution of demand between both infrastructure providers.

The results in Figure 6 show a clear increase in the share of demand assigned to IP2 compared to the *laissez-faire* policy option. Although no explicit emissions cap is enforced, the availability of a greener alternative at no additional cost encourages the system to select the environmentally preferable option more frequently. Consequently, overall carbon emissions are halved, as IP2 operates at zero carbon emissions, while total operational costs remain stable, as the additional expenditure is absorbed by the subsidy rather than passed along the value chain.

Importantly, this policy option provides targeted financial compensation, with the subsidy acting as a market-aligned mechanism. However, the effectiveness of this approach depends critically on how the subsidy is designed and delivered. If subsidies are too broad or poorly targeted, they risk being economically inefficient or failing to promote genuinely greener technologies. In addition, this approach relies on the availability of public funding or incentive schemes, which may not always be feasible or politically viable.

5.5 Policy Option 3: Decarbonisation Level Agreements

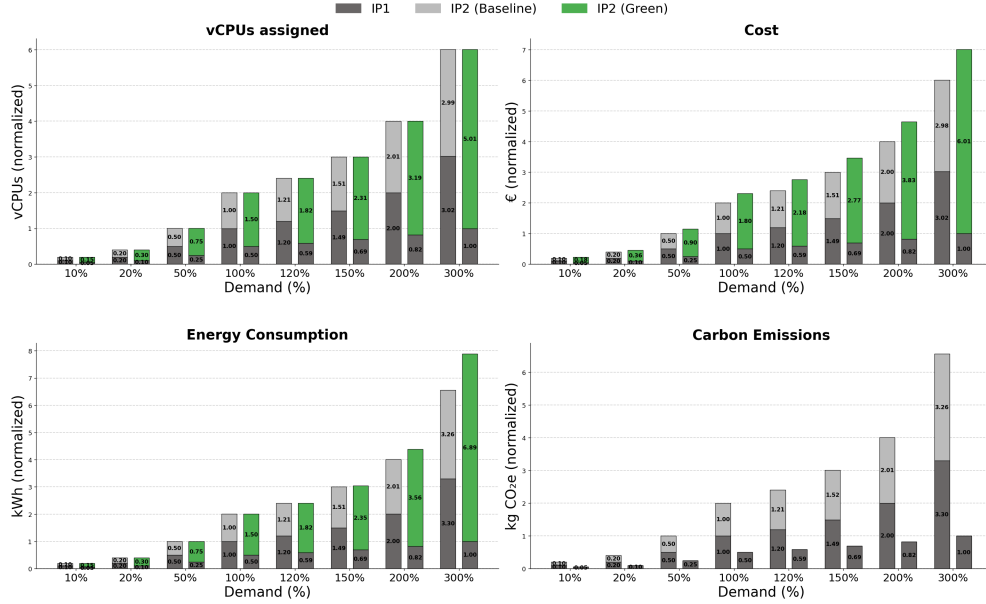


Fig. 7 Introduction of DLAs vs. Baseline

In this policy option, we introduce regulatory constraints in the form of Decarbonisation Level Agreements (DLAs), which impose upper bounds on the allowable carbon

emissions per allocated resource. These constraints aim to ensure a minimum level of sustainability in the orchestration of network slices, nudging the system away from purely cost-driven behaviour. In this scenario, all service slices are treated equally with respect to carbon emissions, and a single regulatory constraint is applied: the maximum allowable carbon emissions are capped at 25% of the baseline reference value for the given demand. IP2, the greener infrastructure provider, continues to incur a 20% higher cost relative to IP1.

The results are shown in Figure 7. The proportion of resources assigned to IP2 rises significantly at all demand levels. This shift is a direct consequence of the DLA constraint. This reallocation is reflected in higher system energy consumption, as the DLA becomes binding at higher loads, total system energy consumption rises due to the shape of the power consumption profile, and reaches around 10% above the baseline at 300% demand. This increase is explained by the fact that IP2 operates at a very high utilisation, above 60% and there the power consumption increases dramatically and NFVIs become less efficient from the perspective of energy consumption [51][Figure 4].

The cost structure also changes accordingly. As more demand is allocated to the higher-cost IP2, total system costs increase compared to baseline, especially at high demand levels. The economic impact of the DLA is, therefore, most pronounced when the system is operating at nearly full capacity and must rely heavily on the greener, but more expensive, infrastructure.

Most notably, the DLA constraint achieves a substantial reduction in carbon emissions. Across all demand levels, total emissions are capped at 25% of the baseline, as intended by the regulatory target. For moderate demand, emissions closely follow this 25% threshold. However, at very high demand levels, where the system would otherwise incur excess emissions due to saturation, the actual reduction is even greater, with emissions falling below 25% of the baseline. This is because the DLA, being set as a fixed proportion of the baseline, does not account for the steep increase in emissions that occurs at high utilisation, making the constraint effectively stricter as the system approaches full capacity.

In summary, the introduction of uniform DLAs is effective in achieving a significant reduction in carbon emissions, primarily by shifting demand towards greener infrastructure. However, this comes at the cost of higher system energy consumption and increased operational expenditure, particularly at high demand levels. These findings highlight that while regulatory constraints can successfully internalise sustainability objectives, they can also create economic distortions if not complemented by financial mechanisms to support stakeholders and maintain market efficiency.

5.6 Policy Option 4: Tiered DLAs for premium services

Finally, in this policy option, two types of network slices are offered: standard and green premium. Green premium slices are subject to zero carbon emissions DLAs and pay 30% price premium. Standard slices remain under the general emissions cap used in the previous case. IP2 continues to incur a 20% higher cost for the greener infrastructure.

This configuration reflects a scenario in which certain vertical applications-such as those addressing environmentally conscious end users or operating in tightly regulated

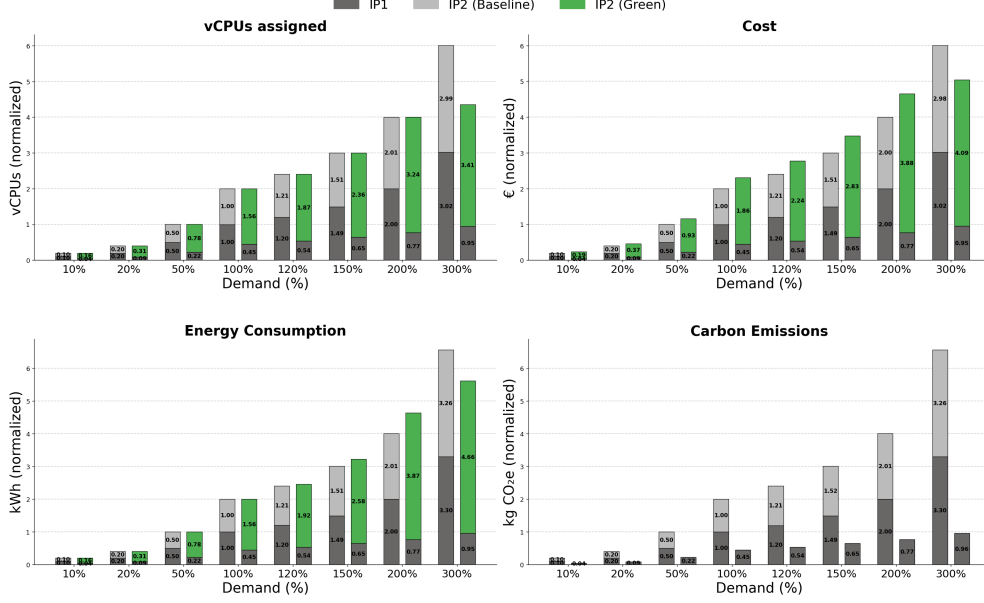


Fig. 8 Tiered DLAs vs. Baseline

domains are willing to pay a premium for guaranteed green performance. The results reveal a dual allocation strategy: premium slices are fully assigned to IP2 to comply with the zero-emission requirement, while standard slices continue to favour IP1 where cost considerations prevail.

Importantly, this policy option enables the introduction of differentiated pricing schemes, allowing the market to adjust to the varying emission requirements across service classes. By assigning higher revenue to premium slices, the system compensates for the increased cost of greener infrastructure, facilitating a more balanced trade-off between sustainability and profitability. Moreover, the imposition of DLAs on these slices significantly alters the allocation strategy compared to previous scenarios. The NPP is now incentivised to allocate premium slices to the green provider (IP2), increasing its profit despite the extra cost.

The results are shown in Figure 8. IP2, being the only provider capable of consistently meeting the emission requirement, takes on the majority of the workload across all demand levels. IP1 is relegated to a minimal supporting role, used only to satisfy residual demand not constrained by the emissions cap.

At very low demand levels, the system exhibits selective slice activation. For instance, at 10% demand, only the most cost- and emissions-efficient slices (eMBB) are instantiated. Slices with high fixed overheads and low efficiency (URLLC and MTC) are not activated since they cannot be justified under the emissions cap. This behaviour underscores how even a moderate regulatory constraint can drive fine-grained optimisation of both provider and slice-level decisions.

As demand grows, the emission cap becomes the dominant constraint, compelling the NPP to assign a substantial portion of resources to IP2 in order to remain compliant, particularly at medium and high demand levels. Notably, at the highest demand level, the demand for green infrastructure and services grows beyond the capacity of IP2. Unable to comply with such strict DLAs, the NPP rejects a slice request and the number of vCPUs drops compared to the baseline. However, this hypothetical situation is unlikely to happen in a real scenario, where NPPs would likely schedule a standard slice instead and renounce the price premium (or provide compensation for non-compliance with DLAs). Furthermore, sustained demand beyond green capacity would incentivise investment in green infrastructure by IPs to revert this shortage.

The energy consumption profile in this policy option closely follows the increase observed in Policy Option 3, except at the highest demand level (300%), where total energy consumption drops by approximately 15% due to the non-assignment of a resource-intensive eMBB slice, a direct result of insufficient capacity at IP2.

Most notably, the carbon emissions profile under this combined policy option shows a substantial improvement over all previous cases: all green premium slices and a significant share of standard slices are assigned to IP2. As a result, total emissions are dramatically reduced to below 25% of the baseline at medium demand levels (down to approximately 22.5%), and to nearly 15% at the maximum demand level of 300%.

This policy option demonstrates that combining targeted regulatory constraints with market-based incentives for premium green services can yield substantial environmental benefits while maintaining economic viability. The differentiated approach aligns sustainability objectives with market realities and highlights the importance of capacity planning and investment to fully realise the potential of green infrastructure.

6 Conclusion and Future Works

In this paper, we have presented a techno-economic framework to incentivise more sustainable 6G networks and services, aligning with the overarching objective of the 6Green project, which seeks to develop mechanisms to make mobile networks more environmentally sustainable. Although technological capabilities to monitor and reduce emissions are evolving, market dynamics often hinder investment in greener infrastructure, particularly when the return on investment remains unclear or when green energy solutions are more expensive than conventional ones. In such cases, policy interventions become essential to realign incentives throughout the value chain.

To explore this challenge, we evaluated four policy options within our framework: (i) a *laissez-faire* scenario, (ii) subsidisation of green investment, (iii) a uniform Decarbonisation Level Agreement (DLA) applicable to all services, and (iv) tiered DLAs to differentiate green services and allow consumers to pay a premium. These represent a spectrum of regulatory and market-based tools to internalise the sustainability cost in mobile network operations.

Subsidies, while effective in promoting greener outcomes, are uncommon in the telecommunications sector. In contrast, DLAs offer a more sector-aligned instrument. Combined with sustainability KPI monitoring, DLAs enable stakeholders in the

ecosystem and regulators to consider sustainability in network operation in exchange of higher costs that need to somehow be internalised by the value chain.

The tiered DLA scenario, which distinguishes between standard and green premium services, offers a particularly promising compromise. It enables market mechanisms to function, letting environmentally aware users opt for more sustainable services—particularly in verticals where service quality or environmental impact are strategic differentiators. Even if this approach does not scale universally, it opens the door to more sophisticated market-based sustainability mechanisms.

However, our results show that if DLA constraints are too aggressive, the system may not be able to service all demand due to the limited capacity of low-emission infrastructure. A well-anticipated and progressive decarbonization glide path could be a way to mitigate this risk, giving stakeholders time to adapt to increasingly restrictive NRA-driven DLAs and invest in new, more efficient, or net-zero technologies.

This model represents a first step towards a more integrated sustainability framework. Future work will extend it to accommodate dynamic operation, non-compliance penalties, and partial slice fulfilment, enabling more realistic orchestration and business logic. We also plan to evaluate scenarios for integrated operators, and other policy incentives for investment in green infrastructure. Furthermore, a dynamic model would support the analysis of more complex pricing schemes that directly internalise the cost of greenhouse gas (GHG) emissions, for example, by charging high-emission services proportionally based on available energy sources and infrastructure.

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