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Toward an integrated framework for developing European 6G innovation

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ABSTRACT

This article contributes to the discussion on 6G and European policy development, outlining an integrated framework for Europe to benefit from 6G innovation in the future, both as a developer and user of 6G technologies. As 6G is envisioned as a general-purpose technology that can transform the whole of society, there is a need to adopt a broader perspective to innovation compared to earlier technology generations. This proposed framework comprises five elements: national and European sovereignty, triple bottom line sustainability, a competitive transformational innovation policy, European values-based anticipatory regulation, and trustworthy networks that addresses the privacy, security, and safety of users and resilience of 6G at the systems level. It is argued that Europe needs both *ex ante* and *ex post* actions to competitively develop and deploy future 6G technologies.

1. Introduction

As an enabling technology (Kapoor & Teece, 2021; Teece, 2018), the currently implemented fifth-generation mobile communication (5G) networks are quickly making mobile connectivity the backbone of digitalization in Europe. With the three envisioned and standardized usage scenarios, enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC), the 5G rollouts in Europe have been considered a strategic rather than a technological choice (Kaska et al., 2019). This approach is reflected in 5G-related innovation policies and especially in the European 5G action plan (EC, 2016) that has set an agenda for aligned roadmaps and priorities for the coordinated *deployment* of 5G. The action plan stresses the importance of removing spectrum-related bottlenecks, promoting early deployment and multi-stakeholder trials with 5G, facilitated venture funds, and calls for leading actors to be united to promote global standards. In addition to the 5G action plan, the EU has funded a substantial number of research projects around the *development* of 5G, but to date, the development and deployment related policies and actions have lacked a common vision.

As a continuum from 5G to 6G, the Smart Networks and Services Joint Undertaking (SNS JU) (EC, 2021a, 2021b) of the European Union (EU) has the mission to foster Europe's technology sovereignty in 6G and boost 5G deployment in Europe in three partly

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overlapping phases: evolutionary 5G 6G exploration of concepts and definitions (2022–2024); 6G detailed design and optimization (2024–2027); and pre-commercial 6G systems (2027–). Within this undertaking, the EU has currently introduced a 6G innovation program (EC, 2021a, 2021b, 2021c, 2021d) with three streams. The first stream focuses on research for revolutionary technology advancements toward 6G, with the objective of delivering innovative solutions toward real-life networks over a long-term period and in collaboration with the USA. The second stream focuses on enablers of Smart Networks and Systems and proofs of concept, aiming to further develop, federate and consolidate Europe-wide experimental infrastructure(s), supporting the various phases of the future networks. The third stream emphasizes large-scale trials and pilots with verticals—including the required infrastructure—to explore and demonstrate technologies and advanced applications and services for vertical domains focusing on automotive, health, smart cities, farming, or education needs.

The recent collaboration between the EU SNS JU and the US (ATIS-Next G Alliance, NSF RINGS) extends the European efforts for a common vision with guiding principles and values of sustainability, privacy, accessibility, openness, and inclusiveness. According to the collaboration aims, 6G should be trustworthy, resilient, and affordable and contribute to closing digital divides in both developed and developing nations. 6G standards should enable enhanced connectivity, be an enabler for sustainability considering environmental, social, and economic perspectives, and be developed with security-by-design, be private-sector led, and built on consensus-based principles to enable an ecosystem of resilient, open, interoperable, and software-based 6G solutions. The collaboration aims at a joint vision on the following key themes: technology challenges and research collaboration; security and resilience; sustainability and energy efficiency; openness and interoperability; efficient radio spectrum usage; and the standardization process (EC, 2023).

Today, single-company innovation efforts still characterize the development of 5G with coordinated industry-level standardization and the cross-licensing of key technologies ensuring interoperability across vendor solutions and extendibility across the developed technology generations. However, the domination of single-company innovation is changing toward ecosystem innovation for future sixth-generation mobile communications (6G). This is due to a variety of reasons related to the nature of 6G (Snihur & Bocken, 2022; Yrjölä et al., 2022a). The *development and planned deployment* of 6G will take place in a different situation compared with that of the earlier generations of mobile connectivity. The emergence of 6G as a new kind *of general-purpose technology* (GPT) platform (Bauer, 2022; Yrjölä et al., 2021)—with business ecosystem-wide innovation efforts (Yrjölä et al., 2022a)—will increasingly be framed by new and heightening tensions concerning innovation. As GPTs have the potential to affect the global economy and alter societies (Bresnahan & Trajtenberg, 1995; Bekar et al., 2018; Hogendorn & Frischmann, 2020), these tensions have implications for the creation and execution of innovation and industrial policies for future 6G.

This paper aims to contribute to the discussion on 6G innovation and broader European 6G innovation and industrial policy development. In the European (EU) context, innovation policy can be seen as the interface between research and technological development policy and industrial policy (EP, 2023), whereas the EU's industrial policy aims to make European industry more competitive so that it can maintain its role as a driver of sustainable growth and employment in Europe (EP, 2023a). Since 6G has been envisioned as a GPT with the potential to affect the global economy and transform societies, there is a need to adopt a broader perspective and to create better integrated, goal-oriented policies and action plans to benefit from 6G innovation. Therefore, this paper grounds and proposes an *integrated framework for developing European 6G innovation efforts* and discusses the interdependencies within the proposed framework. The presented discussion builds on the existing EU strategies, policies, and action plans related to 5G and 6G, extending the discussion into integrated policies related to the development and deployment of future 6G. Specifically, we examine five relevant priority themes related to European 6G innovation: sovereignty, sustainability, innovation policy, regulation, and trustworthy networks. To achieve the aims of the paper, chapter two proceeds with a discussion on the 6G innovation landscape, chapter three discusses recognized themes relevant for European 6G innovation, and chapter 4 concludes the paper by integrating the priority themes.

2. The 6G innovation landscape

Currently, the Smart Networks and Services Joint Undertaking coordinates the European 6G research phase. Several Flagship programs have followed the Finnish 6G Flagship started in 2018 (https://www.6gflagship.com/) and at the European level the Hexa-X project (https://hexa-x.eu/) attempts to unite European stakeholders in the mobile communications ecosystem on the technology front. In parallel, ITU-R has published the technology trends for IMT toward 2030 and beyond (6G) (ITU-R, 2022) and is working on a vision recommendation, that is expected to be published toward the end of 2023. This recommendation will serve as a basis for the subsequent standardization and commercialization activities of 6G technologies.

On the research end, the future 6G in 2030 has been envisioned as ubiquitous wireless intelligence converging human, physical and digital worlds (Latva-Aho & Leppänen, 2019; Hexa-X, 2021). At the technical level, 6G is expected to merge connectivity with sensing, imaging, and increasingly more accurate positioning and locationing to enable a myriad of new services and use cases with the aid of artificial intelligence (AI) (Latva-Aho & Leppänen, 2019). Thus, 6G will converge connectivity platforms with other digital platforms, giving rise to the emergence of a platform economy with respective ecosystems (Ahokangas et al., 2021; Uusitalo et al., 2021). Several ground-breaking capabilities of 6G will render it essential for modern society: it will be the platform for providing ubiquitous near-instant and unlimited mobile connectivity, in addition to humans, serving not only increasingly autonomous things and robots but also organizations and communities and supporting multisensory applications and services such as virtual reality, and ultimately, the metaverse(s). 6G will ensure the privacy, security, and safety of its users and enable massive dynamic twinning, while emphasizing sustainability from integrated economic, societal, and environmental perspectives. It is also expected to lead to transhumanism with new human–machine interfaces (Yrjölä et al., 2021).

6G is expected to emerge through a trajectory of breakthrough inventions introduced by an ecosystem of heterogenous stakeholders

(Yrjölä et al., 2023), resulting in technology variations for the envisioned use cases (Kapoor & Teece, 2021). 6G will also become commercialized in multiple application domains and ecosystems that require the development of complementary assets, potentially slowing down its growth and speed of adoption. 6G may also raise fundamental policy and regulation-related questions when governments seek growth and spillover effects or advance technological progress with public policies and subsidies. From the market and demand perspective, local and private networks have already been introduced to complement the existing public MNO (mobile network operator) networks, especially for industrial customers whose network requirements and service models may significantly differ from those enabled by public networks (Aagaard et al., 2023; Ahokangas, Aagaard, et al., 2023). This trend is expected to continue for 6G. For future 6G, novel use cases like immersive communications or connecting the unconnected, have raised research interest (Ahokangas, Aagaard, Atkova, Yrjölä, & Matinmikko-Blue, 2023a; Ahokangas, Matinmikko-Blue, & Yrjölä, 2023c), but their commercial potential or expected time of availability remains unspecified. It has also been expected, that for 6G the whole business ecosystem will transform as new stakeholders such as over-the-top internet giants, edge cloud companies, and various telecommunications connectivity and service brokers enter the field of mobile connectivity. Similarly, new services such as the metaverse require a combination of capabilities which are planned to be introduced in 6G (Yrjölä et al., 2022a).

3. Priority themes for 6G innovation

The European 5G action plan followed the principles of Teece's (1986, 2018) profiting from innovation (PFI) framework with "*the strength of the appropriability regime, complementary assets, complementary technologies, standards (and associated installed base effects), and timing*" as the central elements behind the plan (Teece, 2018, p. 1369), which leaned on a tradition stemming from the previous mobile communications technology generations. Traditionally, at the regional level, European governments and national regulatory agencies have collaborated extensively. However, at the national level countries have the power to decide who can deploy 5G networks even though the spectrum bands are harmonized. Regarding 5G spectrum awards and the treatment of especially non-MNO (mobile network operator) operated local networks, various countries have run quite diverse strategies, reflecting the lack of a common vision and leading to fragmentation in the development and deployment of 5G (Cave et al., 2019; Matinmikko et al., 2018).

The conducted vision work of several research organizations, industry, and ITU-R has provided direction for 6G development and future deployment. Overall, any 6G vision should be comprised of technology, business, and regulation perspectives and it should identify and utilize fundamental principles such as human centricity and inclusivity in visioning it (Ahokangas, Aagaard, et al., 2023). Similarly, the sustainability-perspective represented, e.g., by the commitment of the EU to United Nation's sustainable development goals or the EU's Green Deal (EC, 2019) also provide direction for 6G development.

New technologies and transformative/mission-oriented innovation policies go hand in hand (Bailey et al., 2019). As transformative innovation policies should consider the innovation process and the innovation agenda (Diercks et al., 2019), the former should take a stance on economic or societal agendas and the breadth of the innovation process to tackle both ecosystem development and open-ended technological challenges with a variety of innovation modes. To achieve a legitimate (commonly accepted) 6G, the legitimation processes of future 6G as a new GPT under development, future innovation work needs to follow the forward-looking logic of transformative innovation policy with purposeful and directional innovation portfolios, concern for system and market failures, as well as developing and expanding new markets while understanding the ongoing change and its impacts (Casula, 2022; Palavicino et al., 2023). Building on this, to advance European 6G innovation, five innovation priority themes can be recognized: national and European sovereignty, triple bottom line sustainability, competitive and transformational innovation policy, European values-based anticipatory regulation, and trustworthy networks in terms of privacy, security, and resilience.

3.1. National and European sovereignty

The EU's Smart Networks and Services Joint Undertaking starts with sovereignty. Sovereignty can be understood as the ability to provide the technologies that a nation or a set of them deem critical for welfare, competitiveness, and the ability to act, develop, or source them without structural dependencies (Edler et al., 2020) and it is directly related to innovation policy, also in mobile communications context (Edler et al., 2023; da Ponte et al., 2023). Timmers (2020) argued that without solving the sovereignty issues of 5G, no global 6G will emerge amidst today's compartmented innovation ecosystems, techno-nationalism, and market protection. Sovereignty is often seen to be enabled by strategic autonomy in terms of capabilities, capacities and control over a territory covering autonomy in economy, society, and democracy (European Commission & European External Action Service, 2017). Moerel and Timmers (2021: 5) posit that "*digital technologies have become the battleground for the competition for global leadership and are leading to ever-increasing geopolitical tensions*". In recent years, phenomena such as trade wars, cyber espionage, disinformation, threats, and sanctions (Robles-Carrillo, 2021), dependence on foreign suppliers, data colonialism via platforms, technological vulnerabilities (also related to foreign suppliers), and risks to the economy, society, and democracy (Timmers, 2020) have started to appear in public discussion.

In the mobile communications context, the EU has traditionally subscribed to open liberal market economy thinking (Timmers & Serentschy, 2023), surpassing strategic autonomy and sovereignty via an internal market consumer benefit approach. The telecommunications policies have remained autonomy-agnostic, with the exception of security concerns, and even research and development programs were for long open to, e.g., Chinese companies. However, the Chinese 5G and 6G programs have not been opened to foreign companies. Only recently has the EU started to recognize the connections between strategic autonomy, sovereignty, and the connectedness of research and development programs, standardization, and the competitiveness of European companies. Indeed, national security and strategic autonomy is central to achieving sovereignty. Timmers and Serentschy (2023) argue for three pathways

that will support European countries toward strategic autonomy: *strategic partnerships* with likeminded actors, promotion of *global commons* which means taking the question of capabilities, capacities, and control to a global level, e.g. in the form of standards like SWIFT (Society for Worldwide Interbank Financial Telecommunications in the banking field), and adopting enhanced *risk management* practices based also on regulation as discussed in the preceding section.

Many EU Member States recognize the need for sovereignty and strategic autonomy, but national action requires EU-level coordination in many fields of society, which is not only a practical but also a legal-political challenge (Moerel & Timmers, 2021). The EU has identified that the main threats to 5G are those related to confidentiality, availability, and integrity (Robles-Carrillo, 2021). It is easy to believe that the same threats will also be faced in the future next-generation networks. Fundamentally, digital sovereignty relates to the control of data, software and algorithms, standards, and protocols, (computing) processes, hardware and equipment, services, and infrastructures (Floridi, 2020). Sovereignty thus embeds the concept of ownership regarding strategic assets such as data, algorithms, and critical infrastructure. Consequently, digital sovereignty concerns governments, firms, and research institutions active in the digital field.

3.2. Triple bottom line of sustainability

Sustainability sets new requirements and design criteria for 6G visioning (Ahokangas, Matinmikko-Blue, & Yrjölä, 2023). The development of prior generations of mobile communication systems has included improving energy efficiency as a design criterion, which has led to "green radios" to improve the resource efficiency of wireless networks (Zhang et al., 2019). This environmental efficiency perspective has existed in the development of mobile communications, and its role is increasingly important in 5G, where the energy consumption of the networks has become a major arena for the MNOs to introduce cost-savings in network operations.

For 6G, the integrated triple bottom line of sustainability, including social, economic, and environmental perspectives, has been introduced as a new holistic design criterion that goes beyond traditional energy efficiency considerations (Matinmikko-Blue et al., 2021; Uusitalo et al., 2021; Hexa, 2023). These three sustainability perspectives should be considered in parallel and as balanced and uncompromised in 6G research and development. Environmental sustainability including minimizing the environmental footprint of 6G networks, devices and services throughout their entire lifecycle should be pursued without sacrificing economic and societal progress. At the same time, societal sustainability targets should be sought without compromising economic and environmental sustainability. Finally, economic sustainability ensuring the profitability of operations and windows for new business opportunity should be sought without causing negative societal or environmental consequences.

Research on 6G has adopted the UN SDGs as the holistic guideline for developing future wireless systems that aim at solving major sustainability challenges while they are developed in line with sustainability principles (Matinmikko-Blue et al., 2020), which are reflected across the three perspectives of integrated sustainability. From the economic sustainability perspective, 6G development should focus on the business opportunities, value creation potential, and advantages of the developed general-purpose technology that contribute to its scalability and replicability. In turn, economic resilience emerges as the combined effect of technology's scalability, replicability, and sustainability. Societal sustainability related to 6G means human-centricity and that people can participate and act in society in a new, inclusive, and beneficial way, provided it is affordable, and if they choose to use it or opt out if required. Finally, environmental sustainability in 6G needs to consider two separate but interrelated directions: the use of 6G to reduce the negative impact on the environment in other sectors of society creating an environmental handprint, in addition to 6G's own negative impact on the environment (i.e., footprint). The latter will need to extend from traditional resource efficiency, where the energy consumption aspect alone is challenging to quantify, to also cover circularity and zero-emission aims (Matinmikko-Blue et al., 2021). There, the lifecycle analysis (LCA) will be an important tool to evaluate 6G services, devices, and networks' environmental impacts over the entire lifecycle (ITU-T, 2014, p. 1410). Recently, BEREC (2023) has published a draft report on sustainability indicators for electronic communications networks and services, providing a framework and set of indicators for measuring environmental sustainability. It shows how different countries in Europe collect different environmental sustainability indicator data, if any. The draft, however, lacks discussion on other forms of sustainability.

Although 6G is not yet directly within the European emission trading system or under specific CO_2 taxation, it is envisioned that such an arrangement could spread to new sectors in the future. The future development of 5G and upcoming 6G will be directly influenced by the need to decrease emissions of greenhouse gases, including CO_2, and the harmful environmental impacts of materials used in manufacturing the necessary hardware. The new growth opportunity of 5G evolution and future 6G is foreseen in the various digitalizing industry verticals that are increasingly being brought to the European Green Deal domain or under different environmental regulations. Mobile communications technologies are expected to converge and merge with other technologies and platforms. They jointly contribute to the development in which the 5G and 6G technologies will become sustainability-regulated and possibly eventually placed within the European emission trading system. A good example of this is the local and private networks that are owned and operated by different stakeholders such as factories. Those stakeholders can already be within the emission trading system in their own sector of operations.

Another sustainability related question is related to the social sustainability of 6G, especially as related to the use of AI in the networks as well as connecting the unconnected. The AI regulation in the EU is already banning activities that could be realized via future 5G and 6G networks as exemplified by the government-run social scoring in China. Connecting the unconnected requires investments from the MNOs in areas where profitability is not guaranteed. Societal sustainability and resilience are also directly related to privacy, security, and sovereignty-related concerns.

3.3. Competitive and transformative innovation policy

The *global race for 6G* has started (Bajpai, 2021; Bauer, 2022); similar initiatives like the Finnish 6G Flagship or European Hexa-X have been launched in several countries including China, the US, South Korea, and Japan. Innovation policies actions should address broader societal goals and the "Grand Challenges" of sustainability (Haddad & Bergek, 2023). To this aim, transformative innovation policies (Diercks et al., 2019) have recently emerged to deal with purposive and directional innovation, system and market failures, and behavioral additionality meaning the expected impacts of the policies on transition processes in different sectors. Current discussions and presented visions on the future of 6G show fundamental differences in how the big three economic blocs—the United States, China, and Europe—are driving 6G development. The US vision of 6G highlights wireless ecosystem leadership, security at all levels, and military needs. The Chinese vision emphasizes state sovereignty, global initiatives, and the digital silk road. The EU vision stresses research sovereignty, the United Nations' Sustainable Development Goals (https://sdgs.un.org/goals), and human centricity (Yrjölä et al., 2022b). The insights drawn from these visions is that innovation policies and related action plans should integrate several aspects of innovation activities.

Firms' competitiveness may become quickly eroded as the "*world of perfect competition never exists*" (Teece, 2022, p. 8), and incumbents may be disrupted by entrants in the increasingly digitalized markets characterized with winner-takes-all outcomes. Innovation policies directly and indirectly impact firms' innovation practices and intellectual property creation, thereby providing the basis for competitiveness. General purpose technologies such as 6G call for cross-industry sector innovation efforts, and achieving global competitiveness requires goal-oriented and vision-driven global collaboration from the start. Furthermore, 6G is also expected to build on the extended use of several complementary technologies such as artificial intelligence, making the development and standardization of 6G a cross-industry effort in which both leading developers and users of 6G need to collaborate with both the developers and users of the complementary and adjacent technologies.

3.4. European values-based anticipatory regulation

Given the current geopolitical tensions, many researchers and businesses are concerned with the fragmentation of the global 6G markets, technologies, and regulations, especially concerning the use of artificial intelligence (Feijóo et al., 2020). Europe may be well positioned to succeed in global competition with its strong ecosystem of technology vendors, mobile network operators, and end users in various industry verticals that are forecast to become the key drivers of new value creation and capture in 6G. However, concerns to the contrary have also been presented. In a recent article, Teece (2022) considers the European Digital Markets Act (EC, 2022a, 2022b, 2022c, d, e, f), a regulation that concerns the mobile connectivity business, as detrimental to the competitiveness of European businesses and economies.

In the artificial intelligence and Interet-of-Things contexts, Hadzovic et al. (2023) classified EU regulations on data, electronic communications, cybersecurity, platforms, and consumer rights-related matters. The provisions of the European Electronic Communications Code Directive (EC, 2018) present the legal framework for the provisioning of electronic communications, regulating the organization of the sector, networks, and services. It creates a legal framework to ensure the freedom to provide electronic communications networks and services. It is the main legal act which aims to stimulate competition and increase investment in very high-capacity networks to enable high-quality connectivity, a high level of consumer protection, and an increased choice of innovative digital services. However, the EECC needs to be complemented with new regulations that consider aspects such as artificial intelligence and cybersecurity. Regulations related to economic, societal, and environmental issues should also be considered (Robles-Carrillo, 2021). The examples of the European General Data Protection Regulation (EC, 2016a) and the regulations stemming from different societal and environmental pressures have paved the way to analyzing the potentially evolving and different vertical-specific regulations. In the 5G context, emerging new service concepts such as local 5G networks and related operator models enable new entrants to enter the business, provided that the regulation makes it possible. To enable this development, researchers have proposed new local spectrum licensing models that have become a reality in some European countries (Matinmikko et al., 2018). Since we are approaching the 6G era, the EU's regulatory frameworks will increasingly be challenged and will require careful strategic European values-based consideration (Cave et al., 2019; Van Duijvenvoorde, 2020).

The legal and regulatory landscape in the EU is becoming more complex. Beyond the EECC, the EU 2030 *Digital Compass* (EC, 2019) provides a generic framework for the digital transition in Europe, focusing on government, skills, infrastructure, and businesses. In summary, at least the following regulations can be seen to influence 6G: the Digital Market Act (EC, 2022a, 2022b), Digital Services Act (EC, 2022a, 2022b), Platform to Business Regulation (EC, 2019a), Directive on E-commerce (EC, 2000), Data Act (EC, 2022a, 2022b), Data Governance Act (EC, 2020), Free Flow Data Regulation (2018a), Open Data Directive (EC, 2019b), e-Privacy Act (EC, 2017), Cybersecurity Act (EC, 2019c), NIS 2 Directive (EC, 2022a, 2022b), Cyber Resilience Act (EC, 2022a, 2022b), AI Act (EC, 2021a, 2021b), and AI Liability directive (EC, 2022a, 2022b).

The above list is indicative of the European regulatory approach on mobile communications but is not exhaustive. Feijóo et al. (2020), although focusing on artificial intelligence, discuss the differences between the market-based US approach, the rights-based European logic, and China's government push-based logic for developing and utilizing technologies. Traditional mobile network operators are losing ground in providing connectivity as new Internet/over-the-top service providers and local and private operators disrupt mobile connectivity in Europe (Matinmikko-Blue et al., 2023). For Europe, the challenge is to understand and manage the joint effects of all the regulations on future 6G.

It can be argued that European values and goals should be at the heart of European regulation, defining the rules for *ex ante* developing 6G, and *ex post* when deploying the services. The parallel consideration of both *ex ante* and *ex post* regulations also

contributes to the recent discussions on the need to make the whole regulatory process more agile with anticipatory regulation in the context of new technologies (Serentschy, 2021). Anticipatory regulation means a proactive, iterative, and responsive approach to the regulation of evolving markets, emphasizing flexibility, collaboration, and innovation. In reviewing the evolution of European regulation—from open telecom markets (version 1.0) to a new (combined) perspective on innovation, investment, and regulation (version 2.0), the birth of the EECC (version 3.0), and the regulation of all digital players (version 4.0) —Serentschy (2021) argues for change. In support of anticipatory regulation, in their analysis of platform regulation, Cioffi et al. (2022) expect the European Digital Market Act and Digital Services Act released in December 2020 to have far-reaching international impacts on businesses relying on digital platforms. As 6G as a connectivity platform is increasingly expected to converge with other digital platforms, the whole regulatory landscape will face convergence and cross-effects in the future.

3.5. Trustworthy 6G in terms of privacy, security, and resilience

The identified 6G use cases intertwine with all the functions of everyday life and will be increasingly driven by societal demands, setting high standards for privacy, security, and safety of communications, data, and intelligence (Ylianttila et al., 2020). A 6G network will be able to locate a person's precise location and position in a room, as well as track their habits. Hacked bio data could be used for sophisticated fraud and extortion attempts. The confidentiality of business data will assume even greater importance, as business models will increasingly rely on controlled access to and ownership of customer, process and business data. Ransomware attacks, corporate espionage and "deep fakes" will pose ever bigger threats in the 6G era. Local 6G industrial and campus networks will become the norm, as will their appeal to attackers, raising the possibility of industrial and critical infrastructure sabotage that could cause considerable damage to business, equipment and lives.

The 6G system characterized by architectural disaggregation, open interfaces, cloud-native design principles, pervasive use of AI-native technologies across management, control, and user plane embedded artificial intelligence (AI) and an environment with multiple stakeholders requires trustworthiness to be assured across devices, sub-networks, heterogeneous cloud, services, and applications (Ziegler et al., 2020; Ziegler et al., 2021). Exposure of network data in multi-party ecosystems is becoming a key new monetization opportunity as well as a privacy and security challenge. The number of threats is increasing significantly due to the billions of connected devices and sensors, millions of subnetworks operating in untrusted domains, and microservices, such as those from open source cannot be trusted. Open interfaces allow for more flexibility, but also open up more opportunities to attack the system. On the other hand, cloud infrastructure is better trusted, because that is in the hands of large companies whose reputation depends on a secure data center infrastructure. Furthermore, there will be a threat that modern cryptographic algorithms may be broken due to significant advances in quantum computing and AI technologies. Extant 6G system and architecture research (see e.g., Hexa-X, 2021) has proposed the following actions related to security features and solutions. First, there is a need to tailor the DevOps paradigm toward Telco's multi-stakeholder network production environments for a secure and automated software supply chain for cloud-native components. Second, it is essential to minimize interruptions for human intervention and hence also to minimize opportunities for malicious human intervention via the auto-creation of SW and automated operation and orchestration enabled by AI/ML. Third, it will be important to adopt the use of a holistic AI-native security and trust framework, which is resilient against conventional and AI-based adversarial attacks to protect from training to inference phases. Fourth, the usage of remote attestation should be developed to validate the integrity of cloud platforms. Fifth, privacy-preserving and confidentiality-preserving technologies such as differential privacy, homomorphic encryption, and confidential computing should be leveraged for secure data exposure across multiple stakeholders. Sixth, the utilization of cross-layer cross-domain optimization of user plane encryption and integrity protection across e2e application, radio access and core networks should be developed. Seventh, in the quantum-safe, future-proof, security architecture context strong post-quantum cryptography algorithms to protect neuralgic points in 6G security architecture such as long-term secrets should be selectively introduced. Finally, the challenge to mitigate potential negative performance and energy efficiency impacts of advanced cryptography algorithms, e.g., via HW acceleration should be addressed.

The European 6G flagship program Hexa-X (Hexa-X, 2021) considers trustworthiness via security considerations that need to cover all the aspects of cybersecurity, including resilience against attacks, preservation of privacy, and ethical, safe application of automation to network operations and applications. Embedded AI/machine learning (ML) techniques deployed on different time scales across distributed radio access, core network and management domains call for transparency and accountability of AI/ML decisions not only toward users but developers, operators, vendors, and regulators. Novel stakeholders such as hyper-scalers and enterprises have been entering the mobile communications market and disrupting the traditional connectivity driven business models with service dominant logic building on the value of data ownership, access to data and AI/ML model ownership (Yrjölä et al., 2022a). Thus, the characteristics of trustworthiness should extend cyber-resilience technologies by privacy-preserving technologies and trust-creating technologies across connectivity, data, and intelligence domains in order to achieve the ultimate goal of trustworthy 6G networks—comprising security, privacy, safety, availability, resilience, and compliance with ethical frameworks.

In the 6G development, 6G connectivity, cloud computing and AI/ML research communities should interact and consider jointly proposing and contributing to new definitions and related metrics to enable trustworthiness in 6G by design. Following the proposals for harmonized regulation and ethical guidelines for AI (Smuha, 2019), a similar policy for trustworthy 6G can be envisioned, focusing on transparency, fairness, accountability, robustness and safety, human agency and oversight, privacy, and data governance as values. The quality of trustworthiness (QoT) in the 6G systems context can be proposed and envisioned to be associated with explainability, fairness, robustness and safety, and privacy and data governance analogous to recent EU AI Act in Apr 2021 (EC, 2021a, 2021b). Explainability associates with transparency, accountability, human agency, and oversight. Transparent 6G systems must be able to explain the technical processes and/or the decisions made by them to stakeholders and the datasets and AI/ML decisions must be

documented in a standardized manner to allow for traceability and auditability. Accountability requires that AI/ML data, algorithms and design practices should be able to be independently audited, systems must clearly communicate any negative impacts to the stakeholders and that trade-offs between the trust and performance of systems must be evaluated based on service-level and risk-level of the use case, reasoned, and documented. Human agency and oversight should provide humans with the knowledge and tools to comprehend and interact with systems supported through governance mechanisms such as human-in-the-loop, human-on-the-loop, and human-in-command approaches. Fairness requires that datasets used by 6G AI/ML systems must be free from historical bias and/or incompleteness, and that the oversight processes must be put in place to detect, understand, and mitigate unfair bias throughout the AI/ML model lifecycle. Robust and safe systems must be resilient to adversarial attacks (e.g., data poisoning, model leakage) and must have safeguards that enable a fallback plan (e.g., switch to a rule-based mechanism) in case of issues. Moreover, embedded AI/ML systems must be reproducible and reliable. Privacy and data governance in 6G systems must protect the privacy of sensitive data throughout its lifecycle, must ensure the integrity of data and ensure that data protocols governing data access must be put in place.

Additional empowerment perspectives on human agency and oversight are identified in the first *Future technology trends toward 2030 and beyond* report published by the ITU-R in 2022 (ITU-R, 2022). Increasing the customization of user experience requires novel user-centric resource orchestration models and localization of demand-supply-consumption models. The roles of communities in service provisioning will grow with community-driven networks and public-private-people partnership arrangements. Citizen empowerment will extend beyond the roles of users and data producers toward knowledge producers and developers contributing to human-centered innovation. Open architectures with the decoupling of technology platforms will lower barriers to entry into a market by allowing multiple entities to contribute to and profit from the innovations. From the business perspective, the appropriability potential can turn to the appropriation of social value, which can be highly relevant in contemporary innovation environments where sustainability has increased in importance. Moreover, a shift from the approach of profiting from innovation to an approach benefiting from the innovation with interactive appropriability and disclosure-oriented processes with the free and shared use of the innovation and the related knowledge can be envisioned (Yang & Hurmelinna-Laukkanen, 2022).

To make 6G trustworthy, deep interaction between academia, industry, communities, and the authorities is required. However, trustworthiness involves more than just privacy, security, and safety: the European framework should consider ethical and regulatory demands and values in a non-biased, inclusive, and empowering way, while fulfilling the demands for social, economic, and environmental sustainability and resilience.

4. Discussion and conclusions

The five innovation priority themes discussed above are deeply intertwined in practice at the national and European levels and are mutually dependent (Fig. 1.) First, *national and European sovereignty*, and *triple bottom line sustainability* set new demands for developing the future 6G to combat climate change and environmental pollution. In addition, it has direct and indirect requirements for societal sustainability in terms of human-centricity and inclusivity to provide the motivation for integrated innovation activities on a larger scale. *Competitive transformational innovation policy* is the fundamental enabler required to benefit from innovation, providing impetus and direction for 6G innovation work, building on a shared 6G vision. These relate to intellectual property development, the

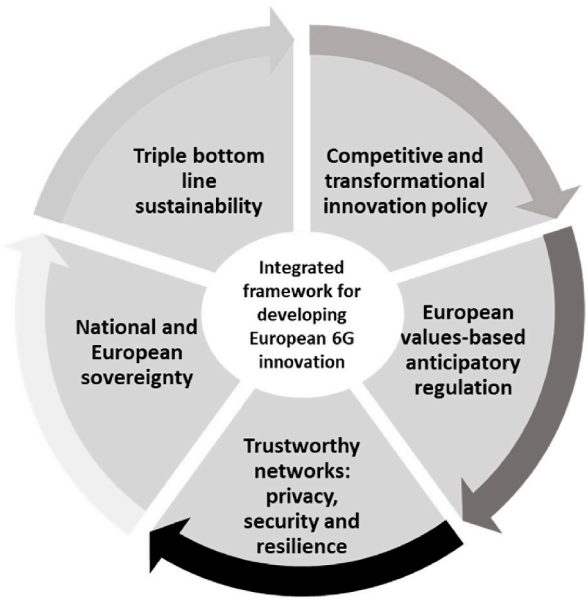

Fig. 1. Integrated framework for developing European 6G innovation.

complementarity of the developed technological solutions, and the ability to benefit from 6G innovation at the firm and market level. In turn, *European values-based anticipatory regulation* delimits market actors' opportunistic or abusive market behaviour, but also creates common grounds for directing European players toward fairer competition and understanding of the rights and responsibilities set forth for the ecosystem. Finally, trustworthy 6G is a cornerstone for strategic autonomy and sovereignty both at the national and European level.

Serentschy (2021) argues that Europe lacks a smart combination of innovation policy and regulations. This lack of smartness appears to hold true also between regulation and sustainability, although the connection between innovation policy and sustainability—especially environmental sustainability—is addressed by the Green Deal. Additionally, the aim to build trustworthy 6G networks is addressed to some degree in innovation policies, regulation, and sovereignty. To create an agile and holistic 6G innovation framework for Europe, we argue for the smart integration of all five priority themes discussed. Being agile implies a new mindset (Oestereich & Schröder, 2017) that enhances regulatory compliance but also promotes flexibility in policymaking. It appears that digitalization—and 6G as part of it—cannot be stopped as it is becoming a ubiquitous part of our lives. Thus, the EU should address *ex ante* and *ex post* mechanisms in its action plan: *ex ante* when 6G is developed and *ex post* when it is deployed. 6G has already become one of the battlefields of global competition—competition that is neither perfect nor fair, indicating that EU's future competitiveness requires immediate action.

Innovations and new disruptive technologies come with lower legitimacy and higher uncertainty (Ansari et al., 2016; Snihur et al., 2021) and may cause regulatory, incumbent, or social resistance (Marano et al., 2020). From second-generation (2G) mobile communications onwards the mobile communications industry has subscribed to the global define-standardize-develop-deploy/use cycle of technology innovation and commercialization (Ahokangas et al., 2024). Given the geopolitical tensions framing global 6G development regarding the discussed priority themes, a broader approach is needed to lay the grounds for any innovation framework. The integration of the European 6G innovation framework needs to be based on two primary underlaying forces: a *shared vision* that provides direction for 6G as a GPT and *legitimation* that integrates and glues together the five priority themes at the national and European levels. In collaborative policymaking contexts, legitimacy relates to the effectiveness and performance for the common good (output legitimacy), stakeholders' participation and representation concerns (input legitimacy), and the quality of stakeholders' governance procedures (throughput legitimacy) (Haus, 2014; Heinelt & Hlepas, 2006; Scharpf, 1999). For these, the four pillars of legitimacy, cognitive (based on comprehensibility or taken-for-grantedness by the stakeholders), moral or normative (alignment with wider social values or norms), pragmatic (alignment with stakeholder's own interests), and regulative (conformity with already-existing laws, rules, and regulations) should be considered (Suchmann, 1995; Binz et al., 2016; Walker et al., 2014). The essence of legitimacy comes from voluntary conformity with collective decisions. The legitimacy of formal institutions within the EU are important because they exercise authority, allocate resources, and create incentives for players to engage in conflict or collaborate. Without legitimacy, stakeholders and individuals lack the long-term capacity to design and implement policies that significantly impact social, economic, and environmental structures. Thus, we posit that Europe needs to adopt a holistic approach to 6G innovation, one that enables the creation of a virtuous circle of competitiveness addressing the European human-centric, rights-based, and triple bottom line sustainability-motivated approach to 6G, *ex ante* when it is developed and *ex post* when it is deployed.

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