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The Adoption of Low Power Wide Area Networks in the IoT Context, with a Focus on Smart Cities

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3GPP	3rd generation partnership project
BME	Burn-and-mint equilibrium
BPSK	Binary phase-shift keying
CAGR	Compound annual growth rate
CSS	Chirp spread spectrum
DC	Data credit
DOI	Diffusion of innovations
ERP	Enterprise resource planning
GMSK	Gaussian minimum-shift keying
HIP	Helium improvement proposal
HNT	Helium network token
ICT	Information and communication technology
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IPR	Intellectual property rights
IS	Information system
IT	Information technology
LPWA	Low power wide area
LPWAN	Low power wide area network(s)
LTE	Long term evolution
LTE-M	Long-term evolution machine-type communication
MAC	Media access control
MCDM	Multi-criteria decision-making
PHY	Physical layer
PoC	Proof-of-coverage
PoS	Proof-of-stake
QPSK	Quadrature phase-shift keying
SDO	Standard developing organization
TOE	Technology-organization-environment
TTN	The Things Network
TTI	The Things Industries
WLAN	Wide local area network
WPN	Wireless personal network
WWAN	Wireless wide area network

Zusammenfassung

Wir sind Zeugen der Entstehung und Verbreitung des Internets der Dinge (IoT) und seiner fortschreitenden Durchdringung verschiedenster Aspekte unseres täglichen Lebens. Diese Dissertation befasst sich mit grundlegenden Technologien für das IoT, den Low Power Wide Area Netzwerktechnologien (LPWAN, selten: Niedrigenergieweitverkehrsnetzwerk-Technologien). Die verschiedenen Technologien verfügen über vergleichbare technische Fähigkeiten, unterscheiden sich interessanterweise jedoch teils erheblich darin, wie sie vermarktet und kontrolliert werden. Somit bieten sie ein vielversprechendes Umfeld, um Vermarktungs- und Kontrollcharakteristika bei der Technologieadoption für das IoT zu untersuchen.

Zunächst fasse ich den aktuellen Stand der Forschung zu Low Power Wide Area Netzwerktechnologien zusammen. Hierbei wird deutlich, dass sie hinsichtlich Vermarktungs- und Kontrollmechanismen nur sehr selten verglichen werden.

Die erste empirische Studie untersucht LPWAN Adoptionsentscheidungen. Auf Basis von 29 qualitativen Interviews werden Entscheidungskriterien und ihre Wahrnehmung durch verschiedene Interessensgruppen herausgearbeitet. Basierend darauf wird das Technology-Organization-Environment Modell (TOE framework) von Tornatzky und Fleischer (1990) angepasst sowie ein Modell zur Erfassung von Technologiepräferenzen in verschiedenen Marktsegmenten entwickelt. Beide Modelle können zukünftig die Technologieentscheidung im LPWAN Umfeld strukturieren und so vereinfachen.

Die zweite Studie konzentriert sich auf die Adoption von LPWAN in Smart Cities und nutzt dazu Interview- und Umfragedaten. Sie untersucht LPWAN Auswahlprozesse und -kriterien in Städten, ihre Erwartungshaltungen hinsichtlich Vorteile durch Smart City Einführung und ihre umgesetzten LPWAN Infrastrukturen. Damit trägt die Studie zu einem tieferen Verständnis der Rolle von steuerungs- und kontrollbezogenen Entscheidungskriterien in einem gesamtgesellschaftlich relevanten Umfeld bei.

Die dritte empirische Studie widmet sich dem Blockchain-basierten Helium Netzwerk, das Ambitionen hegt, das Netzwerk der Bürger:innen zu sein und damit die Bereitstellung von Netzwerken zu dezentralisieren. Nach einer kurzen Einführung der Technologie werden basierend auf den Analysen historischer Blockchaindaten die Entwicklung, die Eigentums- und Wahlrechtkonzentration sowie mögliche Entwicklungspfade für die Zukunft untersucht.

Abstract

We are currently witness to the emergence of the Internet of Things (IoT) and the onset of its permeation of manifold aspects of our lives. In this dissertation, I study Low Power Wide Area Network (LPWAN) technologies as an enabler for the IoT. Interestingly, these different technologies possess similar technical capabilities but differ vastly in governance-related characteristics. As a result, they provide a promising opportunity to study the importance of governance-related features for technology adoption in the IoT.

First, I provide a comprehensive review of LPWAN research and technology comparisons. Therein, I find governance-related technology features to be rarely an object of research, motivating the subsequent studies in this dissertation.

In my first empirical study, I examine the adoption decisions taken in the LPWAN market. To this end, I adapt Tornatzky and Fleischer's Technology Organization Environment framework (1990) with decision criteria unveiled through the analysis of 29 qualitative interviews with different LPWAN stakeholders. This study scrutinizes decision criteria considered by different stakeholders and their preferences for a particular LPWAN technology setup. I systematically map preferred LPWAN technologies onto different market segments. Both developed frameworks can guide and facilitate the technology decision of future LPWAN adopters.

In my second empirical study, I shift my focus on LPWAN adoption in smart cities. Based on interviews and a survey among city representatives. The focus of my investigation is threefold: (1) LPWAN technology decision processes and criteria in smart cities, (2) the expected benefits associated with the smart city concept, and (3) the actual LPWAN infrastructure setups deployed in (aspiring) smart cities. This way, the study provides insights into the role of governance-related decision criteria in a specific domain of public interest.

In my third empirical study, I explore the blockchain-based Helium network, which aspires to be "the People's Network" and decentralizes the provision of IoT networks. After a short introduction to the underlying technology and network, I analyze the quantitative data from the blockchain itself and, in doing so, study its historical development, investigate the concentration of ownership and voting rights, and map out paths for the future development of Helium.

1. Introduction

1.1 Motivation

Low power wide area networks (LPWAN) are a core enabler for the Internet of Things (IoT) (Marini, Mikhaylov, Pasolini, & Buratti, 2022: 21051; Mekki, Bajic, Chaxel, & Meyer, 2018: 413). Given their unique positioning of being a long-range information and communication technology (ICT) with extremely low energy demands for data transmission, they are a popular choice for wireless sensors across sectors (Ibrahim, 2019: 234). Among those sectors are cities, agriculture, industry, logistics, and building management. This dissertation contributes a governance perspective to the primarily technical view on LPWAN. It researches the relevance of governance-related criteria for LPWAN adoption in the market, investigates their role in smart cities, and examines a novel, decentralized approach to building IoT infrastructure.

IoT has become a ubiquitous concept and "far-reaching vision with technological and societal implications" (Telecommunication standardization sector of ITU, 2012: 2), carrying the connotation of being able to connect anything, anywhere, anytime. That means, IoT connects objects of daily life, which traditionally do not include an internet connection, for example, doors and light bulbs, to the internet to share data, receive signals, or be controlled remotely. The notion of "anywhere" refers to the long-range interaction among entities, including tankers on the ocean and water pipes deeply underground that are able to communicate. It also implies, that both in cities and rural areas, deep inside buildings or on their rooftops, people should be able to connect their "things". Finally, the "anytime" affects the mode of operation: high availability, robustness, service-level agreements, and – if needed – real-time data transmission. For some applications, long-lasting batteries are far more critical than constantly sending and receiving data. It is therefore hardly surprisingly, that an entire stack of ICT is required to cater to these very diverse needs, and, concomitantly, they render ICT a fundamental building block and enabler of the IoT (Palattella et al., 2016; Rose et al., 2016).

The World Bank lists IoT as one of the leading Tech disruptors (International Bank for Reconstruction and Development / The World Bank, 2019: 23–26), and it is expected to impact "technology, industry, policy, and engineering circles" (Rose et al., 2016: 4). On an operational level, IoT implementation means that suitable infrastructures, communication technologies, interfaces, transmission protocols and standards in the aforementioned areas are needed (Li, Da Xu, & Zhao, 2015: 243). Given the very heterogeneous requirements for ICT networks, an entire ICT stack is required to meet them. Thus, the IoT network landscape can be considered heterogeneous, too (Mumtaz, Alsohaily, Pang, Rayes, Tsang, & Rodriguez, 2017; Patel & Patel, 2016; Tadayoni, Henten, & Falch, 2017).

Communication networks exhibit strong network effects: a high number of users makes building the network attractive for network operators, and a large network is more attractive to users. This mutual dependency is referred to as the hen-and-egg problem. Thus, the success of IoT implementation depends on both the availability of network infrastructure (also referred to as the "supply side") and the adoption through market participants (also referred to as the "demand side"). (McIntyre & Srinivasan, 2017; Shapiro & Varian, 1999; Tadayoni et al., 2017)

On the supply side, IoT infrastructure ownership is mainly concentrated in the hands of large telecommunication operators. In terms of technologies used, the co-existence of several technologies in a subsegment (e.g., several LPWAN technologies) is possible (Jagtap, Yen, Wu, Schulman, & Pannuto, 2021: 22; Tadayoni et al., 2017: 7). LPWAN differ from other ICT segments as they exhibit different modes of network provisioning. By design, the LoRaWAN technology allows for private networks which can enable decentralized network ownership or self-provisioning in case only local connectivity is needed (Almuhaya, Jabbar, Sulaiman, & Abdulmalek, 2022: 167). The blockchain-based LoRaWAN network "Helium" pioneers this this IoT network approach of decentralized ownership. If it succeeds, it may revolutionize the way IoT infrastructure is provided (Haleem, Allen, Thompson, Nijdam, & Garg, 2018: 1; Jagtap et al., 2021: 22; Musaddiq et al., 2022: 143).

Other actors on the supply side include technology developers, equipment suppliers for infrastructure and end devices, as well as system integrators. For them, it is crucial to understand which technology is most likely to win which market segments to avoid (irreversible) investments into a non-winning technology which, at worst, could put their existence at risk. Adoption mechanisms in the LPWAN segments, even in the broader IoT context, are thus of high interest. Among a comprehensive set of technology adoption models, the TOE framework of Tornatzky and Fleischer (1990) has yielded powerful insights into institutional adoption. It has been employed in and adapted to different use cases. This dissertation systematically examines adoption in the context of the LPWAN market employing the TOE framework. (Awa, Ojiabo, & Orokor, 2017; Oliveira & Martins, 2011; Tu, 2018; Zhu, Kraemer, & Xu, 2006)

It is apparent, that demand for IoT connectivity is certain: forecasts on IoT devices vary in terms of concrete numbers but share the core message that massive growth into billions of connected devices in just a few years has to be expected (Mumtaz et al., 2017: 28; Rose et al., 2016: 4). Thus, a critical mass for the adoption is there. To meet this demand, it is of high interest to understand the mechanisms underlying adoption, and adoption decision criteria and adopters' preferences in specific market subsegments and niches.

1.2 Research setting, objectives, and designs

LPWAN only started to emerge after 2012, making it a young and still developing ICT segment (Iqbal, Md Abdullah, & Shabnam, 2020: 1857). Whle being novel alone does not, per se, qualify LPWAN as an exciting area for research, the fact that a range of technologically similar ICT compete in the LPWAN segment while they strongly differ in their governance structures, though, makes it a promising setting for management research (Tadayoni et al., 2017: 6).

LPWAN technologies have become an important area of IoT research in the past few years, and researchers have taken different approaches to investigate them: through theoretical comparisons of their capabilities (e.g., Almuhaya et al., 2022; Mekki, Bajic, Chaxel, & Meyer, 2019; Raza, Kulkarni, & Sooriyabandara, 2017), comparisons involving simulations (e.g., Marini, Mikhaylov, Pasolini, & Buratti, 2022; Raj, Verma, Dalal, Shukla, & Garg, 2023) and experiments (e.g., Durand, Visagie, & Booysen, 2019; Klaina et al., 2022). Some comparisons focused on specific aspects of the most widely used LPWAN technologies. For example, Coman, Malarski, Petersen, and Ruepp (2019) studied the vulnerability of different LPWAN, and Mekki et al. (2019) scrutinized the cost structure. Researchers have also studied the suitability of different LPWAN for a range of applications, such as smart agriculture (e.g., Klaina et al., 2022), environment monitoring (e.g., Musaddiq et al., 2022) or smart monitoring of a water grid (e.g., Lalle, Fourati, Fourati, & Barraca, 2019). A single, dominating LPWAN technology has yet to emerge; currently, several LPWAN technologies co-exist. It is widely agreed that LoRaWAN, NB-IoT, and Sigfox are the most widely spread ones, making them the focus of this dissertation. (Durand et al., 2019: 2540; Tadayoni et al., 2017: 7)

Any technology's success, however, depends on its adoption by the market. In the context of LPWAN, the market comprises telecommunication system operators, sensor and telecommunications equipment manufacturers, organizations, and individuals seeking to use LPWAN in practice. Hence, success is mostly about institutional adoption where commonly Tornatzky and Fleischer's (1990) TOE framework is used to assess adoption (Gibbs & Kraemer, 2004; Tu, 2018; Wang, Wang, & Yang, 2010). Existing research on LPWAN strongly focuses on technological aspects[1], while the TOE's dimensions of organization and environment are seldom mentioned. A plethora of questions arise here: Which adoption criteria do different stakeholders value? Do governance-related factors matter for technology adoption, and if so, which ones? Are there different dominating LPWAN in sub-segments of the IoT market? If yes, which LPWAN technology dominates where and why?

In my first empirical study, presented in Chapter 3, I aim to assess the adoption decisions taken in the LPWAN market systematically. Deploying the TOE framework of Tornatzky and Fleischer (1990), I employ a qualitative approach to investigate the decision criteria constituting these three dimensions and how different stakeholders apply them. The study is based on 29 semi-structured interviews totaling 22:49 hours. I interviewed practitioners along the value chain using any of the three dominant LPWAN technologies and involving various LPWAN market subsegments, from smart agriculture to smart industry. The emphasis lies on exploring *which decision criteria* different stakeholders consider and *which LPWAN technologies* they consequently prefer.

The second empirical study (Chapter 4) shifts the research focus to smart cities as one main area of application of LPWAN technologies. The research objective of this joint study with Joachim Henkel (TUM) is to examine the role of governance-related decision criteria in LPWAN technology decisions for smart city implementation. Using a mixed-methods approach, we first identify the adoption criteria relevant for smart cities' technology decisions. Subsequently, we examine the actual LPWAN infrastructure setups deployed in (aspiring) smart cities. While technology benchmarking in terms of technical features is common, a more profound understanding of the role of governance-related criteria in decision-making is required. Our mixed-methods design allows us to explore the context of smart city

[1] Chapter 2 examines previous research in detail and conducts a meta-study on the features which previous research has compared for different LPWAN. It also presents a consolidated view on the features themselves distilled from several LPWAN comparisons.

implementation, decision processes, decision criteria, and observable network setups that ensue. The research utilizes theoretically sampled interviews with smart city stakeholders (n = 19, totaling 15:45 hours) and surveys German cities (n = 107 cities) to understand *the expected benefits associated with smart cities* and the *assessment of different technology decision criteria*. The study aims to develop an *understanding of the role of governance-related criteria in technology selection*, deeply rooted in practice but with the possibility of being generalizable.

The third empirical study presented in Chapter 5 makes use of the LPWAN context to study an essential aspect of governance: the degree of centralization or decentralization of power, respectively (Chen, Richter, & Patel, 2021: 1307; Xue, Ray, & Gu, 2011). It studies the decentralized, blockchain-based governance mechanisms of the physical peer-to-peer (IoT) network “Helium”. It is a novel, decentralized approach to building IoT networks by pairing LoRaWAN network technology with blockchain technology and we note that Helium has pioneered this approach since 2019. The study clarifies the terms and mechanisms of the Helium network and blockchain. Moreover, it analyzes empirical data from the blockchain to investigate decentralization, network owners' segmentation, and voter concentration. The study provides insights into the future of this approach and its implications on IoT infrastructures and contributes to research *on decentralized, blockchain-backed IoT networks and their governance*.

In short, this dissertation focuses on bridging the gap between IoT technology research and market adoption. The first study in Chapter 3 explores the LPWAN segment and maps the determinants of LPWAN technology adoption to the TOE framework. Chapter 4 builds on that with an in-depth case study of smart city. Chapter 5 is dedicated to exploring a novel, decentralized and blockchain-powered approach to building IoT infrastructure and overcoming the inherent hen-and-egg problem of ICT networks. The three studies in conjunction contribute to a better understanding of ICT adoption paving the way for a more informed IoT implementation.

1.3 Structure of the dissertation

My dissertation includes an introduction to the LPWAN technologies and research on them, followed by three empirical studies in the field. It is structured as follows:

Chapter 2 introduces the research setting for the three studies, the ICT segment of LPWAN. After outlining the role of ICT within IoT (2.1), I introduce LPWAN technologies in Section 2.2. This section describes the three dominating LPWAN technologies – LoRaWAN, Sigfox, and NB-IoT – in detail. A literature review of LPWAN comparisons (2.3) complements these descriptions. The chapter concludes by contextualizing this dissertation within the presented LPWAN research. It particularly highlights which research gaps this dissertation addresses (2.4).

Chapter 3 explores the LPWAN technology adoption process empirically. I explain the need for an empirical investigation of LPWAN adoption (3.1), before presenting theoretical considerations on institutional technology adoption (3.2.1 and 3.2.2) and the research questions (3.2.3). Section 3.3 discusses the methods applied: semi-structured interviews and thematic coding. In 3.4, I present the results of the qualitative empirical study. In the following (3.5) I discuss their implications for LPWAN technology adoption and future research in this domain. Section 3.6 concludes this first empirical study.

Chapter 4 is dedicated to the role of governance-related decision criteria in adopting LPWAN technologies in smart cities and is joint work with Joachim Henkel. Following a short introduction to LPWAN adoption in smart cities(4.1), we present the research context of smart cities in Germany in greater detail (4.2.3). In 4.2.4, we discuss technology selection criteria for LPWAN in smart cities and present our research question. Later, Section 4.3.1 is dedicated to the exploratory mixed-methods design we follow in this study. Therein we also address data processing and give an overview of the demographics for the qualitative and the quantitative part of the study (4.3.2 and 4.3.3, respectively). In the following section (4.4), we present our findings. We discuss these findings and discuss our study’s limitations in Section 4.5. We summarize key insights and, comparatively, put them into context (4.6).

Chapter 5 focuses on the blockchain-based Helium network as a decentralized approach to IoT infrastructure. The chapter is divided into six sections. The first section, Section 5.1, introduces the topic. After that, Section 5.2 offers comprehensive background information: it explains Helium’s novel approach to IoT infrastructure (5.2.1), reviews the literature on decentralized governance and infrastructure-focused blockchains (5.2.2), and provides an introduction to the research setting, the Helium network and its underlying blockchain (5.2.3). Section 5.2 closes by commenting on the ongoing debate and introducing the guiding questions for the exploratory research. The third section (5.3) outlines the methodology used for the empirical study, including a section on the single case study (5.3.1) and an explanation of the data extraction and analytical approach of the study (5.3.2). In Section 5.4, I present the results of the empirical research on the Helium network and blockchain. The fifth section, Section 5.5, puts these results into context and discusses them in the light of Helium as the “People's Network” (5.5.1), and evaluates the suitability of Helium as IoT infrastructure, including the proposition of a research agenda for the future (5.5.2). The sixth and final section of this chapter, Section 5.6, provides a conclusion to the chapter.

In **Chapter 6,** I conclude this dissertation by bringing together the main insights from all three studies and discussing their contributions to theory (6.1) and practice (6.2). Moreover, I elaborate on future research opportunities beyond the scope of this dissertation (6.3).

2. Background: Low Power Wide Area Networks for the IoT

2.1 Information and communication technologies as enabler for the IoT

IoT promises to revolutionize our daily lives so that "every day and everywhere things and objects have capabilities of data communication" (Ibrahim, 2019: 234). The novel dimension therein is that humans do not necessarily play an active role anymore but objects which are usually not considered computers themselves connect to the internet, humans benefit passively. These things and objects can record, exchange, receive and process data (Rose et al., 2016: 1) – in other words: things become smart (Patel & Patel, 2016: 6122; Trappey, Trappey, Hareesh Govindarajan, Chuang, & Sun, 2017: 210).

The International Telecommunications Union differentiated the IoT versus existing internet by its "enormous scale" (2012: 5). The number of connected IoT devices reflects this: At the end of 2021, according to the market insights provider IoT analytics, around 12.2 billion connected IoT devices existed worldwide (Hasan, 2022). For the year 2025, the same company forecasts 27 billion connected IoT devices (Hasan, 2022), while the International Data Corporation (IDC) expects 55.7 billion connected IoT devices for the same time (Hojlo, 2021). Forecasts from the information services provider IHS Markit (2017: 2) amount to 125 billion connected IoT devices in 2030. Eventually, none of these numbers will be exactly right, nevertheless they illustrate the sheer growth of IoT devices. The expected compound annual growth rate (CAGR) of the IoT market volume in US$ forecasted by various studies echoes these growth expectations: their forecasted CAGR ranges between 21% and 38% for the IoT market until 2030, as a meta study of Al-Sarawi, Anbar, Abdullah, and Al Hawari (2020) shows.

Ubiquitous connectivity plays a key role in the recent rise of connected devices and objects (Rose et al., 2016). Palattella et al. (2016) add that a variety of communication technologies beyond the still dominant broadband – both fixed-line and wireless – will be needed to further support the growth of the IoT. Especially wireless technologies are central for the IoT as they allow to connect mobiles objects as well as objects at remote locations where wired connectivity is not feasible (Rose et al., 2016: 8; Shaikh, Zeadally, & Exposito, 2017: 984). As the wireless ICT technologies need to cater to a variety of needs with regards to transmission bandwidth, energy efficiency, security, latency, and reliability, a heterogeneous set of wireless networks is crucial for the further growth and flourishing of the IoT (Li et al., 2015: 250; Patel & Patel, 2016: 6123; Rose et al., 2016: 8).

Wireless communication technologies differ significantly in their range. This allows us to classify them into four groups as shown in Figure 1: “Proximity” denotes anything below 10 meters of distance and a popular technology used in this range is RFID. Distances from 10 to 100 meters are covered by wireless personal networks (WPN), such as Zigbee and Bluetooth. Distances up to one thousand meters are covered by wireless local area networks (WLAN), such as WiFi. Distances larger than a kilometer, long-range areas, are covered by Wireless wide area networks (WWAN). Among WWANs are cellular and low power wide area networks (LPWAN or LPWA networks), a class of wireless communication technologies whose name was coined only in 2013. (Ibrahim, 2019; Mekki et al., 2019)

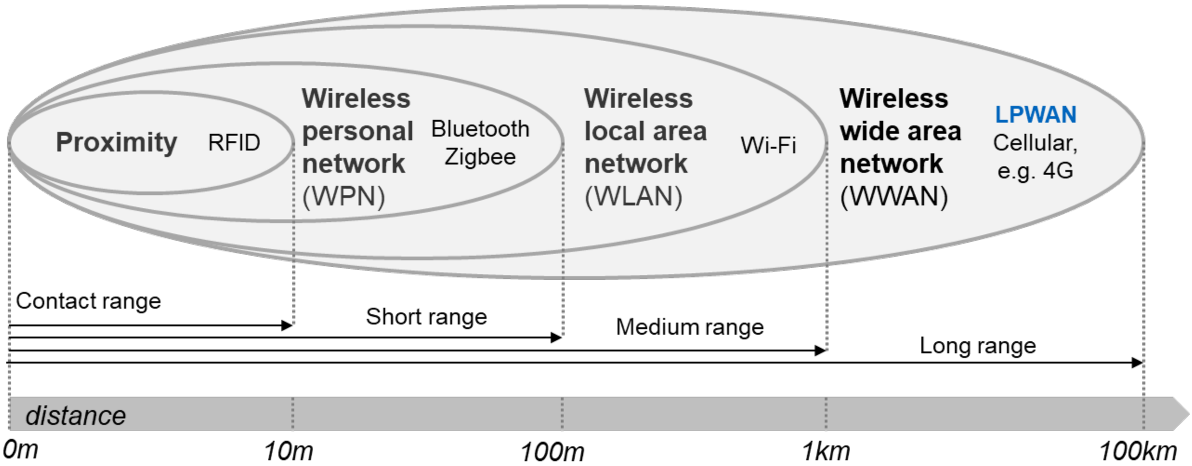

Figure 1 Types of wireless communication networks and their ranges (based on Ibrahim 2019)

While currently LPWAN devices only account for around 5% of all IoT devices, the market insights company IoT analytics, expects the LPWAN segment to grow strongest with a CAGR of 34% until 2025. They expect a stronger growth only for the 5G segment. (Hasan, 2022)

2.2 LPWAN technologies

“Low Power Wide Area (LPWA) networks represent a novel communication paradigm, which will complement traditional cellular and short-range wireless technologies in addressing diverse requirements of IoT applications” as Raza et al. (2017: 855) emphasize. This gap between existing cellular networks such as LTE and 5G and established short-range networks

(Wi-Fi, Zigbee) is also identified by other authors (e.g., Ayoub, Samhat, Nouvel, Mroue, & Prevotet, 2019b; Mekki, Bajic, Chaxel, & Meyer, 2018; Sinha, Wei, & Hwang, 2017) and "there is a growing need to design LPWAN technologies to fill this gap" (Ibrahim, 2019: 234).

> *"LPWA connectivity solutions are developed based on a simple, albeit challenging, set of correlated requirements: efficient signaling and channel access protocols to support massive connection densities, **extreme energy efficiency** to extend a battery-powered device operation to ten years, the **ultralow cost** to enable large scale adoption in an economically feasible manner, and **extended coverage** to enable versatile device deployment with high reliability". (Mumtaz et al., 2017: 29; emphases added)*

Palattella et al. (2016) additionally highlight the **small data packages** exchanged as a critical characteristic of LPWAN.

LPWAN technologies meet all these requirements. The "LP" (low power) means that in practice LPWAN sensors can often run on a single battery for five to ten years. The "WA" (wide area) stands for ranges of up to two kilometers in urban areas and up to 40 kilometers in the flat countryside – covered by one base station, or gateway, as it is sometimes referred to. As Sinha et al. (2017: 15) summarize, this "is perfectly suitable for the IoT applications that only need to transmit tiny amounts of information in a long-range". Indeed, the aforementioned low-cost aspect for both the end devices and connectivity also supported the strong growth and popularity of LPWAN technologies in the past few years (Raza et al., 2017: 859).

With the strengths of LPWAN technologies come several weaknesses: LPWAN technologies have a far higher latency and smaller bandwidth than cellular technologies, making them unsuitable for any application relying on real-time data or large data volumes. Moreover, especially the technologies operating in the unlicensed spectrum do not allow end devices to send data via the network constantly but limit their sending time. As a result, their data packages might get delayed and sometimes fail to reach their target at all. Any application relying on LPWAN technologies has to consider these constraints.

Currently, three LPWAN technologies are considered the most promising ones: LoRaWAN, Sigfox, and Narrowband-IoT (NB-IoT) (Almuhaya et al., 2022; Lalle et al., 2019; Raj et al., 2023). I present them in detail in the following sections. A glossary of technology-related terms is provided in Appendix A.

2.2.1 LoRaWAN

The French start-up Cycleo developed LoRaWAN in Grenoble in 2009. Three years later, in 2012, the US-based semiconductor firm Semtech acquired the technology. Semtech founded the LoRa Alliance, a nonprofit association, as standardizing body for the LoRaWAN technology in 2015 and transferred the intellectual property rights for the MAC layer protocol LoRaWAN to it. (Mekki et al., 2019: 2; Tadayoni et al., 2017: 4–5) Today, the LoRa Alliance with its committees, develops the LoRaWAN standard further, and Semtech remains the largest semiconductor company manufacturing the LoRa chips. However, several other actors plan to start manufacturing LoRa chips as well[2]. As of April 2023, 181 operators[3] worldwide provide LoRaWAN coverage through their network[4].

In a LoRaWAN network, a LoRaWAN end device transmits a message to all gateways in its range. The gateways forward the message via conventional internet connections to the backend systems. The network operator hosts these backend systems centrally. When processing the data, they detect duplicates, remove them, and then forward the message to the application server. This redundant transmission improves the reliability of the system.

LoRaWAN consists of the physical layer (PHY) called LoRa, and a Medium Access Control (MAC) protocol called LoRaWAN. The physical LoRa layer uses a particular modulation technique, Chirp Spread Spectrum (CSS), which makes it particularly robust against interferences. The LoRa part of the technology is proprietary. The MAC layer is responsible for the transmission protocol, including activities like message handling. Semtech transferred the MAC layer IPR to the LoRa Alliance, while keeping the PHY layer LoRa. This differentiation of IPR ownership between PHY layer and MAC layer is unique to LoRaWAN; for NB-IoT and Sigfox there is no difference in the ownership (Almuhaya et al., 2022: 172–173; Hossain & Markendahl, 2021: 890). End device owners pay a small yearly fee to their network operators who forward it to Semtech. For LoRa Alliance members the use of the

[2] https://lora-alliance.org/about-lora-alliance/, last accessed 04/04/2023.

[3] Operators own the physical infrastructure of gateways, additionally, they provide backend server(s) processing the incoming messages collected by the gateways. The backend server(s) then forward(s) the messages to the respective application server, i.e., to one company's server, for further processing, interpretation, and use of the data in the message.

[4] https://lora-alliance.org/, last accessed 04/13/2023.

technology is royalty-free, however they may need to pay certifications for their manufactured products (LoRa Alliance, 2017).

To cater for different data transmission needs, LoRaWAN comes with multiple communication classes (A-, B- and C-class) varying in terms of latency and bi- vs. unidirectional communication, and subsequently then also with regards to energy consumption. LoRaWAN operates in the unlicensed spectrum (in Europe: 863-870 MHz). Therein, for end nodes, their time to send data is restricted to 1% of the time, called the duty cycle. This means, every day an end node can only send data for 14 minutes and 24 seconds (864 seconds are equivalent to 1% of one day) (Hossain & Markendahl, 2021: 890; Marini et al., 2022: 21053).

By founding the LoRa Alliance in 2015, Semtech laid the foundation for a strong ecosystem around the LoRaWAN technology: as of December 2022, the LoRa Alliance counted more than 400 members, whereof 93 joined in 2022 (LoRa Alliance, 2022: 42–49).

LoRaWAN has widely adopted and, in several countries, even national telecommunication providers, for which connectivity in the unlicensed spectrum was beyond their traditional business model, started their own national LoRaWAN. For example, KPN deployed the Dutch network as the first national LoRaWAN worldwide in 2016 and Swisscom did so for Switzerland (Reichert, 2016).

LoRaWAN, though, offers a second promising way of commercialization: setting up an own network and hereby becoming independent of existing network operators is possible. In this study I refer to this feature as “self-provisioning”. Such a self-provisioned network could be set up by any actor for their own purposes. The possibility to install an own network also paves the way for a second and popular option: an open-source network (Almuhaya et al., 2022: 167). The most prominent one is The Things Network (TTN). Hosted by the company The Things Industries (TTI), the TTN is a network any interested person can use with his or her sensor after completing an online registration free of charge. The TTN is also open to contributions from the community: by purchasing a gateway and connecting it to the TTN network, anyone can expand this network. The network has organically grown and does not only serve hobbyists, but also commercial applications, like interviewees L01 and L15 in Chapter 3. The TTN-associated yearly summit “The Things Conference” is one of the most important events on LoRaWAN every year, it is "the flagship event about LoRaWAN"[5]. (Almuhaya et al., 2022: 175; LoRa Alliance, 2022)

Another recently emerging network based on this private network feature is the Helium network. It is a blockchain-based LoRaWAN aiming to become a world-wide IoT network by leveraging a similar crowd-based approach as the TTN. Peers can purchase base stations and help building the network, while – and here lies the difference to TTN – they are rewarded for their contributions with a cryptocurrency. (Coinbase, 2022; Haleem et al., 2018)

2.2.2 Sigfox

Sigfox is a proprietary technology with origins in the city of Toulouse in France, where it was developed in 2010. Sigfox denotes both the technology and an LPWAN operator (Lalle et al., 2019: 1). In February 2022, Sigfox filed for bankruptcy and UnaBiz acquired the company later that year. With this acquisition UnaBiz announced to "strive towards the convergence of LPWAN" and continued operations of both the technology company and the network operator part of the firm (Swinhoe, 2022). UnaBiz already operates several LPWAN[6] and their above cited announcement nurtures speculation around a future deviation from the current closed Sigfox model (Kasujee & Mackenzie, 2022). Given that currently, the integration has not yet taken place, I elaborate on the Sigfox model as it is in place now and has been over the past years.

Sigfox was developed as a "0G" network[7] using Europe's unlicensed spectrum of 868 MHz. In the early days, restricted to uplink messages, soon they introduced downlink messages, so they are available to end users now. (Almuhaya et al., 2022: 169; Hossain & Markendahl, 2021: 889–890; Mekki et al., 2018: 198; Tadayoni et al., 2017: 4) IPR of the Sigfox technology for both the physical and the MAC protocol layer are in the hands of the company Sigfox, or now UnaBiz respectively. (Tadayoni et al., 2017: 6)

[5] https://lora-alliance.org/event/the-things-conference-2022/, last accessed 05/04/2023. In addition to developers and device manufacturers, also operators and Semtech regularly attend this event and engage there with the community.

[6] UnaBiz uses LoRaWAN, LTE-M, as well as cellular technologies (2G, 3G, 4G LTE) according to https://www.unabiz.com/iot-connectivity/#satellite, last accessed 04/05/2023.

[7] This term was coined by Sigfox. It does not imply that "0G" is a predecessor or 2G, 3G, LTE, and 5G, but should be understood in the sense that the data rate is even smaller than it was in 2G, and latency is higher than for 2G and successors. The term "0G" is regularly used by Sigfox to refer to a low-power and wide-area network.

For commercialization, Sigfox founded local businesses to roll out the network in its core markets such as France, Germany, and the US. For smaller markets, Sigfox relied on partners to build the network. For example, Sigfox founded its German network operator Sigfox Germany GmbH in 2016 and by 2020 the European operator Heliot took over the operation of the German Sigfox network. By that time Heliot was already an established player who had built up the Sigfox network in Austria, Switzerland and Liechtenstein – smaller markets for which the Sigfox company had relied on partnerships from the very beginning. (Heliot Europe GmbH, 2020; Mekki et al., 2018: 197) By April 2023, 74 Sigfox operators were active worldwide, ranging from Andorra to Uruguay[8]. While Sigfox grants licenses to end device manufacturers for low cost or even for free, the company aims to earn money from the royalties on the technology stack which operators sell to customers as well as from the connectivity itself. Overall, Sigfox favors a closed approach and only collaborates with selected partners for commercialization of their technology, joint technical development is not known. (Tadayoni et al., 2017: 6) As of 1st of April 2023, the Sigfox partner network consists of 805 companies (component or end device suppliers and service providers)[9].

In April 2023, a significant novelty was the release of the previously proprietary Sigfox code, which can be seen as a step towards UnaBiz's "technology convergence" mission. As UnaBiz already deploys NB-IoT and other technological solutions for IoT, further integration could be a strategic direction that UnaBiz pursues. High-rank employees at UnaBiz justify the release of Sigfox code with the need for co-development with the community and the aim to foster standardization and interoperability with other technologies. (Blackman, 2023; Sigfox, 2023)

2.2.3 NB-IoT

NB-IoT uses is standardized by the 3rd Generation Partnership Program (3GPP) which included its specification in Release 13 (LTE Advanced Pro) in mid-2016. It thus entered the already existing LPWAN market as an additional alternative. From the beginning it was associated with existing cellular technologies, their standardizing organization 3GPP and their network providers. (Marini et al., 2022: 21054; Mekki et al., 2019: 2) IPR for the technology

[8] https://www.sigfox.com/coverage/, last accessed 04/13/2023.
[9] https://partners.sigfox.com/, last accessed 04/01/2023.

are widely spread and only in November 2022 Sisvel set up a patent pool combining the standard-essential patents for NB-IoT from 20 different patent owners[10] (Mueller, 2022).

NB-IoT is technologically and in terms of commercialization closely linked to the LTE-M technology. Looking at the adoption of the technologies, geographic differences persist: while LTE-M is popular in North America, the rest of the world shows a slight preference for NB-IoT so far. A critical technological difference is that LTE-M is much more flexible with regard to the data rate transmitted, and this goes hand in hand with higher energy consumption. (Tadayoni et al., 2017: 7) Hence, due to lacking similarity to LoRaWAN and Sigfox, as well as this dissertation's technological focus on genuine low-power technology as well as a geographic focus on Europe, LTE-M is excluded from further research in this dissertation.

NB-IoT can be deployed within the existing LTE infrastructure, but in contrast to LTE, it targets the small and infrequent data packages. By reducing the LTE features to a minimum, NB-IoT limits itself to use only one frequency band in the licensed spectrum in LTE or GSM, this is 900 MHz or 800 MHz, respectively. The technology allows for up- and downlinks, traditionally (until Release 15 in 2019) on different frequency bands. After that, it became possible to have up- and downlinks in the same frequency band, and today both options coexist. In addition to this deployment in the licensed frequency spectrum, which is the typical case, technically also deployment in unlicensed frequency bands is possible. Deployments in the unlicensed frequency spectrum are subject to the duty cycle limitations of these bands. (Ayoub et al., 2019b: 1576; Hossain & Markendahl, 2021: 890; Mekki et al., 2019: 3–4)

The technical limitation that NB-IoT is deployed within existing LTE network infrastructures implies that only network operators with this license can become NB-IoT providers. Deploying NB-IoT is mainly a software update for them. In the case of old base stations, they additionally need to conduct a hardware update to enable NB-IoT within their existing LTE network. Marini et al. see this LTE compatibility both as "an advantage and a drawback" (2022: 21061) because, on the one hand, this enables a fast adoption, but on the other hand, only mobile network providers can become NB-IoT network operators. Private network installations in remote areas are technically feasible but unlikely because they are

[10] Among those were Ericsson, Datang, KDDI, NTT DoCoMo, Orange, Telefónica, ETRI, Langbo, MediaTek, Sony Group Corporation, Unwired Planet, Optis Wireless, and Optis Cellular.

commercially unattractive to those mobile network providers. (Almuhaya et al., 2022: 168; Marini et al., 2022: 21054; Mekki et al., 2018: 199)

NB-IoT does not only, per setup, have strong allies among telecommunication providers but has also received a strong push in eastern geographies: already in June 2017, the Chinese Ministry of Industry & Information Technology, the regulatory authority for telecommunications in China, committed to promoting the NB-IoT standard (Huang, 2018: 1). In the western hemisphere, NB-IoT became available relatively late compared to other LPWAN, also adoption occurred later. In all geographies, however, NB-IoT could build on the existing LTE infrastructure and achieve high coverage quickly. For example, Vodafone announced the roll-out in Germany only in late 2017. Still, they were able to offer good coverage shortly after that: already in October 2018, Vodafone claimed that 90% of its LTE-covered area in Germany had NB-IoT connectivity. (Vodafone Corporate Communications, 02.03.2021; Krzossa, 2018; Möcker, 2017)

2.3 The three dominant LPWAN technologies in the literature

Most authors start their work on LPWAN with a literature- or specification-based comparison of the three dominating technologies and their characteristics, for example, Mekki et al. (2019), Raj et al. (2023), and Tadayoni et al. (2017) did so. An exception is Durand et al. (2019): they mostly use empirical data to evaluate the three dominating LPWAN and the legacy technology GPRS in their work.

Even though LoRaWAN, NB-IoT, and Sigfox are widely agreed to be the most promising LPWAN technologies by the time of writing this dissertation, in the past, authors have also included other technologies in their comparisons: from Wi-SUN (Tadayoni et al., 2017), over EC-GSM to Ingenu (Mumtaz et al., 2017). Not surprisingly, LTE-M, which has a similar provenience as NB-IoT, has been included in the comparison a few times as well (see Hossain & Markendahl, 2021; Tadayoni et al., 2017).

I bring these past research efforts comparing LPWAN technologies together in a joint overview. The complete comparison, including sources can be found in Appendix B. Table 1 is a summary thereof.

Table 1 Comparison of LPWAN technologies LoRaWAN, Sigfox, and NB-IoT

	LoRaWAN	**NB-IoT**	**Sigfox**
End device battery	Up to 10 years on a single battery	Up to 10 years on a single battery	Up to 10 years on a single battery
Maximum range	5 km (urban) to 20 km (rural)	5 km(urban) to 40 km (rural)	10 km (urban) to 40 km (rural)
Spectrum	Unlicensed spectrum	Licensed spectrum	Unlicensed spectrum
Cost	End device: US$3 to US$6 Deployment:US$100 to US$1,000 /base station Spectrum: free	End device: US$5 to US$12 Deployment: US$15,000 /base station Spectrum: >500M US$/MHz	End device: <US$3 Deployment: US$4,000 /base station Spectrum: free
Self-provisioning	Possible	No	No
Network operators in Germany	Many local providers, but so far, no national one; *The Things Network* a global “grassroots” network	*Vodafone,* *Deutsche Telekom*	*Heliot Europe* (operating the Sigfox Germany network)

In their comparisons, most authors focused on the physical or communicative characteristics of the technologies. Costs are the center of attention in Hossain and Markendahl’s (2021) work, and Mekki et al.’s (2019), too. Tadayoni et al. (2017) put greater emphasis on the standardization process of each technology, an aspect which also Durand et al. (2019) briefly touch upon. To visualize the foci of previous comparisons, I carry out a comparison of the comparisons. In this meta-analysis I examine which technology characteristics were frequently compared by other authors in their articles on LoRaWAN, NB-IoT, and Sigfox. Table 2 presents the results of this meta-analysis.

Table 2 LPWAN technology comparisons in literature: overview of characteristics compared

Category	**Characteristic**		**LPWAN articles**								
			[1]	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**	**[8]**	**[9]**
Range in km	Urban areas	9	x	x	x	x	x	x	x	x	x
	Rural areas	9	x	x	x	x	x	x	x	x	x
Signal character-istics	Spectrum (unlicensed/licensed)	4		x	x		x				x
	Frequency bands	8	x	x	x		x	x	x	x	x
	Sub-channel bandwidth	8	x		x	x	x	x	x	x	x
	Modulation	9	x	x	x	x	x	x	x	x	x
	Latency	2						x		x	
	Device capacity/cell	6		x	x	x		x	x	x	
Data trans-mission	Bi-directional	4			x	x			x	x	
	Download capacity in bytes	5	x	x	x				x		x
	Upload capacity in bytes	5	x	x	x				x		x
	Data rate	8	x	x	x	x	x	x	x	x	
	Adaptive data rate	5	x			x		x	x	x	
	Duty cycle	3			x		x		x		
	Inference immunity	4	x			x			x	x	
	Maximum coupling loss in dB	2		x							x
Network setup	Topology	3	x						x	x	
	Localization	4	x	x		x		x			
Security	Authentication and encryption	2				x			x		
Power	Battery lifetime of end devices	6		x		x	x	x		x	x
Cost	Equipment cost per gateway/base station	2			x					x	
	Installation cost per gateway/base station	2			x					x	
	Spectrum cost for licensed bands	2			x					x	
	End device purchasing price	2								x	x
Maturity	Deployment readiness	2		x				x			
Governance	Standardization organization involved	2	x						x		
	Allow private networks	4	x			x			x	x	

[1] Almuhaya, Jabbar, Sulaiman, & Abdulmalek, 2022; [2] Durand, Visagie, & Booysen, 2019; [3] Hossain & Markendahl, 2021; [4] Iqbal et al., 2020; [5] Klaina et al., 2022; [6] Lalle et al., 2019; [7] Mekki et al., 2018; [8] Mekki et al., 2019; [9] Raj, Verma, Dalal, Shukla, & Garg, 2023.
Note: only characteristics mentioned two or more times are included in this overview.

The meta-analysis shows that all authors consider long-range low-power key characteristics of LPWAN technologies: range in rural and urban areas are included in every article which was subject of this meta-analysis, and battery lifetime for end devices is included in two-thirds of the articles in scope. Furthermore, authors frequently compare signal and data transmission features, even though some characteristics (e.g., latency, duty cycle, maximum coupling loss) receive little attention. The category of network setup is discussed in less than half of the papers. Reasons could be that it is considered less critical by end users and primarily of interest for infrastructure-building market participants. Those categories with a less technical focus and higher relevance for business and management-related considerations, such as cost and governance, are only discussed by a few authors.

The articles presented in Table 2 took only papers studying all three dominating LPWAN technologies into consideration. Of course, there are also studies comparing only two of the dominant LPWAN technologies:

Sinha et al. (2017) compare LoRaWAN and NB-IoT and illustrate the technologies' respective application areas by listing ongoing projects in Korea, Japan, and China. The comparison of LoRaWAN and NB-IoT which Marini et al. (2022) conducted, also concludes that both LoRaWAN and NB-IoT can have their application areas. They reach this conclusion, however, following a strictly analytical approach: They conduct simulations exploring factors such as energy consumption and throughput. Ayoub et al. (2019b) also studied LoRaWAN and NB-IoT. They found that depending on the specific use case within mobility applications, either LoRaWAN, NB-IoT, or other technologies can be most suitable. But not only LoRaWAN and NB-IoT were compared but, the authors also had different foci: Centenaro, Vangelista, Zanella, and Zorzi (2016) as well as Raza et al. (2017) focus on LPWAN technologies in the unlicensed spectrum. Hence, they study LoRaWAN and Sigfox, alongside with Ingenu (both) and Telensa (Raza et al., 2017, only). In both articles, especially the areas of application for LPWAN are of interest. Raza et al. (2017) scrutinize standardization efforts on the technology level and conclude that the LPWAN segment is a highly fragmented or heterogeneous one. They identify standardization in the application areas as a crucial future effort which could also speed up and facilitate future LPWAN adoption. Centenaro et al. (2016) explore one of these areas of application: smart city. Their theoretical comparison of LPWAN technologies led them to an experimental evaluation of the suitability of LoRaWAN for smart city applications, from which they concluded that this is an area with immense potential in the future.

In recent years, these areas of applications[11] were also explored by authors who studied all three LPWAN technologies in focus. Several of them derive recommendations on LPWAN use for all areas of application based on their theoretical comparison (e.g., Durand et al., 2019; Mekki et al., 2018, 2019) or based on summaries of demo projects (Iqbal et al., 2020). Others strengthen their conclusions by further analyses, simulations, and experiments, which I outline in the following paragraphs.

Smart city: Lalle et al. (2019) investigate the scalability of different LPWAN for smart water grids, a smart city application, through simulations. In their study, they identify NB-IoT as the most promising LPWAN technology. Based on the theoretical comparison and simulations of technical parameters such as energy efficiency and payload transmission, Raj et al. (2023) identified LoRaWAN as most promising for smart city applications.

Smart agriculture: Klaina et al. (2022) conduct experiments for large-scale farm monitoring, trying out all three LPWAN in focus on real farmland in Spain. They still need to identify a clear favorite technology but recommend closely monitoring their developments, especially regarding scalability and higher end device density.

Smart building: Mumtaz et al. (2017) discuss the general suitability of LPWAN technologies in the smart building context and associated requirements without assessing the LPWAN technologies' suitability.

Other application areas for LPWAN, such as **Smart metering**, **Smart logistics**, and **Smart industry** (manufacturing, indoor applications), were not discussed in detail in the papers assessing all three LPWAN technologies in focus.

To facilitate adoption decisions, also simulations have become a frequently used tool. Almuhaya et al. (2022) provide an overview and compare LoRaWAN simulation tools. Shortly after the commercial availability of all LPWAN technologies in focus, Vejlgaard, Lauridsen, Nguyen, Kovacs, Mogensen, and Sorensen (2017) conducted an experiment testing indoor coverage and outdoor coverage in Northern Denmark. For indoor coverage they identify NB-IoT as particularly promising, while outdoor all technologies perform well. The experimental study of Durand et al. (2019) focuses on comparing end device performance in all three

[11] The areas of application used here are based on the categorizations brought forward by Sigfox and the LoRa Alliance (https://www.sigfox.com/use-cases/, last accessed 04/24/2023; https://lora-alliance.org/, last accessed 04/24/2023). This is the convention decided upon for this work, however, it has to be noted that there are other authors using a far more granular segmentation of the areas of application (e.g., Durand et al. , 2019, differentiate pet tracking and asset tracking) or propose different segmentation and labeling (e.g., Iqbal et al. , 2020).

networks and cannot identify a superior technology. This is supported by the results of the experiments of Klaina et al. (2022). Further experimental studies may also provide novel insights into the strengths and weaknesses of each technology in practice. However, the results of each of these studies, must be seen in the light of technology (im)maturity when the experiment was conducted.

Around the technologies themselves, many questions of a rather technical nature remain open: for LPWAN in the unlicensed bands, it remains to clarify how much interference is to be expected, how scalability impacts LoRaWAN and Sigfox, and if, for that reason, further regulation beyond the definition of duty cycles is needed in these bands (Almuhaya et al., 2022; Hossain & Markendahl, 2021). Moreover, the parameter fine-tuning to optimize transmission features of each technology is a field where future research is needed (Lalle et al., 2019).

2.4 LPWAN technologies as an essential enabler for the IoT

Having studied the three dominating LPWAN technologies, Marini et al. conclude that "Low-power wide-area networks […] have become an important enabler for the Internet of Things (IoT) connectivity" (2022: 21051) – an opinion shared by many other researchers (e.g., Ibrahim, 2019: 234; Lalle et al., 2019: 1; Sinha et al., 2017: 15). The IoT is a construct in which engineering aspects come together with the technology industry, policy, and societal aspects (Rose et al., 2016: 4; Telecommunication standardization sector of ITU, 2012: 2). In the IoT market, "developments in technologies and businesses take place in parallel in different industry-specific sub-markets" (Tadayoni et al., 2017: 3). The literature presented in 2.3 points out directions for future research in the LPWAN segment which can benefit the wider IoT space. This dissertation aims to contribute to the management-related questions around market structure, technology decisions, governance and self-provisioning of IoT networks:

The LPWAN market has been described as "heterogeneous" (Ayoub, Samhat, Mroue, Joumaa, Nouvel, & Prévotet, 2019a: 21) or "fragmented" (Mumtaz et al., 2017: 31). While the view of a heterogeneous market, where different technologies are dominant in various areas of application, is shared among several authors (Durand et al., 2019: 2540; Hossain & Markendahl, 2021: 888), little empirical data has been collected in it. Up to this point, it remains unclear which LPWAN technology could become dominant where – may it be an area of application, a geographically confined area, or any other unit of the overall LPWAN market.

Thus, in the next chapter, I analyze interviews with LPWAN market stakeholders and their technology preferences to add this practitioner's perspective to the LPWAN research.

For the IoT, the relevance of a novel technology is a direct consequence of its adoption. Hence, it is worth looking at the adoption process, particularly the technology decision: Which characteristics of an IoT technology are important for adopters? The role of the governance-related characteristics of LPWAN technologies for the actual technology adoption decision has only theoretically been discussed in light of standardization so far (see Tadayoni et al., 2017). The question is, how relevant are these governance-related characteristics of LPWAN technologies for the adoption decision in practice? I study this by turning towards one specific area of application, the smart city, for which IoT constitutes the technical backbone (Mohanty, Choppali, & Kougianos, 2016: 68). Chapter 4 focuses on the technology decision process by German aspiring smart cities, as the technology decision is a crucial step in the adoption process.

The open access specification of the LoRaWAN technology, the precondition for self-provisioning an LPWAN, is a particular case of governance-related characteristics (Almuhaya et al., 2022: 176). Self-provisioning is also the technological feature that allowed for the emergence of global network platforms such as the TTN and the blockchain-based Helium network, which both challenge the traditional, centralized approach to ICT infrastructure. Will we build and use decentrally owned and governed networks in the context of IoT? In Chapter 5, I explore Helium's blockchain-based peer-to-peer network and its ability to serve as a blueprint for decentralization of providing infrastructure and connectivity for the IoT.

This dissertation targets the economic and societal aspects of LPWAN: market dynamics, adoption of the LPWAN technologies by cities and citizens, and blockchain-based peer-to-peer communication networks as a novel approach to solving the hen-and-egg problem of ICT networks.

3. Criteria of LPWAN technology adoption for the IoT

3.1 Introduction

Data has become a valuable currency in the "information age," and is frequently called the new oil (Rose et al., 2016: 3). Data itself is worthless, it is about what it represents: data describing the real world is a source of wealth. The IoT interconnects physical and virtual things[12] to allow for advanced services (Ibrahim, 2019; Telecommunication standardization sector of ITU, 2012), for example, remote monitoring of buildings or smart traffic routing in crowded cities. For the IoT's key feature – interconnectivity – we rely on ICT to transmit the data between the different actors and processing units (Li et al., 2015). Given different transmission requirements, for example, regarding latency and data package size, a large variety of ICT enables the IoT (Palattella et al., 2016; Rose et al., 2016). One such ICT segment are LPWAN technologies.

In the LPWAN segment, currently, three technologies compete for dominance: LoRaWAN, Sigfox, and NB-IoT (Hossain & Markendahl, 2021: 889; Mekki et al., 2018: 197). They are essential for the IoT because they have extremely low power consumption and thus enable devices to operate for several years without a battery change. In addition, they have a wide range of dozens of kilometers in rural areas or at least several kilometers in cities. (Almuhaya et al., 2022; Durand et al., 2019). The LPWAN technologies emerged in the 2010s, and while being technologically similar, they strongly differ in how they are marketed and governed. Tadayoni et al. (2017) first discussed this theoretically. However, the actual perception and relevance of different decision criteria in the market still need to be studied so far. Understanding which is the most suitable LPWAN technology for their use case is essential for (potential) end users and hence (potential) adopters. Similarly, other stakeholders – network providers, equipment manufacturers, software providers, consultants, or integrators – must understand the market's adoption dynamics to choose their LPWAN technology accordingly: which one(s) do they want to use for their business? Adopting a technology that shortly after

[12] The IoT describes the increasing number of devices and things that connect to the internet. "Things" in the IoT context can be any product or object equipped with sensors and with the ability to connect to the internet and transmit data. This includes cars, buildings, kitchen appliances, water and power meters, and parking lots.

that disappears from the market implies sunk costs and wasted R&D capacity, and thus is a considerable commercial risk.

From a research perspective, LPWAN have exhaustively been compared in technical dimensions. Other adoption criteria, however, have yet to be touched upon, as Chapter 2 has shown. Thus, it is fair to say that LPWAN adoption has yet to be well understood. This study aims to fill this gap.

In technology management research, the TOE framework of Tornatzky and Fleischer (1990) is frequently used to describe institutional adoption (Gibbs & Kraemer, 2004; Oliveira & Martins, 2011; Zhu et al., 2006). Its advantage lies in its adaptability, which researchers have exploited to describe different technology adoption decisions in high-tech and IoT (Awa et al., 2017; Wang et al., 2010). As no LPWAN-specific TOE framework has been developed, this study will do so using and extensive exploration of practitioners' LPWAN adoption decision criteria and decision processes.

The present study uses the thematic coding method for balancing an inductive, informant-centric approach with a deductive, theory-driven perspective (Boyatzis, 1998; Braun & Clarke, 2006; Nowell, Norris, White, & Moules, 2017). For the informant-centric part, I collect data through 29 semi-structured interviews with stakeholders along the value chain, including end users, using at least one of the three dominant LPWAN technologies. By involving such a broad set of practitioners, it accounts for the importance of the entire ecosystem in the LPWAN segment. After thoughtful initial coding and organization of these rich qualitative data, I link it to known theoretical concepts. In this study, I adapt the TOE framework to LPWAN technology adoption based on decision criteria distilled from the interviews. Furthermore, I summarize which LPWAN technology is most used for which IoT application, such as smart city, smart agriculture, or smart industry, and why this is considered a good fit.

For the LPWAN segment specifically, this study contributes a detailed description of adoption decisions and criteria applied by different actors in the LPWAN context. Furthermore, I developed a tailored TOE framework summarizing the vital decision criteria in the LPWAN adoption. As a result of this distill insights from the semi-structured interviews into structures and terms well-known in management research. Finally, this study develops a framework summarizing the most common LPWAN technologies for various popular IoT use cases, in the following referred to as the framework for LPWAN application areas. For LPWAN adopters, end users, and other stakeholders alike, this study investigates essential decision criteria for technology selection beyond the often-compared technological features. It presents common applications of each dominating LPWAN technology. Regarding LPWAN research, this study further strengthens the claim that not only are technical features important for adoption decisions, but stakeholders and potential adopters carefully evaluate economic considerations, including coverage and payment schemes, as well as governance-related criteria such as the possibility to self-provision a network.

The development of the framework for LPWAN application areas shows there are common technology choices for specific IoT use chases and with that this study challenges the claim that one dominant technology wins over the entire LPWAN segment (Mumtaz et al., 2017). These observations may point towards a co-existence of different LPWAN technologies, eventually each dominating a specific application or sub-segment (Ayoub et al., 2019a). Understanding LPWAN adoption expands the understanding of IoT adoption, a megatrend for the upcoming years affecting many areas of daily life (International Bank for Reconstruction and Development / The World Bank, 2019).

The study has the following structure: the next section, I introduce the TOE framework as the theoretical background for technology adoption (3.2.1 and 3.2.2)and outline the research questions which will guide this empirical study(3.2.3). After that I present the method of this case study, including the research context (3.3.1 to 3.3.4). Thereafter I present the findings. First, I present the LPWAN characteristics valued by adopters organized by stakeholder type along the value chain (3.4.1) and in a separate section for end users (3.4.2). Based on these insights I develop the TOE framework for the LPWAN segment (3.4.3). In the fourth section of the findings (3.4.4), I present and explain the framework for LPWAN application areas. In Section 3.5 I discuss the results, their implications for future research, and I evaluate the strengths and limitations of this study. This chapter concludes with a summary of this study's contributions (3.6).

3.2 Theoretical background

3.2.1 Frameworks for institutional technology adoption: selection of the TOE framework

A range of adoption models has been proposed over the last few decades; for institutional adoption, two dominant ones emerged: the TOE by Tornatzky and Fleischer (1990) and the diffusion of innovations (DOI) framework by Rogers (1995) (Tu, 2018: 135). While the outcome the DOI seeks to explain is "Organizational Innovativeness," the TOE aims to identify and systematize the factors that lead to "Technological innovation decision-making" (Oliveira & Martins, 2011). The latter focusing on the adoption decision matches the research objectives of this study and hence is selected. In the following, I will briefly explain the TOE framework.

With their TOE framework Tornatzky and Fleischer (1990) aimed to map the "aspects of an enterprise's context that influence the process by which it adopts and implements a technological innovation" (Oliveira & Martins, 2011: 112). Tornatzky and Fleischer identified three categories that influence a firm's decision-making on technological innovations: Technology, Organization, and the External task environment (see Figure 2).

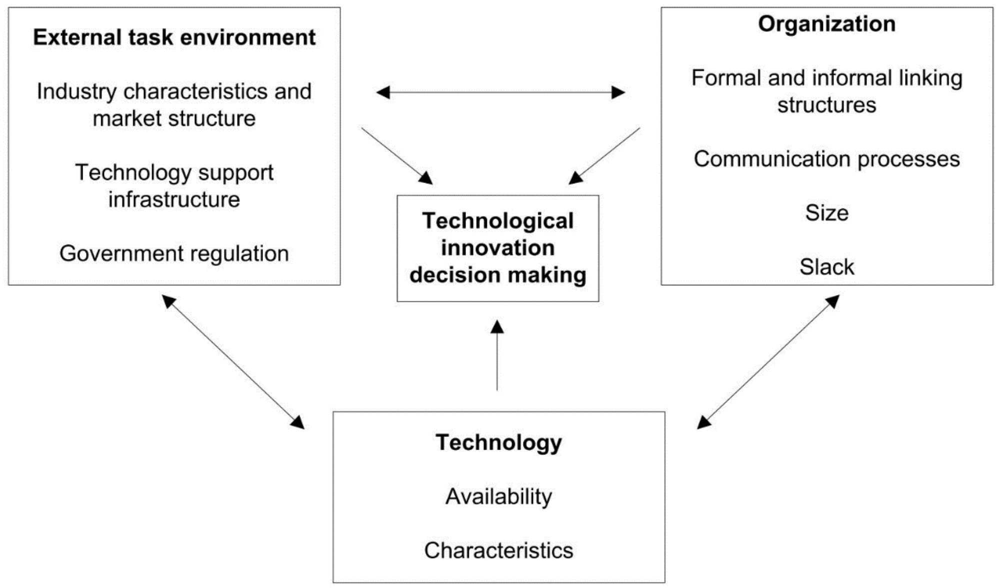

Figure 2 Technology, organization, and environment (TOE) framework (Tornatzky & Fleischer, 1990)

Technology or the technological context refers to existing and emerging technologies relevant to the firm. They may be either internal, i.e., currently being used by the firm, or externally available technologies, i.e., not (yet) adopted by the firm. All technologies‘ *availability* to the firm and other *characteristics*, such as ease of integration with the existing technologies and practices, are relevant for successful adoption. (Gibbs & Kraemer, 2004: 126; Wang et al., 2010: 804; Zhu et al., 2006: 1559–1560)

Organization – the organizational context – refers to firm characteristics such as centralization, formalization (*formal and informal linking structures*), *communication processes, slack* resources, and firm *size*. These categories are very similar to the "Internal characteristics of organizational structure" category in Roger's (1995) popular DOI framework. Indeed, researchers widely acknowledge these two models as consistent. (Wang et al., 2010:; Zhu et al., 2006)

External task environment, or often simply "Environment," is the third aspect of the model. It denominates the "arena in which an organization conducts its business" (Wang et al., 2010: 805). Hence it covers *government regulation* as a framing condition, *technology support infrastructure*, which might present an opportunity, and *industry characteristics and market structure*. With this, this category includes business constraints and opportunities. (Oliveira & Martins, 2011: 112; Wang et al., 2010: 805)

3.2.2 The TOE framework for LPWAN research

Several studies in the field of IT adoption have built their conceptual models upon the TOE framework, as Oliveira and Martins (2011) show. Researchers used it to model IT adoptions of open systems (e.g., Chau & Tam, 1997) over e-business topics (e.g., Zhu et al., 2006) to RFID adoption (e.g., Wang et al., 2010). In recent years, several studies on IoT adoption by organizations used the TOE framework, including Lin, Lee, and Lin (2016) and Tu (2018).

Most of these authors adjusted the original TOE as it was proposed by Tornatzky and Fleischer in 1990. Gibbs and Kraemer (2004) stay close to the original TOE; the most significant changes can be observed in the organizational context, where they exchange "formal and informal linking structures" and "communication processes" with "perceived benefits" and "organizational compatibility" for their study on e-commerce. Wang et al. (2010) stick with the three top-level aspects but then propose different determinants for each. For example, they assess the relative advantage, complexity, and compatibility for the technological context, which seems to be inspired by the DOI.

The TOE's versatile nature allows customization for different research environments. However, in the past, it has also led to the criticism that the framework would need to be more specific and abstract. This criticism implies that the specific determinants investigated in different studies most likely vary and are inconsistent. (Wang et al., 2010) This versatile nature is beneficial for the LPWAN study at hand: adoption in the LPWAN context still needs to be better understood. Hence, inviting novel decision criteria emerging from empirical research rather than imposing a fixed set of adoption criteria leaves room for exploration – a key objective of this research endeavor.

3.2.3 Resulting research questions

When customers purchase a product or firms want to join a market, they are constantly faced with the question: "Which technology will persist in this market?" But not only customers or final implementers, i.e., the technology users, must make this decision. It also affects other stakeholders along the value chain. They also wish to spend their money, time, and energy on the most promising technology instead of betting on the wrong one and being left with sunk costs shortly after.[13]

They key question for all stakeholders is: "Which LPWAN technology/technologies will win?" This question is highly relevant for practitioners as choosing the future dominating standard may determine a business's success. Choosing the dominating standard is especially crucial in the IoT context, where applications are very diverse, ICT standards are complex, and the number of participants is growing (Grindley, Sherry, & Teece, 2017: 41; Trappey et al., 2017: 221). "The IoT market is, therefore, not only a market with high expectations, but also a highly fragmented market, where developments in technologies and businesses take place in parallel in different industry-specific sub-markets developing industry- or application-specific standards" (Tadayoni et al., 2017: 3). Hence, it is not just the question which technology will win in a specific segment of ICT like the LPWAN segment, but there is also the possibility that several technologies may prevail. Each could become a dominant technology in a specific application segment, a niche technology. Or, even within these niches, several technologies could be in use because there are different small and local solutions. Betting on a technology that is eventually unsuccessful can be very costly for adopters, both for final users and other adopting stakeholders along the supply chain. Thus, it is vital to identify the most promising LPWAN technology in one's business environment as early on as possible. This holds for IoT adopters across industries and all stakeholders in the supply chain that have strong lock-in effects once they commit to a technology.

Acceptance of the LPWAN technology by the market is decisive as this makes it "the winning one." Hence, this study aims to answer the following questions:

(I) Which characteristics of an LPWAN technology do (potential) stakeholders along the value chain consider essential for their adoption decision?

(II) Which characteristics of an LPWAN technology do (potential) end users consider essential for their adoption decision?

[13] Stakeholders considered in this study are: Technology developers as the ones involved in developing and then commercializing LPWAN technologies; End device manufacturers as those manufacturing and developing end devices connecting via LPWANs, often they manufacture sensors; Network operators selecting ICT they build a network with and then offer connectivity for their clients; Software developers who provide exclusively software for LPWANs, often this includes a server component; Integrators who help end users set up their devices and the related IT, and lastly, End users who either use LPWAN connectivity themselves or include it into one of their own products they then commercialize as either B2B or B2C product.

(III) Can we observe different dominant LPWAN technologies in different market segments? If yes, how can the choice of a specific LPWAN technology be explained?

This study conducts a case study of LPWAN technologies to answer the outlined research questions. This approach is explained and discussed in the next section.

3.3 Method

3.3.1 Research context and qualitative study design

Studying IoT adoption in the specific research setting of LPWAN is promising for at least three reasons: first, LPWAN are an important segment in the IoT industry (Ibrahim, 2019: 234; Marini et al., 2022: 21051), yet they have not been broadly studied and may allow for novel insights (Ayoub et al., 2019a: 21). Secondly, the three major technologies are very diverse. Past work in the LPWAN segment has elaborated that in primarily technical comparisons (e.g., Ayoub et al., 2019b; Hossain & Markendahl, 2021; Marini et al., 2022; Mekki et al., 2018, 2019). As outlined in Chapter 2, LPWAN technologies also vastly differ regarding governance-related criteria, and this has not yet been well-researched. Third, considering that the three most popular LPWAN technologies were only available after 2016[14], this is a relatively novel and still developing area of high practical relevance. Yet, the market has already been existing for a few years and there was time for business relationships to form, and adoption trends to develop, which makes it interesting for research.

For these reasons, this study aims to contribute insights on the adoption criteria in a still developing and strongly growing IoT segment. While propositions may be inadequate for such an exploratory endeavor, a clear purpose is necessary to guide the research (Yin, 2009: 28). The research questions presented in 3.2.3 shall guide this exploratory research endeavor.

A case study is the appropriate empirical research method to "investigate a contemporary phenomenon (the 'case') in depth and within its real-world context" (Yin, 2009: 15). Schramm adds the notion that it should "illuminate a decision or set of decisions" (1971: abstract). The case studied here is the adoption decision by market participants along the value chain for one or more of the three leading LPWAN technology standards: LoRaWAN, Sigfox,

[14] 3GPP standardized NB-IoT as the last of these three LPWAN technologies in their release 13 in June 2016, as discussed by Mekki et al. (2018: 413).

and NB-IoT. The LPWAN segment as it represents an IoT subsegment in which different technology standards compete for market dominance and sometimes co-exist.

In exploratory research endeavors like mine, where one "may not know … the variables that need to be measured, and the theories that may guide the study [...], it is best to explore qualitatively to learn what questions, variables, theories, and so forth need to be studied" (Creswell & Plano Clark, 2011: 9). For this study, I explore a phenomenon, hence aim for the full development of information – an ambition where qualitative interviews can yield valuable insights (Weiss, 1994: 3). Interviews allow researchers to "learn about settings that would otherwise be closed to [them]" (Weiss, 1994: 1). Given the variety of stakeholders along the value chain that participate the LPWAN market, qualitative interviews are a powerful data collection method. They "give voice to people's lives and their perceptions [...] and allow the researcher to understand the way they see the world." (Arsel, 2017: 939)

For data analysis, I employ thematic analysis, a method building on "pattern recognition in the data" (Fereday & Muir-Cochrane, 2006: 82). Braun and Clarke (2006: 79) define thematic analysis as "a method for identifying, analysing [sic!] and reporting patterns (themes) within data". It is considered particularly useful "for examining the perspectives of different research participants, highlighting similarities and differences, and generating unanticipated insights" (Nowell et al., 2017: 2). As it is pretty flexible, it has been widely used (Braun & Clarke, 2006), however, it has not been widely appreciated or "poorly branded" as Nowell et al. (2017: 2) put it. Thematic analysis requires the researcher to combine openness and flexibility with a basic understanding of the domain to identify patterns in the data (Boyatzis, 1998: 7–8). As a researcher, I bring some previous knowledge of the LPWAN domain and of technology adoption models like the TOE framework to the table. At the same time, I consciously opted for semi-structured interviews to give me the flexibility to follow my interviewees and explore what is important to them. This required openness for interviewees' opinions and views, their vocabulary, and words – aligned with what Corbin and Strauss (1990) ask from grounded theory researchers. Yet, thematic analysis is more flexible than grounded theory and can be inductive and deductive (Nowell et al., 2017: 8). The present research starts exploratory, aiming for inductive insights. Later, it seeks to contextualize the findings with previously known structures, a rather deductive behavior. Scholars working with thematic analysis frequently employ this hybrid approach to capturing social phenomena (Fereday & Muir-Cochrane, 2006).

In the following section, I describe the data collection through semi-structured interviews. After that, I explain the thematic analysis research process as my means of data analysis in detail.

3.3.2 Data collection: sampling for and conducting semi-structured interviews

Depending on the degree of formality, three types of interviews can be distinguished: standardized, semi-standardized (or semi-structured), and unstandardized (Berg & Lune, 2017; Reeves, Peller, Goldman, & Kitto, 2013). Standardized interviews are primarily used in deductive research where a proposed claim shall be confirmed or refuted (Arsel, 2017: 940) and thus are unsuitable for this study. Unstructured interviews are frequently used in ethnographic research, where the researcher aims to engage with the research subject and immerse into its surroundings, often complementing the unstructured interview with participant observation (Reeves et al., 2013: 1369). This study aims for comparability of the interviews allowing the researcher to follow up on adjacent topics mentioned by each interviewee flexibly. Hence, the semi-structured interview is a well-suited data collection method. (Berg & Lune, 2017)

Prior to collecting data with interviews, the interviewees need to be sampled. This has to be done carefully for thematic analysis, as it tremendously influences the validity of the results (Boyatzis, 1998: 15) and constitutes the base for insightful qualitative research (Eisenhardt, 1989). Theoretical sampling assembles the most informative sample regarding the phenomenon being studied (Corbin & Strauss, 1990: 420). I will specify the population and sampling for my study in the next paragraph. Data collection can be concluded once theoretical saturation is achieved, so when “fresh data or new settings no longer produce new insights, your research circle is finally closed” (Silverman, 2014: 123).

Sampling. As this study explores the LPWAN market in depth and breadth, it aims for a diverse set of interviewees whom all represent stakeholders already engaged in the space. Diversity with regards to actor type (single user, company from the private sector, representative of a public sector entity), varied sizes of companies, a broad spectrum of applications, and a variety of national origins within Europe (e.g., Austria, France, Germany, Italy, Netherlands, Switzerland) is needed to reflect the whole variety of stakeholders. I limit the geographical scope to Europe as it establishes a common basis, especially regarding socioeconomic factors and settlement structure. The iterative approach used in this study allows me, as a researcher, to add new interviewees until theoretical saturation is achieved (Silverman, 2014: 123). This is also how I determined the number of interviewees for this study. When sampling the interviewees, I followed Eisenhardt's (1989: 537) proposed sampling strategy for theory-building studies: this study uses theoretical sampling, one form of purposeful sampling. In essence, "theoretical sampling aims to choose cases likely to replicate or extend the emergent theory" (ibid. 1989: 537). To satisfy the need for diverse interviewees, the extremes (e.g., large corporate vs. startups with less than five employees) were explored, which one could also see as a polar sampling strategy. Langley and Abdallah (2011: 111) support this approach, seeing the maximization of selected differences while maintaining other conditions stable as a way to ensure broad coverage of perspectives successfully.

I identified potential interviewees through desktop research: I started my search with organizations and individuals involved in LPWAN conferences or publications (newspapers, blogs, specialized magazines). Additionally, I identified members of the LoRa Alliance and Sigfox partners on their respective websites. If no personal contact was already, I searched for contacts on the organizations' website or via LinkedIn. Finally, I approached potential interviewees via LinkedIn private message or email with a short description of our project and an interview request. After the first interviews, some contacts were also established, thanks to other interviewees' referrals.

Interview process. When conducting the interviews, I follow Arsel (2017): first, I commit myself to an epistemological tradition, and then I prepare an interview guideline. In the third step, I conduct the interview and then finally analyze it, and if new questions emerge, I adjust the interview guideline. This research follows an existential-phenomenology world view which, in essence, "is a *contextualist* view in which experience is seen as a pattern that emerges from a context" (Thompson, Locander, & Pollio, 1989: 137). I use qualitative methods to gather data on this experience from people immersed in the context (Creswell & Plano Clark, 2011: 87). I collect subjective narratives through semi-structured interviews in sessions scheduled explicitly for this purpose. An interview guideline allows me to prepare and prioritize topics addressed in the interview. It helps to maintain the focus on the research question while having a natural-like conversation in which adjacent issues can be explored (Arsel, 2017: 942). I iteratively refined the interview guideline and adjusted it for each interviewee, as suggested by Berg and Lune (2017: 69). The interview execution took place as the third step. In the following, the interview guide was iteratively refined. To allow for these iterations, Arsel (2017: 940) recommends spreading the interviews across a few months, which I did for this study.

Interview guide. The interview guide was regularly updated and refined, and adjusted to each interviewee's specific position, e.g., companies manufacturing LoRaWAN devices were instead asked about licensing aspects. In contrast, The Things Network (TTN) participants were asked how they first heard about the TTN. The interview guide followed common best practices such as a personal introduction of the interviewer, a short outline of the topic and purpose of the interview in non-scientific language, and asking for the interviewee's consent to the recording (Arsel, 2017: 941). I usually started interviews with a warm-up question[15] as recommended by Arsel (2017: 942), and I asked interviewees to introduce themselves and describe how they first got in contact with LPWAN technologies. Figure 3 is an example of an interview guide targeting an LPWAN equipment manufacturing firm.

[15] Despite being frequently labeled as a warm-up question, this question was by no means of minor importance. The contrary is the case: it often revealed much about the interviewees' opinion about LPWAN, their experience with the technology, and their assessment of its future potential.

Interview guide
Version for companies in the IoT

1 Personal introduction & interview formalities

2 Personal introduction and company

- Start: So of course I read a bit about you and your LPWAN product (INSERT) online, however, could you briefly outline for me when and how you came across LPWANs for the first time and how it became part of your product offering?
- Are you part of any industry/startup organizations (e.g., LoRa Alliance)? And if Yes,how do you engage with this community/other actors?

3 Product and LPWAN technology

- Could you please briefly describe your product range and what makes it/them an IoT device? Which LPWAN do you use for it?
- Did you consider an alternative LPWAN? If yes, why?
- How would you describe your main customers? Is this hobbyists or professionals?
- Did you ever look into technology ownership/standardization?
    - LoRaWAN: LoRa Alliance – relationship with it? Perception?
    - Sigfox
    - NB-IoT: contact to 3GPP?
- Are you in exchange with other actors in the community of your technology? Whom/why?

4 Knowledge capture & exchange

- How did you initially approach your technology?
- Where do you get support on challenging questions and solving technological issues? (associations, hobbyists, the seller,…)
- How did you find knowledgeable people regarding the technology to further grow your business?
- [If using one technology only] Are you still scanning the technology landscape for alternative technologies?
- [If using several technologies] Why are you using several technologies? Do you think in five years from now you still offer all of them? New ones?

5 Licensing landscape

- Which role did IP and licensing conditions play in your technology decision?
- Do you by any means ensure your sourced modules have a full SEP license? (fully licensed from supplier, separate deals, licensing pool)

Figure 3 Questionnaire for semi-structured interviews – an example of the questionnaire for end device manufacturers using LPWAN technology

Data collection. I conducted 29 interviews with 30 individuals between March and September 2021. The sample was diversified concerning previously mentioned characteristics, as seen in Table 3. Interviews were numbered in line with the leading technologies the actor is associated with. L stands for LoRaWAN, N for NB-IoT, S for Sigfox, and M denotes actors manufacturing, distributing, or using several of those. The interviews‘ duration ranged from 00:18 hrs to 1:08 hrs with a median of 00:49 hrs, resulting in a total of 22:49 hrs. I conducted most interviews in German (22, equivalent to 17:11 hrs), all others in English. I used Zoom software for the conversation and parallel recording. Only interviewee N03 preferred to be interviewed via phone, which I then recorded on another device.

Table 3 Overview of interviews conducted

Interview	Technology			Value chain position	Role	Language	Duration	Month
ID	LoRa-WAN	NB-IoT	Sigfox			German (GER) & English (ENG)	hh:mm	M/YYYY
L01	X			End device manufacturer	Founder & CEO	GER	0:57	3/2021
L02	X			Community	Founder of a local TTN group	GER	0:49	4/2021
L03	X			Network operator	Department leader in a district's administration	GER	0:45	4/2021
L04	X			End user	Manager for IoT; Innovation manager	GER	0:42	4/2021
L05	X			Integrator	Senior Product Manager & Technical Consultant	GER	0:54	4/2021
L06	X			End user	City staff position – Project Leader Smart City	GER	0:39	4/2021
L07	X			Technology developer	Senior Director of Business Development	ENG	0:54	5/2021
L08	X			Integrator, network operator	Chief Technical Officer	GER	1:04	5/2021
L09	X			Software developer	Self-employed	ENG	0:58	5/2021
L10	X			Network operator	Chief Executive Officer	GER	1:04	5/2021
L11	X			Integrator	Chief Technical Officer	GER	0:34	5/2021
L12	X			Integrator	Chief Executive Officer	GER	0:51	6/2021
L13	X			End user	Senior Systems Engineer	GER	1:08	6/2021
L14	X			End user	Chief Digital Officer	GER	0:57	7/2021
L15	X			End user	Project Leader	GER	0:53	7/2021
L16	X			End user	Enterprise Architect for Logistics and IoT strategy.	GER	0:57	8/2021
M01	X	X		End device manufacturer	Co-Founder & Chief Technical Officer	GER	0:38	4/2021
M02	X	X		End device manufacturer	Head of Business Unit	ENG	0:52	5/2021
M03	X	X		End device manufacturer	Project Manager & Senior Hardware Engineer	ENG	0:45	5/2021
M05	X	X		Network operator	Commercial Product Manager IoT	ENG	0:47	7/2021
M06	X	X		Network operator	Head of Product Management in IoT	GER	0:40	7/2021
M07	X		X	End device manufacturer	IoT EMEA Manager	ENG	0:34	9/2021
N01		X		Adopter	Head of IT Engineering	GER	0:18	5/2021
N02		X		Network operator	Chief Innovation Architect	GER	0:28	6/2021
N03		X		End user	Department Head Trends & Technology Research	GER	0:41	7/2021
N04		X		End unser	Founder & CEO	GER	0:42	7/2021
S01			X	Network operator	Head of M&A and Strategic Development	GER	0:51	8/2021
S02			X	End user	Head of Strategic Procurement and Logistics	GER	0:38	8/2021
S03			X	Techn. developer	Co-founder & CEO	ENG	0:58	9/2021
Sum	16	9	4			GER: 22 ENG: 7	22:49	

Electronic recording of interviews and their transcription are frequently mentioned measures to establish validity and reliability in an interview study and thematic analysis approaches (Braun & Clarke, 2006: 87; Creswell, 2016; Fereday & Muir-Cochrane, 2006; Langley & Abdallah, 2011). For this case study, all interviewees consented to be recorded, and I produced verbatim transcriptions of all interviews from these records.

3.3.3 Data analysis: thematic analysis

Describing data analysis methods in detail is an integral part of achieving credibility in thematic analyses (Nowell et al., 2017), and hence this section addresses the execution of the thematic analysis in detail. I follow a process that allows me to balance data-driven, inductive insights with the theory-driven, deductive perspective. Figure 4 shows an adapted visualization of the thematic analysis approach based on Braun and Clarke (2006) and Fereday and Muir-Cochrane (2006).

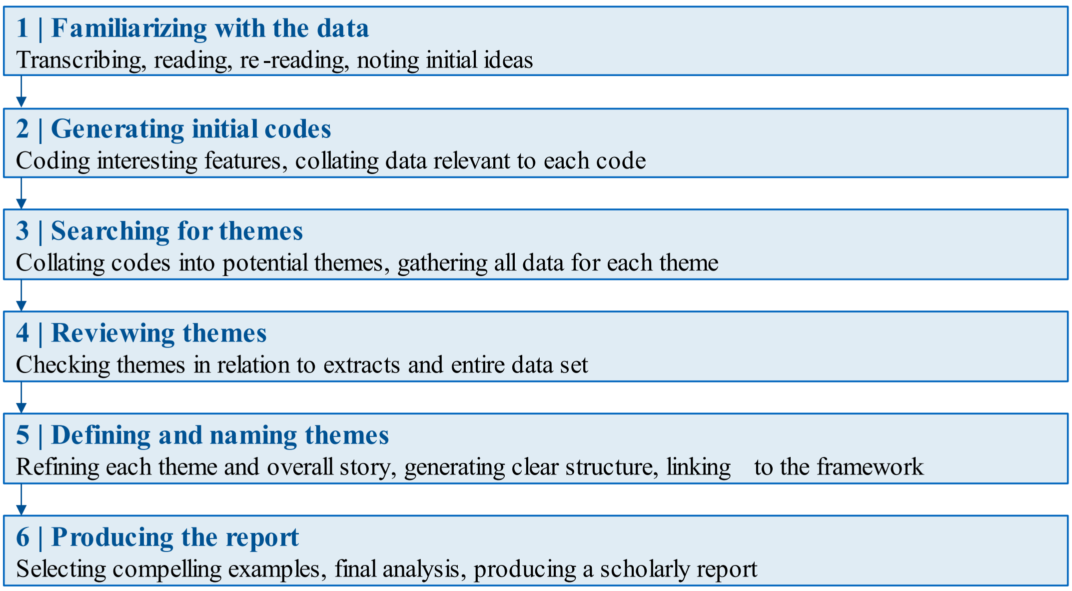

Figure 4 Thematic analysis approach (own visualization based on Braun and Clarke, 2006; Fereday and Muir-Cochrane, 2006)

In the first step, I used the MaxQDA software tool to produce verbatim transcribed interviews within few days after recording them. I opted for manual transcription to reduce potential errors generated by natural language processing algorithms. Furthermore, manual transcription allowed me to listen and read each of the interviews several times and, with this familiarize myself with the interviewees' positions, which is part of any thorough thematic analysis (Braun & Clarke, 2006: 87). The resulting verbatim transcripts are the database for the next steps of the data analysis. Additionally, I noted down crucial observations I made during this process to serve as an inspiration for later processes.

Next, I coded the data. Coding denotes "the operations by which data are broken down, conceptualized, and put back together in new ways" (Flick, 2009: 307), hence the analytical part of this study. In this first coding round, I took an interviewee-centric approach, primarily using the interviewees' wording and expression. This allowed me to deeply immerse into the interviewees' view of the world rather than immediately labeling everything in my researcher-centric vocabulary. Hereby I aimed to avoid overlooking unexpected yet very important comments from the interviewees. This 1st level of coding in informant-centric terms is commonly used in inductive research coding (Gioia, Corley, & Hamilton, 2013: 20). I focused on capturing anything that was apparently very important to the interviewee, maybe surprising me or related to the guiding questions. In total, I coded 686 text snippets or sections in this step.

The third step comprises the organization of the codes into themes. Hence it is an essential step in thematic analysis which requires researchers to exert pattern recognition (Boyatzis, 1998: 7–8). It cannot strictly be separated from the previous step, as it is highly dependent on the data, and hence both steps were executed iteratively.

In the fourth step, I reviewed the themes that had emerged previously. This involved the removal of repetitions, clear differentiation between similar themes, and – if required – rephrasing of the themes. Resolving these inconsistencies and unclarity strengthens the thematic analysis and makes it convincing (Braun & Clarke, 2006: 94). Figure 5 shows an excerpt from the code organization in MaxQDA.

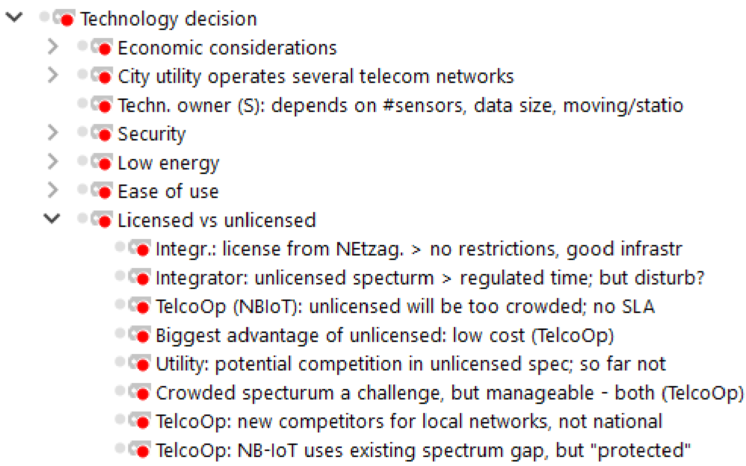

Figure 5 Third step of thematic coding process: organization of codes into themes – an excerpt from the analysis executed in MaxQDA

Next, I further organized the themes into groups with the theoretical background and the guiding questions for this research in mind. The overarching categories are also labeled in more researcher-centric, theory-informed, or one could say deductive terms (Fereday & Muir-Cochrane, 2006: 91). Similar to what Gioia et al. (2013) label as “2nd level coding” or “axial coding” in grounded theory (Corbin & Strauss, 1990), this step aims to describe and explain the phenomenon contextualized and embedded in existing literature and knowledge.

Step 6 is fulfilled as I present my results in Chapter 4. Sections 3.4.1 and 3.4.2 answer the first two research questions in an inductive way, compiling observations and key quotes from the interviews. Based on the theory-informed perspective executed in the fifth step, I present the resulting adapted TOE framework for LPWAN technology adoptions in section 3.4.3. I address the third research question on LPWAN technology dominance in specific application areas in section 3.4.4.

Validity and reliability. With this transparent separation, I aim to contribute to methodic rigor in thematic analysis application (Nowell et al., 2017: 8). Regarding validity, I achieve internal validity, in this case, study through iterative and rigorous coding of the interviews, which allows to identify patterns and build explanations (Yin, 2009: 44–45). This study addresses concerns regarding reliability by “make[ing] as many procedures as explicit as possible and … conduct[ing] research as if someone were looking over your shoulder” (Yin, 2009: 46). I aimed to do so by giving transparency on data collection processes and data analysis through thematic coding presented in this section.

3.3.4 Ethical considerations and limitations

Ethical considerations, biases, and limitations can occur on the level of data collection and analysis, but especially bias and limitations may also be inherent to the choice of the method. I address these concerns in the following, starting with data collection through interviews, then turning towards the limitations of thematic analysis, and then zooming out to address the implications of studying a single case.

Ethical considerations in using interviews. Interviews as a data collection method bear the risk of revealing identities, deception on the interviewees‘ side, and exploitation in case of research on marginalized groups (Silverman, 2014: 141–161). All interviewees participated voluntarily in our study and were not promised any reward. At the end of the interview, I offered them to receive a notification in case of a successful publication using their interview and sending them the entire paper once finished. Interviewees were also granted anonymity, first stated in the invitation email but then also repeated at the beginning of the interview. The purpose was to establish a secure environment for the interviewees and allow them to also voice criticism of business-related concerns and strategies without fearing consequences for them personally or their respective organizations. To manage expectations, the invite email also contained a timeframe (suggested 45 minutes) and a short description of the research interest. That way, deceptions on the interviewees' side should be reduced as far as possible. In the cases where the interviews took longer than the suggested 45min, this was aligned with the interviewee. Of course, during an interview, power differences can be a severe concern (Arsel, 2017: 944). However, this research does not target marginalized groups. Thus, I evaluated this risk to be low. Nevertheless, I addressed it in the interviews: I framed the interview as a learning opportunity for me as the researcher, and if interviewees voiced a concern like: "I am not sure if this is fully right, maybe it is not.", I, as a researcher emphasized my interest in the interviewee's personal view.

Research bias in interviews. As a means for clarification on the potential bias, Creswell (2016: 208) encourages researchers to provide details on their past experiences, prejudices, and orientations to clarify the researcher's position, which I wish to comply with in the following: Before this study, I was not aware of the existence of LoRaWAN networks. Initially, I read a few newspaper articles or blog entries on the web, but then started the interviews, very much from a position of a curious person aiming to learn from experts, the interviewees. Initially, I sought to dig deeper into technology licensing. Still, I soon discovered that it was puzzling that different interviewees often preferred one LPWAN technology, even though the LPWAN technologies seemed very similar technologically. This raised questions about the requirements of the users, technology availability, technology selection, and implementation, which then became the focus of the interviews. Beyond transparency on potential biases, the selected thematic analysis approach also contributes to generalizability through repeated abstraction in the coding process, and the continuous comparison between different pieces of data supports abstraction from the individual researcher (Braun & Clarke, 2006; Corbin & Strauss, 1990).

Limitations in interviews. Some candidates were unavailable for interviews during interviewee recruitment or had limited time. This particularly applies to some large German logistics companies and telco operators. Hence, the picture may not be as rich as ideally imagined. However, alternatives could be identified during the data collection, limiting the effect of this unfortunate circumstance. Regarding data analysis, one must remember that this study, as part of a dissertation, is an individual researcher's work. The additional engagement of a second or even third coder could establish further generalizability during the coding process. Hence different coders might be added in the future. Findings of this study could be further strengthened by another independent data collection and analysis of another researcher, a proceeding recommended by Eisenhardt (1989).

Limitations of thematic coding. Thematic coding relies on the researcher's capability to identify patterns and themes related to the research question(s) and the phenomenon of interest. Thus, inherently, this approach has a subjective notion (Braun & Clarke, 2006: 80; Nowell et al., 2017: 8). Making the research process transparent, as done in the previous section, is one way to deal with this subjective nature and make the data processing transparent. A further method that could be deployed in the future is intercoder analyses. For those, several researchers code the same data set independently, and if they achieve consistent results, they can strengthen the robustness of the results, even claiming objectivity.

Limitations of the single case study. Strengths of case studies lie in their detailed description, in-depth understanding, and powerful explanations for "hows" and "whys" (Yin, 2009: 4). And indeed, the "thick description" associated with using the thematic analysis approach contributes to this perception and also increases transferability of the findings of this single case study (Braun & Clarke, 2006: 97; Creswell, 2016: 209). However, The novelty of case studies' theoretical contributions is frequently criticized (Langley & Abdallah, 2011: 116). This exploratory case study does not aim to establish an entirely novel theory; it seeks to characterize and explore a phenomenon in a different light. Specifically, the case study aims to move from technical comparisons of LPWAN technologies to understanding adoption processes in this market segment. Of course, generalizability is a discussion point in case study research: while a single case study cannot be used to establish statistical generalizability, it is a powerful tool for exploring dynamics and adoption patterns that also matter for other IoT segments (Yin, 2009: 44–45).

3.4 Results of the empirical study

3.4.1 LPWAN technologies' characteristics valued by (potential) stakeholders

The first research question investigates which characteristics of an LPWAN technology (potential) allies value and why they ultimately decide to join one technology's ecosystem. Potential or actual end users as adopters are not included in the analysis in this section but will be dealt with separately in the next section. The results presented in this chapter are views by different stakeholders along the value chain: network operators, device manufacturers, integrators, and software developers. I present the results grouped by stakeholder type, including illustrative quotes from the interviews, preserving an informant-centric perspective.

The interviewed **network operators** fall into two groups: one focusing on NB-IoT only and the other deploying NB-IoT and LoRaWAN side by side. While the first group sticks to its cellular business model with the well-established standard-developing organization (SDO) 3GPP, the second group believes in a possible co-existence of NB-IoT and LoRaWAN. The first group of NB-IoT-only operating network providers argues that the unlicensed band and the IPR ownership by Semtech are risks (L10, N11). An operator using LoRaWAN (L10) and another market participant (M02) interpret this behavior differently: they state that operators preferred to stick to their known business model, relying on past infrastructure and license investments.

> *"And the problem is this fragmentation: if I offer seven options to a customer, then she waits and doesn't do anything, and so on. Hence, it is imperative to keep it together,*

> *otherwise, the customers are completely lost, and don't do anything and run 70 strategic analyses and don't make up their minds."*[16] *(N02)*

> *"And in Germany, unlike in other countries [...], none among the cellular network providers decided to do it [i.e., the rollout of a national LoRaWAN], because right from the beginning they all bet on Narrowband-IoT and consider LoRaWAN rather a competition."*[17] *(L11)*

The second group of network operators who offer LoRaWAN and NB-IoT to their customers does so because they perceive small local LoRaWAN operators as competition (M05, M06) or think the LoRaWAN end devices would be much cheaper than NB-IoT ones (M05). They even see LoRaWAN as a chance to break up traditional telecommunication businesses and wish to explore the space (M05), making it less of a cost or technological but rather a strategic question (L10). Lastly, timing mattered: for example, M06 decided to implement a national LoRaWAN even before NB-IoT was available.

> *"I personally believe that LoRa is really here to stay. You are talking to an operator, and operator adoption will evolve so that some operators will adopt. Still, considering the tracking market, there will be more LoRa networks, maybe in Europe. But as it is an unlicensed spectrum, you also see adoption from other operators, and also not operators, but other players than traditional telco players." (M05)*

> *"But the marketing value of stepping outside the borders of the traditional telco business is a very strong value for us, and it also helped us develop new kinds of solutions (...). There are different ways you can look at innovation: (...) You go on a road where you won't for sure see what is happening, and it will evolve somehow someway, and this is also one of the – I wouldn't know if it's one of the reasons why we invested – but looking in hindsight, it's one of the things we truly value [about investing into a national LoRaWAN]." (M05)*

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[16] Translation of the German statement: „Und das Problem ist ja die Fragmentierung: wenn ich einem Kunden sieben Optionen gebe, dann wartet er ja und macht nichts – und so weiter. Also es ist ganz wichtig das zusammenzuhalten, sonst sind die Kunden komplett verwirrt, machen nichts, und machen 70 strategische Analysen und kommen nicht zu Potte."

[17] Translation of the German statement: „Und in Deutschland haben sich halt unter den Mobilfunkprovider nicht wie das in anderen Ländern [...] hat sich keiner gefunden, der das machen wollte, weil die alle von vornerein auf Narrowband-IoT setzen wollten und das eher als Konkurrenz wahrnehmen, das LoRaWAN."

Sigfox, as exclusively deployed by the Sigfox company in the beginning, was not an option for network operators and hence did not spark interest among them (L10).

For **device manufacturers,** standardization is crucial, as it allows them to develop their products accordingly. As research and development are costly and take time, device manufacturers carefully decide which technology to adopt or, if possible and reasonable from a cost perspective, make their devices compatible with multiple technologies. Some consider the fuzziness of the LoRaWAN ecosystem a challenge and appreciate the more centralized Sigfox partner network (M07). On the other hand, the openness of the LoRaWAN ecosystem also comes with benefits:

> *"I was not here when the decision was made, but I know that the problem was that … Sigfox is closed." (M03)*

> *"Sometimes this happens: 'Oh, we have to hire this guy because he made a lot of great stuff with our boards that we never thought about!' And this is the open-source approach, right? So, you provide a product with a set of features that is open, and then… you give the technology, you give the knowledge, and then it's on the user side to improve, to adapt, and again, to find bugs. On the other side, if you provide the closed black box, you can do only one, two, and three. That's it." (M02)*

Those who engage in LoRaWAN device manufacturing see the LoRa Alliance as a certification body for their devices. They are less interested in any other way of interacting with the alliance and its members (M01, M03, M07). The certification facilitates market access (M02), and manufacturers appreciate the marketing the LoRa Alliance does for the technology itself (M01) and indirectly also for the devices of its manufacturers (M02).

> *"The main reason for us to join the LoRa Alliance is that we are allowed to label our products LoRaWAN and that we can also use the logo on our webpage, otherwise no one would find us."[18] (M01)*

[18] Translation of the German statement: „Der Hauptgrund für uns in die LoRa Alliance zu gehen ist, dass wir unsere Produkte LoRaWan nennen dürfen und dass wir das Logo auch auf der Homepage verwenden dürfen, denn sonst findet einen ja auch keiner."

"If you want to play it seriously, you probably have to [...] be part of the LoRa Alliance. This is mainly for our users to have a product that is known in the market – we are not the, you know, an unknown manufacturer." (M02)

"And we have most of the sensors LoRa Alliance-certified because it is a key point for the big customers to have the sensor LoRa-Alliance-compliant. Sometimes, if the sensors are not certified, you cannot sell them. In some cases, it is more important the LoRa-Alliance-certification than to have the CE-certification." (M03)

"So, I attend to the payload committee, to the regional committee; but for the deep LoRa protocol committees, I'm not interested because (...) we are focused on the sensor itself. LoRaWAN is the protocol. We don't provide the network server; we don't provide the application; we are quite agnostic." (M07)

The TTN community, as part of the LoRaWAN ecosystem, also is seen as beneficial. An ally in the promotion of the LoRaWAN technology by several actors: for example, test their devices with some of the TTN members (M03), consider the TTN as crucial for LoRaWAN infrastructure (M02), and appreciate the knowledge resources of the community (M01). Regarding NB-IoT, equipment manufacturers partially criticize that roaming was unclear for a long time and that Europe is a patchwork rug of NB-IoT and LTE-M rollout (M02).

Software developers and integrators who help customers to combine end devices with a suitable server and data platform are mostly standard agnostic. They focus on delivering maximum value to their customers and often develop partnerships across the value chain. They profit mainly from the integration as a service they charge for and hence mostly do not favor a specific type of connectivity but try to satisfy their customers' needs. Their business models and service depth vary: from consulting and connecting customers' sensor data to their data platform (L05) to renting out whole systems, including connectivity, software, and sensors (L08).

"Alright, currently, with the [project name] project, we are connecting NB-IoT data to our platform, too, and accordingly, we are open. We started from the LoRa corner,

but if we now realize that more and more customers also want to realize things with NB-IoT, we will advertise that actively."[19] *(L05)*

The depth of the service provided by the software developers and integrators strongly influences their flexibility to switch between different LPWAN technologies. As stated above, L05, which offers a software product, has low switching costs. Customized products, like the LoRaWAN software by L09, are less adaptable. Hence, the *"offering portfolio,"* including the service depth, strongly affects the adoption decision of these stakeholders and, as such, is part of the revised TOE framework.

3.4.2 LPWAN technologies' characteristics valued by (potential) end users

To answer the second research question, "Which characteristics of a standard do (potential) end users value?" I first look at the composition of this adopter group, then turn towards their starting position and how technology selection processes work for end users before discussing the decision criteria mentioned by adopting end users across industries.

The group of **end users** is a heterogeneous group with differing preferences. Large customers reported co-development with their network operators or the technology owners across technologies (L16, N03, S02), sometimes even in a symbiosis setup where they, in exchange, give the network operators access to locations for gateways or base stations (S02):

"We now have a good knowledge base, which we acquired both as an R&D department, but also in collaboration with different technology providers, for example with [name of the national NB-IoT operator]."[20] *(N03)*

[19] Translation of the German statement: „Ja, also wir sind gerade in dem [Projektname]-Projekt dabei auch, auch NB-IoT Daten auf unserer Plattform anzubinden, und wir sind dementsprechend offen. Wir kommen halt aus der LoRa-Ecke und sind damit gestartet, wenn wir jetzt aber natürlich merken, dass mehr und mehr Kunden auch Dinge mit Narrowband umsetzen wollen, dann werden wir das dann auch aktiv bewerben."

[20] Translation of the German statement: „So haben wir jetzt eine ganz gute Wissensbasis, die wir uns zum einen als R&D Abteilung aufgebaut haben und zum anderen auch in Zusammenarbeit mit verschiedenen Technologieanbietern wie beispielsweise [Name des national NB-IoT Anbieters]."

> *"But we also support Sigfox itself by providing buildings. We have many buildings in [country name] […] which we offer them so that they can put up their gateways there."*[21] *(S02)*

Most end users start technology-agnostic, and their search for technology is triggered by a specific use case (e.g., M07, S02). Only some end users were first excited about a technology, namely LoRaWAN, and then were actively looking for a use case to justify the investment into the technology (L04, L16).

> *"[People] do not care about [the] technology they are using because Sigfox and LoRaWAN at the time, they do similar stuff. It's more about understanding what they want to do, what network availability they do have in the area they want to apply, and work with IoT and then suggest them the best solution possible." (M07)*

When selecting a suitable LPWAN, adopters considered factors such as low power use of end devices (e.g., N03), the use of licensed or unlicensed spectrum (e.g., L15), the availability of end devices and equipment (e.g., L13, L15), and IT security (e.g., L15, N04). Service-level agreements are essential for some end users, like N01 and N04. In addition, the perceived ease of use is mentioned by L03 and L15. Openness is a regularly mentioned concept, covering several dimensions: an open network without charges per message (e.g., L06), the possibility for a network user to set up their own network (e.g., L15), and an open versus a proprietary standard (e.g., L16, M03). The most frequently mentioned criteria are economic considerations and coverage, which I present in detail in the following paragraphs.

Economic considerations. Interviewees across industries (e.g., L10, N01, N03) stress the importance of economic considerations for their technology selection. "*Today, all IoT [use] cases are cost-cutting [use] cases. So, they are all somehow… they always need to optimize something"*[22], as interviewee L10 explained. The payment schemes associated with the different LPWAN technologies vary significantly, with NB-IoT being closest to what is known from cellular technologies such as LTE and 5G. Sigfox is using a subscription model for connectivity and LoRaWAN allows for a range of setups, either via its own network or

[21] Translation of the German statement: „Aber wir unterstützen Sigfox auf der einen Seite selbst durch die Bereitstellung von Gebäuden. Wir haben ja in [Ländername] sehr viele Gebäude […], die wir ihnen zur Verfügung stellen, sodass sie dort ihre Sender aufbauen können."

[22] Translation of the German statement: „IoT Cases sind heute alle cost-cutting Cases. Also sind irgendwie... sie müssen immer irgendwas optimieren."

leveraging an operator's network in a setting like cellular technologies. The focus within the economic criteria largely depends on the adopter's situation: the Chief Digital Officer of a large city prefers a one-off investment into its own LoRaWAN, even for testing purposes. He explains that it is much easier to get approval for this investment from the city council once than having to ask for money repeatedly in case of annual operating costs (L14). For use cases with a few sensors only, customers prefer to use an existing network and pay recurringly for each sensor deployed (e.g., S02). Flexibility, including sign-on and sign-off of sensors, and handling of exceptions like a spamming sensor, is a prerequisite also mentioned by interviewee S02. In the end, the total cost of connectivity, either by a provider network or the own, plus the price for the end device, including battery changes, determines how attractive and feasible a use case financially can be. Right now, this is still a challenge because the technologies are novel, and costs are still evolving, as interviewee L15 points out:

> *"Well, the exciting challenge with operating LoRa[WAN] is, as with any other novel technology, i.e., now calculating as exactly as possible: 'How much does it cost us?' it's sometimes a bit difficult."*[23] (L15)

Regarding **geographic coverage (and roaming),** one must differentiate between stationary and moving use cases. Stationary use cases include cities but also airports *("we see our airport area like a city,"* N01) and fixed nodes in infrastructure networks, such as train stations, post offices, or mailboxes. While dead spots in externally provided networks can be an obstacle to adoption, stationary applications, in many cases, use the installation of their own LoRaWAN – what we call self-provisioning in the following – and as a result of this leverage, one of LoRaWANs significant advantages:

> *"If there is a dead spot, the mailbox at the wall in your house remains in the dead spot. That means it [i.e., a stationary application] makes sense only after a certain level of maturity of the [Sigfox] network is achieved. Then we will also look into those more closely."*[24] *(S02)*

[23] Translation of the German statement: „Also ja, die spannende Herausforderung im Betrieb von LoRa ist wie bei jeder neuen Technologie, d.h. jetzt möglichst zu kalkulieren was kostet es uns, ist manchmal ein bisschen schwierig."

[24] Translation of the German statement: „Der Briefkasten, der an der Wand bei Ihnen im Haus hängt, bleibt in dem Loch mehr beschäftigen."

> *"I can guarantee to everyone, if you have a demand for LoRa[WAN] anywhere, you will get LoRaWAN connectivity from me within two weeks, even if there is none [today]."*[25] *(L10)*

> *"So, there is one financial benefit [to LoRaWAN] and also the fact that you can install and enter a good connectivity of your sensor because you install the gateway where you want inside your area." (M07)*

National or even international coverage is crucial for moving applications like containers or vehicles (asset tracking). This characteristic may even largely drive the technology selection: *"My impression is somewhat that, of course, in the end, Sigfox has been selected because there is no comparable covering LoRa network in Germany or Austria"*[26] (L16). When assets and items move across borders, roaming becomes essential. Initially, roaming has been an advantage of the centralized Sigfox network (M07), but it is now becoming more widely available to users of all three LPWAN technologies (M06). For LoRaWAN, agreements between telecommunication providers have been made to allow for roaming, supported by joint efforts within the LoRa Alliance. And NB-IoT could also build on existing business relationships in other technologies, such as 3G, among their providers and quickly establish international connectivity through roaming agreements. However, the conclusion concerning roaming broadly differs among customers:

> *"With LoRaWAN, we lacked the roaming capability. It was important to us that, especially with the large telecommunication operators, we would have partners worldwide that do not only roll out the topic broadly but also take care that I can drive across borders without interruption. Just now, I read an announcement from [name of their network operator] that 99% of Germany is covered with NB-IoT by now. That is even more than one can say about cellular communication today."*[27] *(N04)*

[25] Translation of the German statement: „Aber ich kann jedem garantieren, wenn du irgendwo LoRa[WAN]-Bedarf hast, innerhalb von 2 Wochen ist da LoRa-Netz von mir, auch wenn da keines da ist."

[26] Translation of the German statement: "Mein Eindruck ist ein bisschen, dass es natürlich auch am Ende dann Sigfox geworden ist, weil es kein vergleichbar abdeckendes LoRa Netz in Deutschland und Österreich gibt."

[27] Translation of the German statement: „Bei LoRaWAN hat uns die Roaming-Fähigkeit gefehlt. Da war es uns wichtig, dass wir gerade mit den großen Mobilfunkanbietern weltweit Partner haben, die das Thema nicht nur flächig ausrollen, sondern auch dafür sorgen, dass ich über Landesgrenzen hinaus ohne Unterbrechung fahren kann. Jetzt gerade habe ich eine Information von [Name des Telekommunikationsunternehmens] gelesen, dass

"These… are the first rudimentary insights which we created [with our Sigfox use case], and where insofar Sigfox also helps and comes with a huge advantage, because in the end, it is a European network."[28] *(S02)*

And statements by telecommunication operators bring in even one more view, where also LoRaWAN now has some roaming capabilities.

"NB-IoT versus LoRaWAN roaming: well, there are still some hurdles with regards to NB-IoT roaming. Of course, we already have some collaborations, but currently, I do not see the big advantage compared to LoRaWAN. In the end, the question always is: 'In which country does the use case have to work?' and 'Do we have an agreement in place there for one or the other technology?'"[29] *(M06)*

Recalling that a customer's size often determines their negotiation power towards telecommunication network operators, the size of the customers also influences their options to affect coverage. Large customers can ask for additional coverage where needed; small ones will have to deal with the coverage offered by a network provider or must set up their own network with LoRaWAN. LoRaWAN is the only technology that gives them this opportunity to self-provision an LPWAN.

Looking at the smart city segment, cities, and utilities frequently choose LoRaWAN as their LPWAN technology. Mainly utilities use their existing knowledge-sharing structures and meetings to exchange their know-how (L11, L13) or collaborate with local education institutions (L13, L14). Utilities usually do not compete with one another because they are in a monopole-like situation in their city. Cities are financed by tax money, which might lead to an increased aspiration to provide a free-of-charge and open network to their citizens (L05), which can be achieved by either setting up their own LoRaWAN or joining the TTN and expanding its coverage.

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mittlerweile 99% von Deutschland mit Narrowband abgedeckt sind. Das ist sogar etwas mehr als man das heute vom Mobilfunk sagen kann."

[28] Translation of the German statement: „Das heißt das sind schon mal die ersten rudimentären Erkenntnisse, die wir gemacht haben und wo Sigfox auch insofern hilft und einen großen Vorteil bringt weil es ja im Endeffekt ein europäisches Netz ist."

[29] Translation of the German statement: „NB-IoT Roaming versus LoRaWAN Roaming, ja, NB-IoT hat aktuell auch noch einige Hürden zu nehmen bezüglich dem Roaming. Wir haben natürlich schon gewisse Zusammenschlüsse, aber ich sehe jetzt da noch nicht den großen Vorteil gegenüber LoRaWAN. Die Frage ist dann natürlich schlussendlich dann immer: in welchem Land muss der use case funktionieren? Und haben wir da ein Agreement auf der einen oder anderen Technologie."

3.4.3 A TOE technology adoption framework for the LPWAN segment

Summarizing the observations from the different stakeholder groups, Sigfox is perceived as a centralistic ecosystem with less development freedom. Its strengths, however, are strong standardization and centralized coverage buildup; huge customers who benefit from co-development value these characteristics. These selected large customers, often deploying hundreds of thousands or even millions of sensors, have a strong negotiation position. For Sigfox, their success is important, and hence they are willing to expand the network to make these large customers' use cases work. The result – connectivity wherever the client needs it – is comparable to what some (smaller) LoRaWAN adopters have reported: self-provisioning a network to have connectivity wherever required.

LoRaWAN is an open ecosystem with many different interested parties, and especially the open TTN community offers less centralized support and attracts open-source developers and experimenters, which may sometimes be at the expense of streamlined development. NB-IoT entered the market last but can build on an existing structure of operators and 3GPP as the established standardizing organizations and, with this, also gets adopted in the market.

LoRaWAN profits from its openness. The LoRa Alliance is perceived as an important stakeholder in this ecosystem, providing certification for device manufacturers and marketing the technology. For implementers and developers alike, the TTN plays an important role, too. Large customers seeking customization and needing national coverage often co-develop their use cases with Sigfox. NB-IoT can offer similar coverage and leverage an existing ecosystem around 3GPP. However, operators do not always rely on these established structures; some consider the technologies in the unlicensed band a novel business opportunity, and they opt to join in search of innovation. There are end users for each LPWAN technology, and the following section sheds light on why they choose one or the other.

For the modified TOE adoption model, I combine the insights from the two previous sections and do so per major category: technology, organization, and external task environment. Undoubtedly, one TOE framework, which summarizes crucial adoption criteria for stakeholders along the value chain in the LPWAN segment, cannot provide a mechanic process for decision-making. It must be understood as a framework steering the conversation and guiding investigations in every individual adoption decision.

Technology. For end users, we have seen that the *economic considerations* are crucial, as they often have a cost-saving target they want to achieve by using IoT or even, specifically, by using LPWAN. Financial aspects are also important for all other stakeholders as they are businesses with a commercial interest. Furthermore, end users, especially smaller ones with lower negotiation power, must rely on an LPWAN's *availability in the end user's geography*. The previous section shows that geographic coverage and roaming possibilities are highly important and decisive for their LPWAN technology selection. For stakeholders providing equipment or services to these end users, it is also decisive for their adoption decision, which LPWAN technology their clients can access. Furthermore, the *strength of technology lock-in effects* of each LPWAN technology on adopters, end users, or other stakeholders is fundamental in the adoption decision: end users experience lock-in effects through sensors that can be compatible with one or many LPWAN technologies as well as through investments in own network hardware (in case of LoRaWAN self-provisioning). For service providers and integrators, their lock-in depends mainly on their service or product offered: while some consulting services are easily transferable, often hardware development is strictly tied to one LPWAN technology, as, for example, M02 explained. End users may have other requirements when adopting LPWAN, like specific velocities when moving their tracked assets (e.g., S02), need for exact locations with tolerances below one meter (e.g., L08), or deep indoor coverage in buildings (e.g., N01). These specific requirements are considered during the technology adoption process and in the modified TOE, referred to as *specific technical use case requirements.*

Organization. By different stakeholders, *partnerships and collaborations* are seen as beneficial and thus potentially they influence their adoption decision. These partnerships can be between operators and end users (e.g., S02, N01) but also between software providers and their customers (e.g., L05, L09) or equipment manufacturers and end users (e.g., M01). These partnerships and collaborations often include a *communication and knowledge-sharing* facet next to the pure business relationship. Cities, as end users, use their established communication forums also to discuss their LPWAN (mostly LoRaWAN) implementation and exchange learnings (e.g., L13). Established network operators also talk with their peers (e.g., M05). The previous sections have shown that the *offering portfolio* of a potential adopter may also influence their LPWAN adoption decision. In the case of the integrators, the depth of service provided (hardware development, software development, device installation, consulting) influenced the strength of technology lock-in. For established network operators, their existing LTE portfolio, including the expensive licenses for the associated bands, made the NB-IoT adoption very appealing. To them, it seemed like a minor addition, not fundamentally challenging the business model like Sigfox and LoRaWAN could potentially have done as technologies operating in the unlicensed band. End users' *size and associated negotiation power* influenced their ability to make network operators provide connectivity where they needed it (e.g., S02 closely collaborated with Sigfox on network expansion). I have also observed that some smaller firms and startups used local network providers (e.g., L02) or the TTN (e.g., L01). Their negotiation power towards larger operators would have been marginal, and S03 explicitly stated that network operators need the large-number use cases on their networks to get the LPWAN segment to grow more substantially. Given that no national LoRaWAN is available in Germany until now, for many users with national use cases in Germany, this option was not available for selection. Hence, I conclude that the end users' *geographic area of operation* is essential in the adoption process. For other stakeholders along the value chain, this factor is also of interest, as their clients may face a restriction of their choice due to geographic circumstances.

External task environment. The external environment, sometimes also referred to as the industry setting of the (potential) adopter (Gibbs & Kraemer, 2004: 126), includes the *view of the competitive environment* by the (potential) adopter. As the in-depth study of the network operators has shown, the scope of competition is seen differently by different actors of the same stakeholder group. Some established network operators considered operators in the unlicensed band as competition for the licensed bands, and some national telecommunication companies considered regional operators as novel competition. Furthermore, as the different views of the same actor group revealed, it is important to consider each (potential) adopter's *perspective on the possible co-existence of LPWAN in the market*. It has fundamental strategic implications whether one expects only one LPWAN technology to win the entire market or whether one expects the coexistence of several LPWAN technologies. Especially regarding equipment manufacturers and their products, a possible *certification of products and services* was also found to be essential for the adoption decision. LoRaWAN certification was found to serve as a powerful marketing for the products of smaller firms (e.g., M03). Lastly, several stakeholders mentioned exchange groups and forums as important platforms for exchange and learning. One event that brings many different stakeholders together and has become a lighthouse for the whole LoRaWAN world is the yearly The Things Conference (L01, L07, L09). Other end users and TTN users have indicated that they benefit from the technical advice the TTN community created around LoRaWAN (e.g., L01, L02). One end device manufacturer (M02) even claimed that any technology succeeding in the market in the upcoming years “will be part of a bigger movement, a movement like an alliance.” Thus, *communities, standard developing organizations, industry associations, and others* are included as important aspects supporting LPWAN technology adoption.

These factors are summarized in the LPWAN-specific TOE framework, as shown in Figure 6. The exhaustiveness of this model was assured as all themes from the qualitative analysis could be mapped to it. It can also be regarded sufficiently specific, as most themes matched exactly one aspect.

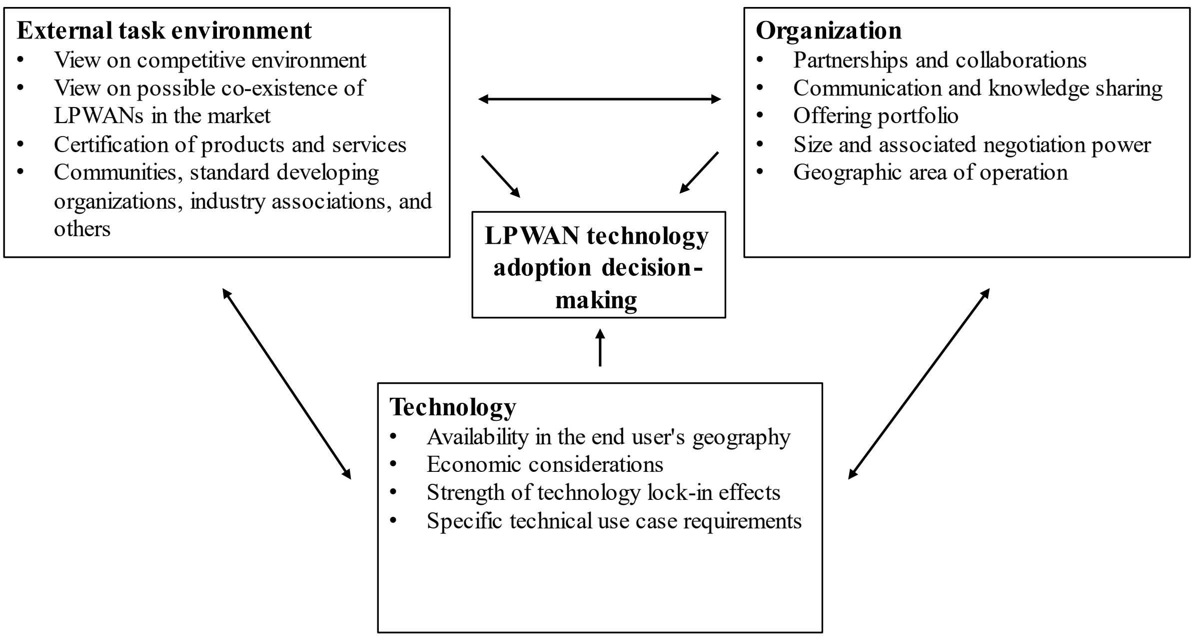

Figure 6 TOE framework for LPWAN technology adoption decision-making

3.4.4 Market subsegments and selected LPWAN technologies

This section presents the findings on which LPWAN technologies can be observed in different subsegments of a fragmented IoT market and searches for why these are selected. This study’s interviews cover most adoption segments – smart city, smart logistics, smart industry, and smart building. Table 4 provides an overview of these use cases. None of the end users ran applications on multiple of these technologies even though some indicated plans to do so in the future (e.g., L04, N03).

Table 4 Overview of LPWAN-adopting end users and their use cases

	Interv. ID	Adopter description	Use Case	Stationary vs. moving	Coverage needed	IoT segment
LoRaWAN	L04	Utility	Operates own network to monitor own assets; also connected to TTN	Stationary	Local	Smart city
	L06	City	Ideas for use cases around environmental monitoring: flood prevention, soil humidity	Stationary	Local	Smart city
	L13	Utility	Operates own network, still developing use cases	Stationary	Local	Smart city
	L14	City	Operates own network; monitors power network and district heating shafts	Stationary	Local	Smart city
	L15	Large infrastructure company	Monitors buildings across the country with LoRaWAN, e.g., pax counters	Stationary	National	Smart building
	L16	Logistics services provider.	Order management at each endpoint with LoRaWAN, a stationary application	Stationary	National	Smart industry
NB-IoT	N01	Large company	Trials for asset management at only a large site; ideas for smart metering	Stationary	Local	Smart industry/ smart building
	N03	Logistics services provider	Asset tracking nationally and internationally	Moving	National & international	Smart logistics
	N04	Tracking startup	Selling tracking as a service for high-value devices B2B	Moving	National & international	Smart logistics
Sigf	S02	Logistics services provider	Asset tracking nationally and internationally	Moving	National & international	Smart logistics

City administrations (e.g., L06 and L14) and their utilities (e.g., L04 and L13) are the main actors within the **smart city** segment. In their city, they pursue use cases in the areas of support as well as facilitation of iterative work. The first one, support, includes parking management (L08, L13), soil humidity monitoring and smart water management for green areas (L13), counting people (L13), as well as monitoring water heights in local rivers and lakes for flood prevention (L06). The latter covers applications such as filling height monitoring of bins (L08), surveillance of the district heating network (L04, L13), monitoring of the power network (L13), as well as potential leakage identification in the water supply network (L13). These applications are stationary and need reliable connectivity, sometimes even at hard-to-access locations. For example, deep indoor coverage is necessary for underground parking lots or district heating shafts. Cities understand that they are a relatively small and local player and might have low negotiation power to make traditional operators install an additional base station there just because they need it for their application. M05, an operator having a LoRaWAN offering, supports this hypothesis.

> *"… and in our own network, we simply place a gateway there and done (…).District heating shafts, for example, are simply located two and a half meters below ground, and they are isolated by a meter of reinforced concrete. We won't get any [name of a telecommunications operator] and any [name of another telecommunications operator] to place another base station there just because we'd like to have one there."*[30] *(L04)*

> *"Smart City is one of the target groups [where] I said: 'Ok, we are not going to use our sales capacity to focus on that segment.' I see the business opportunity, but the chance that you will do business – any significant – is really, really low." (M05)*

Hence, many decide to build their own network and opt for self-provisioning. LoRaWAN is the only LPWAN that allows for this and thus is – non-surprisingly – very popular among utilities and cities for their smart city applications.

The **smart building** segment has similar requirements: it is also a stationary application, strictly locally limited, and needs deep indoor connectivity. The connectivity in the building can be used for many applications, ranging from counting people passing through (L15), carbon dioxide monitoring (L08, L14), which was quite popular during the Covid-19 pandemic, to storage temperature monitoring (L08). Again, this only locally needed connectivity makes it attractive for users to equip their assets with a self-provisioned network rather than relying on external partners.

> *"We have locations, these are quite a few, around 400 locations in Germany. But these are single locations that I can then equip separately. I don't need general LoRa things; I don't need a network which provides coverage somewhere outside of my [type of*

[30] Translation of the German statement: „…und in unserer eigenen Struktur setzen wir da einfach ein Gateway hin und fertig, (…). Für Fernwärmeschächte, zum Beispiel: Die liegen nun mal zweieinhalb Meter unter der Erde und sind von einem Meter Stahlbeton abgeschottet – da kriegen wir keine [Name eines Telekommunikationsunternehmens] und keine [Name eines anderen Telekommunikationsunternehmens] dazu, da mal einen Mast hinzusetzen, nur weil wir das jetzt gerne hätten.“

their assets]; I have quite location-fixed applications for me that I can then build up."[31] *(L14)*

The **smart agriculture** segment has similar requirements to the smart building: limited geographic scope. The popular case of environmental sensors for humidity or temperature is stationary applications, for example, farms, golf courts, or others managing large green areas can use this technology. In the past, farms sometimes used cellular technologies, but it turned out to be very costly (L03). Actors across the value chain see LoRaWAN as an up-and-coming technology for smart agriculture, mainly because farms are often located in remote areas where cellular technologies currently might still have white spots. Several actors (M03, M06) point out that adoption in this segment also depends on the size of the farms, with far slower adoption by the small European farms compared to those in the USA or Canada.

"In agriculture, you have big spaces to cover so that you can use sensors – battery-powered sensors or solar-powered sensors, so I think in agriculture LoRaWAN could be a good choice." (M03)

"Of course, we also have large farmers here; ultimately, they are almost industrial producers. Yeah… so they – or also golf courts! – regularly must water their farmland, which happens with a large time investment. Someone must drive there, manually check how crumbly the soil is, [...] and in the past, at least where it was developed with cellular, they partially already implemented it [smart agriculture] using cellular – but at high fees of up to 400€ per month. However, cellular is not developed in many areas, they have so-called white spots, and with LoRaWAN, we can now cover that easily. No communication costs, investment costs very low."[32] *(L03)*

[31] Translation of the German statement: „Wir haben Standorte, das sind eine Menge, quasi 400 Standorte in Deutschland. Aber es sind einzelne Standorte, die ich dann eben jeweils standortbezogen ausstatten kann. Ich habe keine übergreifende LoRa Dinge, ich brauche kein Netz was irgendwo einem Coverage bietet, die außerhalb meines [Art des Gebäudes] ist, ich habe relativ ortsfeste Anwendungsfälle für mich, die ich dann eben ausbauen kann."

[32] Translation of the German statement: „Natürlich haben wir hier auch große Landwirte, das ist ja fast Industriebetriebe am Ende. Ja …die müssen halt regelmäßig [...] – oder Golfplätze! – die müssen auch regelmäßig ihre Flächen wässern und das passiert unter sehr hohem Zeitaufwand. Dass jemand hinfahren muss, muss also mit den Händen prüfen ist die Erde krümelig, [...] und in der Vergangenheit, da zumindest, wo es durch Mobilfunk erschlossen war, haben die das [smarte Landwirtschaft] zum Teil sogar schon über Mobilfunk umgesetzt – allerdings mit hohen Gebühren von bis zu 400€ im Monat. Aber viele Flächen sind zum Teil nicht mobilfunkmäßig erschlossen, haben sogenannte weiße Flecken, und das kriegen wir mit LoRaWAN jetzt wunderbar abgedeckt. Keinerlei Kommunikationskosten, Investitionskosten sehr gering. "

The **smart industry** is a broad segment that covers industrial IoT applications. They can be related to environment measurements for predictive maintenance (L05), tracking trucks and smaller vehicles in a factory (L05, L08), monitoring of energy or water consumption on site (N01), and to alerts and communication between a central unit and the actual service delivery point (L16).

The **smart metering** segment is not represented in the sample, yet it is closely tied to many previously mentioned use cases, e.g., to power and water consumption in buildings. Interviewees have regularly pointed out that metering could be excellently smartified through LPWAN. However, current legislation, especially in Germany, prevents the successful implementation of smart meters with LPWAN technologies (e.g., L11, L12, L14). Smart meters are usually location-fixed, and their distribution depends on their provider‘s geographical scope, i.e., a power supplier only needs smart meters in the households they deliver to, not internationally. Several power providers, though, cover large parts of the country and might, precisely for that reason, require regional or even national coverage.

The **smart logistics** segment introduces a novel challenge compared to the previously discussed segments: moving items with a need for national or even international connectivity. One can distinguish shipment and asset tracking: while LPWAN are too expensive for regular shipment tracking, the tracking of assets, such as containers or special boxes as expensive transportation aids, is an area where LPWAN are regularly used (N03).

> *“Regarding asset tracking, that means containers, vehicles, boxes, and loading aids, that is an area where we are already implementing things. The other area is shipment tracking, where single shipments are tracked. We don’t have a satisfactory solution in this area yet.”*[33] *(N03)*

> *“[W]e are a logistics services provider, who on the one hand has a strong European road traffic network, on the other hand, we are also active in the intercontinental area… That is why for us, the network coverage everywhere was important. Obviously, we cannot achieve that with the construction of networks. That is why it was clear to us early on that we need public networks or a network provider who aims to provide*

[33] Translation of the German statement: “Einmal zum Thema Asset Tracking, das heißt Container, Fahrzeuge, Behälter und Ladehilfsmittel, wo wir bereits dran sind die Dinge umzusetzen, Der andere Einsatzbereich ist das sogenannte Shipment Tracking, bei dem einzelne Sendungen verfolgt werden. Das ist ein Einsatzbereich, in dem wir noch keine zufriedenstellenden Lösungen haben.“

high coverage – thinking of Sigfox. Pretty early on, LoRaWAN was not the right one for us."[34] *(N03)*

"[T]his 'across-borders' was at the beginning no selling argument for us because we had the hypothesis that they [the loading aids] were stolen or something like that. Our main selling argument, why we, in the end, decided on it, was that we could track the assets in [name of the country] not only on our sites but also everywhere else. And all of this at a reasonable cost. This was our main goal. The other [the cross-borders tracking] was a goodie which – as we learned afterwards – was a very important goodie! But initially, we didn't assume that."[35] *(S02)*

Across the different customer segments, two decisive factors for the adoption of specific technology can be observed: (1) geographical scope ranging from local to international (including intercontinental), and (2) stationary vs. moving applications. Mapping the segments onto a matrix with these two dimensions, one can observe a clear pattern, as shown in Figure 7: Stationary applications which mostly require local or maximum regional coverage, such as smart city and smart agriculture, have shown a preference for LoRaWAN. Their direct counterpart, so moving applications operating nationally or even internationally, have shown a preference for networks with national or international coverage. They mostly preferred either Sigfox or NB-IoT.

[34] Translation of the German statement „[W]ir sind ein Logistik Dienstleister, der auf der einen Seite ein starkes europäisches Landverkehrsnetzwerk unterhält, auf der anderen Seite sind wir auch im interkontinentalen Bereich… Deshalb ist für uns die gesamte Netzabdeckung überall relevant gewesen. Das können wir natürlich nicht mit dem Aufbau eigener Systeme schaffen. Deshalb war uns recht schnell klar, dass wir für unsere Use Cases öffentliche Netze oder einen Netzprovider, der einen hohe Netzabdeckung – wenn Sie an Sigfox denken – versucht herzustellen. LoRa war dann relativ schnell für uns nicht der richtige."

[35] Translation of the German statement: „[D]ieses Grenzüberschreitende war für uns ganz am Anfang, nachdem wir ja die Hypothese hatten, dass sie [die Ladehilfsmittel] gestohlen werden oder Ähnliches, nicht mal ein Verkaufsargument. Sondern unser Hauptverkaufsargument, warum wir uns dafür entschieden haben, war eigentlich, dass wir in [Name des Landes] nicht nur auf unseren eigenen Standorten, sondern sonst auch überall die Assets tracken. Und das Ganze noch zu einem vernünftigen Preis. Das war eigentlich unser Hauptziel. Das andere [das grenzüberschreitendes Tracking] war ein Goodie, das – wie sich jetzt herausstellt, im Nachhinein, sogar als ein sehr wichtiges Goodie – aber davon sind wir anfänglich gar nicht ausgegangen."

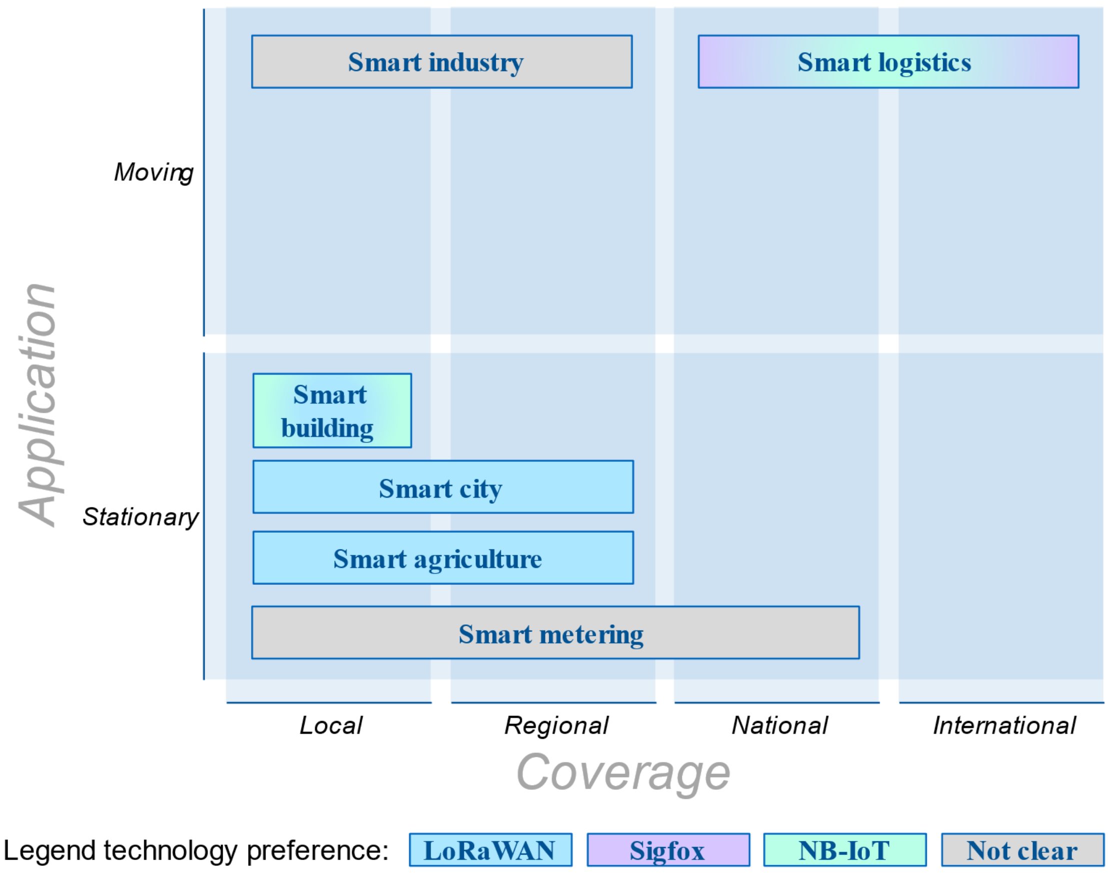

Figure 7 Framework for LPWAN application areas

The smart industry[36] as a local application at one site mainly involves moving items like vehicles or boxes and uses a broad range of technologies. From interviews, I learned (e.g., S02) that in some cases also, local Wi-Fi and hybrid sensors are used for data transmission and localization. Given the small number of observations, no clear conclusion can be drawn for this sub-segment.

Smart metering, as a highly regulated sub-segment, is a stationary application. The trials of N01 with NB-IoT on a local scale proved feasibility, yet the sensors used consumed way too much energy. In theory, all three technologies could satisfy the need, and it may be more dependent on who meters where: while local utilities likely prefer LoRaWAN sensors which they can operate using their own local network, national providers of utilities might choose to

[36] Applications in industry which involve tracking across several sites are not referred to as "smart industry" but would rather be "smart logistics". The here referred to cases are applications within one site, can either be stationary (e.g., monitoring temperature in storages) or moving (e.g., tracking movement of boxes anywhere in the site)

have one national partner for all their metering activities in the country and hence team up with a national NB-IoT or Sigfox provider. A logistics services provider (N03) summarizes these thoughts: “I still believe that LoRa is an option for a locally confined area like a site or even a city. Beyond that LoRa is no solution for us”[37].

3.5 Discussion

3.5.1 Contributions the LPWAN and IoT literature

The presented case study is the first one to compile a “thick description” (Creswell, 2016: 209; Yin, 2009: 18) of technology adoption in the LPWAN segment and distill these insights into an adapted TOE framework. The formulation of a specific TOE adoption model can guide further research, and often, such frameworks serve as a starting point for quantitative adoption studies in the same segment (Awa et al., 2017: 894). This case study further delivered a systematic overview of different LPWAN technologies’ selection for use cases in various IoT segments, resulting in a framework for LPWAN application areas (recall Figure 7). In the following, I highlight three key insights derived from this research endeavor:

A broad range of factors matters for LPWAN adoption, including partnerships, competitive dynamics, marketing, and governance of the different LPWAN technologies. The interviews with stakeholders and end users have unveiled a variety of considerations important in LPWAN adoption decisions, and the adapted TOE framework for LPWAN adoption distills these findings into a usable framework. For LPWAN research, these findings from interviews with practitioners mean that the current focus on the technical features of LPWAN technologies (recall Chapter 2) needs to be broadened to understand adoption and market dynamics. The TOE framework should not be understood as a mechanic framework but as an overview of potentially relevant factors where each (potential) adopter may assign their own importance to each factor. So far, in research the focus has been firmly on the “technology” dimension. This study has shown that also the adopter’s environment is highly relevant for adoption—for example, certification and platforms of knowledge exchange matter. Semtech as the owner of the LoRaWAN technology, understood that early on and built what Teece (2018:

[37] Translation of the German statement: „Ich glaube nach wie vor, dass LoRa nach wie vor für ein lokal abgegrenztes Gebiet wie einen Betriebshof oder vielleicht sogar eine Stadt eine Option ist. Darüber hinaus ist LoRa für uns aber keine Lösung.”

1372) labeled "ecosystem strength": To profit from their own innovation, they transferred parts of the LoRaWAN IPR to a specifically founded LoRa Alliance. This alliance granted access to many interested stakeholders and provided certification. With this, Semtech established an open, collaborative environment, which was perceived positively by many interviewees. Another critical factor in the adapted TOE framework is the competitive environment, which is also associated then with the internal *offering portfolio* of a firm. In particular, the case of operators choosing between sticking to their classical business in the licensed spectrum and implementing NB-IoT only or deviating from known business models by additionally implementing a technology in the unlicensed spectrum, powerfully illustrated this choice and the different views adopters may have on those.

Coverage is decisive in LPWAN adoption, and self-provisioning might democratize connectivity provisioning. Many interviewees appreciated LoRaWAN's feature to allow for self-provisioned networks, providing them with deep indoor coverage and the ability to have connectivity wherever needed (e.g., L04, L13). The possibility of self-provisioning additionally seemed attractive as adopters were less afraid of vendor lock-in. For LoRaWAN, self-provisioning is a technical feature per design usable by anyone. When Sigfox collaborated with its large clients and brought connectivity to them, in case they needed it, the result was similar: connectivity. Still, in the Sigfox case, only huge customers had the negotiation power to make the network operator establish connectivity exactly where they needed it. For Sigfox, this was an opportunity to spur adoption through high volumes. It was not used to its maximum potential, according to one former high-rank Sigfox employee:

> *"I haven't explained Sigfox as the provider of data, but more as a technology solution, which for me was a mistake. And unfortunately, all these technology owners did the same thing that they pushed technologies in front of customers. And the customers, they were completely lost [...], and everybody is waiting [...] But for all the LoRa guys, Sigfox and so on, it is a big issue because there are no volumes for that today! Because we are not focusing on main opportunities where there are big volumes and where the only way to create ROI is to use an LPWA network."* (S03)

While Sigfox partnered with large customers, the self-provisioning feature of LoRaWAN, is accessible to anyone regardless of size and thus could be interpreted as a democratization of IoT, facilitating access for smaller adopters and resolving the dependency of adopters on network operators and the coverage they provide. When discussing IoT's future and its adoption, I think this is a powerful insight that could speed up LPWAN adoption massively. It has the potential to showcase high-speed IoT adoption, making this self-provisioning feature interesting for the broader IoT audience beyond LPWAN.

The dominance of single LPWAN technologies in subsegments depends on coverage needs and type of application (stationary vs. moving). The framework for LPWAN application areas (recall Figure 7) can concretize Tadayoni et al.'s findings "that in spite of network effects following the networked character of IoT communications, the network effects will be strongest in geographically or otherwise confined areas and that different technology solutions can coexist globally but also regionally and nationally" (ibid. 2017: 7). The study has confirmed the coexistence of different technology solutions and with this also clearly contradicts the work of other scholars like Mumtaz et al., who predicted that "a single LPWA solution is universally adopted" (ibid. 2017: 31). This study's results do not point towards dominance based on geographical areas, but instead depending on the application, differentiating it along the dimensions of moving versus stationary application and coverage. Coverage depends on the mode of provision, where LoRaWAN offers the self-provisioning feature for everyone, while in the case of Sigfox and NB-IoT, the technology and the design do not allow for it. Large adopters may circumvent this technological restriction by using negotiation power and agreeing with network operators to provide them with connectivity wherever they need it for their large use cases.

The LPWAN market should not only be understood as one homogeneous IoT segment but rather as a fragmented market in itself with subsegments which allow for the co-existence of different LPWAN technologies. The developed framework for LPWAN application areas shows that both stationary and moving applications can use LPWAN technologies. However, stationary applications are inclined towards LoRaWAN, while the moving ones requiring national or international coverage often prefer NB-IoT or Sigfox. These insights go beyond previous claims in literature according to which LPWAN are meeting the IoT markets' requirements (Ayoub et al., 2019a: 21) and are only suitable for stationary applications (Ibrahim, 2019: 234) and may facilitate and guide future LPWAN adoption decisions of end users. The developed framework is based on 29 interviews in the LPWAN market, among those ten interviews with adopters. Recent work on single applications supports the identified technology preferences: Lalle et al. (2019) identify NB-IoT as most promising in a smart metering use case in the water system, and Klaina et al. (2022) consider LoRaWAN particularly promising for smart agriculture. Both are pieces of anecdotal evidence, and hence, further validation in the market is needed, for example, a quantitative study in the form of a survey among adopters, could do so.

Implications for practitioners. Practitioners are heterogeneous and may include the stakeholder groups and allies involved in this study, other SDOs, and future adopters of LPWAN or other ICT. To facilitate the adoption decision for novel (potential) adopters in the LPWAN segment, this case study offers a systematic overview of subsegments, also called verticals, and the preferred technology or technologies in this sub-segment. Network operators and device manufacturers may use it to better understand who their core customers are and which characteristics they value most. For anyone being engaged with IoT outside the LPWAN segment, it can serve as a case study to understand the dynamics in ICT technology competitions and draw strategic conclusions from it.

3.5.2 Strengths and limitations of the study

While interviewees were carefully selected through theoretical sampling, this also implies that some were consciously not considered. For example, the geographic focus of this study relies on democratically governed states in Europe. Potential effects of the commitment to NB-IoT made by the Chinese government in 2017 (Huang, 2018) are not considered here and could be subject to further studies. Similarly, most European countries are relatively densely populated and small compared to other big, industrialized nations like the USA or Australia, which most likely impacts the coverage development and, thereby, the diffusion dynamics. Sigfox's struggle to succeed in the USA might already hint in this direction and could be subject to future research. The great advantage the European setting provided for this study is the presence of the three dominating LPWAN technologies, national coverage in at least one country by each of these technologies, adopters of each technology, and the absence of governmental guidelines for adoption for most segments. All data were sampled in 2021, so before Sigfox filed for insolvency in 2022, was acquired UnaBiz, and some major strategic changes were introduced (Blackman, 2023; Kasujee & Mackenzie, 2022). These major changes have not been subject to this research.

The data collection method of interviewing also comes with potential pitfalls. While validity and reliability were already addressed in the method section, the subjective nature of this data collection method shall briefly be discussed here: a qualitative approach is appropriate to understand the market dynamics and understand different stakeholders' views. The exploratory nature of this study allowed me, as a researcher, to start with superficial knowledge and deepen it through iterative data collection and analysis. Alongside my learning process and with progressing research, I was able to ask further and more detailed questions in the semi-structured interviews. This subjective component can be irritating and hence raises the question: "Is interviewing an art, a craft, a contest of wills, or something entirely different?" (Berg & Lune, 2017: 65). Gaining interviewees' trust is an art, and my position as a doctoral researcher at a well-known university indeed has helped me here. Asking open-ended and intelligent questions is a craft. And finally, when some interviewees try to receive information about other interviewees, it might be a contest of wills. Despite these concerns, well executed, interviews are a powerful tool to extract very rich information from practitioners themselves and to give them a voice. This is how this study shall be understood and where – in my opinion – it makes its most significant contribution: it is a study of the LPWAN market, a phenomenological study, and it can offer a "thick description" of the LPWAN adoption. And then, in a second step, I stepped out of the informant-centric perspective and linked the findings to the concepts konwn from academic literature, using more academic terms for the description. The results of both steps were presented in this chapter to make the process understandable.

The IoT is an area of the highest relevance, many studies have been conducted, and theoretical models have been developed. However, implementation still needs to catch up, and guidance is required (Atzori et al., 2017; Trappey et al., 2017). Many of the actors in the IoT space can financially and timewise not afford to bet on a technology that disappears shortly after that. Hence, they need to understand the dynamics of IoT technology adoption and possible competition between technologies in the same segment. This study contributes to this understanding by informing LPWAN stakeholders' decisions in three ways: first, the TOE framework for LPWAN adoption decisions (Figure 6) allows novel market entrants to assess their own needs quickly. It may guide their discussions when deciding which LPWAN technology to implement. Second, the developed framework for LPWAN application areas (Figure 7) allows novel end users of an LPWAN technology and anyone doing business with them to evaluate their positioning and likely also their technology choice. Third, this study aims to sharpen market participants' awareness of the variety of factors influencing LPWAN adoption decisions and, with this, gives them the understanding to shape ecosystems for the technologies accordingly.

Regarding the LPWAN stakeholder groups, the observations may lead to further questions: operators either see LoRaWAN as competition and solely focus on NB-IoT, or they see it as a business opportunity and implement LoRaWAN and NB-IoT. Further investigations could show which determinants lead to one or the other positioning. In the smart city use case, utilities or city administrations were the main actors. They had a strong interest in openness, control, and independence and often wanted to self-provision their network, leading them to adopt LoRaWAN. Understanding where this urge comes from and how smart city applications are set up could clarify the adoption mechanism for smart cities and facilitate the globally ongoing implementation of it.

Both developed frameworks are the results of an in-depth qualitative interview study. Further validation could be achieved through additional testing in the field and validation through appropriate quantitative data from the LPWAN segment.

If the here observed tendency towards a co-existence of multiple LPWAN technologies were to materialize, this would equal a market fragmentation and imply a novel challenge. Fragmentation reduces the value which can be achieved through standardization (Grindley et al., 2017: 5) and threatens cost-effectiveness (Mumtaz et al., 2017: 31). Future studies may also focus on the impact this fragmentation in the LPWAN segment has on the diffusion of the IoT overall as well as on the IoT technology stack.

3.6 Conclusion

This study set out to gather a rich understanding of LPWAN technology adoption processes of end users and other stakeholders rooted in practice. In addition to understanding the decision criteria they apply in their technology decision process; I aimed to investigate and systematize the use of LPWAN technologies in different application areas of the IoT.

The exploration of LPWAN adoption from practitioners' perspective provides a detailed description of adoption dynamics, criteria, and considerations in the LPWAN segment. This study further contributes two powerful frameworks to understanding LPWAN adoption: first, the adapted TOE framework for LPWAN technology adoption summarizes key decision criteria for LPWAN adoption. Second, distilling the LPWAN choice for different use cases into the framework for LPWAN application areas is the first attempt to structure technology adoption outcomes in the LPWAN segment and identify dominant technologies in its subsegments. It can facilitate and speed up future adoption in the field.

This study shifts the focus away from comparisons of technical features of LPWAN to discussing marketing and governance-related aspects relevant to LPWAN technology adoption. Despite its use in IoT and high-tech adoption studies (Oliveira & Martins, 2011), the TOE framework for institutional adoption was only introduced to the LPWAN field with this study. The systematic analysis of LPWAN adoption carries the potential to understand IoT adoption from a different perspective and transfer insights to segments other than LPWAN. The vital role of self-provisioning as a possible way to democratize IoT should be further investigated.

Both developed frameworks summarize novel findings and can guide discussions; further validation and refinement of them in practice will increase their robustness and credibility. Moreover, the geographic focus of this study on central Europe calls for additional assurance in other cultural contexts, especially China, with a very different regulatory environment that could add valuable insights.

In summary, this study brings the important perspective of practitioners to LPWAN research, developed two meaningful frameworks on LPWAN technology adoption criteria and LPWAN technologies' use in different IoT application areas, contributing to a better understanding of LPWAN technology adoption. It further identified self-provisioning as an exciting area for further research with the potential to democratize IoT and, with this, shape IoT adoption beyond the LPWAN segment.

4. Technology governance as a selection criterion – the case of smart cities

4.1 Introduction

Cities consume 75% of the world's resources and energy, generate around 80% of global greenhouse gases, and by 2050 will be home to 70% of the world's population. It is thus worth to think about how we want to live in cities, how we can improve life there and how they remain attractive living environments for their citizens. This is where the concept smart city lies, at the intersection of the macro trends of urbanization and smartification. Objects and the environment become "smart" with the addition of sensors and data transmission modules. A smart city uses such smart objects and environments and makes use of advanced information and communication technologies to implement improvements in the city. These can comprise better waste management, more efficient use of water, or better tracking and maintenance of their assets. (Dameri, 2013; Mohanty, Choppali, & Kougianos, 2016)

The backbone of such a smart city is its communication technology which ensures data transmission as a cornerstone of any decision in any operation in the smart city. While benchmarking of technologies about technical features is very common, there is a lack of understanding of the role of governance-related decision criteria. This study makes use of a technologically speaking homogeneous communication technology class, but with significant differences in the governance-related criterion of self-provisioning connectivity: LPWAN technologies. So far, literature focused on technology-related criteria to evaluate LPWAN (e.g., Ayoub et al., 2019a; Hossain & Markendahl, 2021; Raza et al., 2017) and select the most promising technology for their use.

This paper aims to clarify the role of governance-related criteria in technology decisions by systematically examining the context of smart city implementation, the technology decision processes and criteria used in practice as well as the observable resulting network setups. To do so, this research deploys a mixed-methods design. It combines strengths of qualitative and quantitative research in an exploratory sequential design. First, we systematically analyze theoretically sampled interviews with smart city stakeholders in which we explored the mentioned context, decision process, criteria, and network setups. Building on those insights, we surveyed German cities and focused on crucial aspects discovered during the qualitative part, such as expected benefits associated with smart cities and assessment of different technology decision criteria. Combining these two data collection methods we avoid collecting quantitative data without understanding the underlying mechanisms, but we also do not limit ourselves to telling stories derived from anecdotal evidence only: we aim to develop an understanding of the role of governance-related criteria in technology selection, deeply rooted in practice but with the ambition to be generalizable.

This research is structured as follows: in Section 4.2 we introduce the concept of a smart city, discuss LPWAN as an important component within the cities' communication infrastructure, and present our research question. Thereafter, in 4.3, we briefly introduce our research context of smart cities in Germany and elaborate on the study design and methods used. We also address data processing and give an overview of the demographics. In the following Section 4.4, we present findings from both the qualitative and the quantitative study. We interpret the findings in 4.5, and discuss the limitations of our study. We conclude with summarizing key insights and contextualizing them (4.6).

4.2 Background

4.2.1 Smart cities

The concept smart city is a rather fuzzy one. Various actors, technologies, goals, and benefits can be put into the spotlight. In the following, we thus elaborate on the concept and understanding of a smart city and how it is used in this study. We rely on Dameri's widely cited definition which considers various perspectives:

> *"a smart city is a well defined geographical area, in which high technologies such as ICT [Information and Communication Technology], logistics, energy production, and so on, cooperate to create benefits for citizens in terms of well being, inclusion and participation, environmental quality, intelligent development; it is governed by a well defined pool of subjects, able to state the rules and policy for the city government and development" (ibid. 2013: 2549)*

Stübinger and Schneider (2020) reviewed the top 200 smart city publications listed on Google Scholar in 2020 and found five highly relevant literature streams namely: "'smart infrastructure', 'smart economy & policy', 'smart technology', 'smart sustainability', and 'smart health'" (ibid. 2020: 8470–8471). While initially the role of ICT was emphasized, in recent years multi-dimensional concepts emerged and the role of citizens and sustainability came into focus (Hilbig, Rottmann, Grüttner, Wagner, & Banaschik, 2020). Additional stakeholders come from a variety of areas associated with the smart city concept, such as the general public, technology, ecology, science, economy and construction industry, in which cities and communities as the target group of smart city keep a special position (Anthopoulos & Reddick, 2016; Hilbig et al., 2020; Stübinger & Schneider, 2020). The benefits associated with the smart city are thus also targeting this group and promise an improved "way of living and working in the region" (Stübinger & Schneider, 2020: 8459), including better public services, the lower environmental impact of cities and improved resource efficiency (Mohanty et al., 2016: 61).

Practitioners and academics alike agree on the crucial role of communication technologies in a smart city. Technology is "[t]he main driver for smart city birth and development" (Dameri, 2013: 2545), and – as the Smart City Charter puts it - with the use of "information and communication technologies… [cities] link municipal infrastructures such as energy buildings, traffic, water, and sewage" (Federal Ministry for the Environment, Nature Conservation Building and Nuclear Safety, 2017: 25). ICT are the underlying infrastructure that enables public participation and modern city development concepts (Hilbig et al., 2020: 9). As such, they are a crucial component of the smart city concept as a whole (Stübinger & Schneider, 2020: 8459). Mohanty et al. even call ICT the "nerve center" of a smart city and as such "enabling keys for transforming traditional cities into smart cities" (ibid. 2016: 60).

While ICT ensures communication and data transmission a second concept, the IoT, is also part of "the technical backbone of smart cities" (Mohanty et al., 2016: 68). IoT describes the "smartification" of things, i.e., equipping them with sensors and communication capabilities and with this enabling "interconnectivity between the real world and the digital one" (Ibrahim, 2019: 234) – a crucial feature in smart cities. Sensors and communication modules fulfill this role. As many of the sensors are either placed on moving "things" such as trams or buses or at remote places (such as humidity sensors in parks and temperature sensors in district heating or cooling shafts), wireless communication technologies play a crucial role in making "things" smart in a smart city.

Nevertheless, what remains unclear, is the extent to which the smart city concepts are already being implemented, which criteria cities employ for their communication technology selection process, and which communication technologies and setups they use in practice.

4.2.2 Research question

With the rising implementation of smart city concepts also the role of ICT as its technological backbone becomes more and more important. LPWAN technologies are a key element of this ICT stack. The selection of the technologies of this ICT stack often follows the process of multi-criteria decision-making (MCDM). Anecdotal evidence points towards the fact, that governance-related criteria play an important role in this technology decision. In contrast to this the existent literature which compares different LPWAN technologies mostly focuses on technology-related criteria and mostly omits the governance-related ones. To clarify the role of governance-related criteria in these cases we ask the following question in our research:

How do governance-related criteria affect the technology selection in smart cities?

This question includes both, a qualitative and a quantitative component. On the one hand, the "how" of influencing calls for a classic process study examining governance-related criteria' *in technology selection in smart cities* through a qualitative lens. On the other hand, "affect" is a call to *capture these ties quantitatively*. Hence, we employ a mixed-methods research design for our study. (Creswell & Plano Clark, 2011)

4.2.3 Research setting: smart cities in Germany

In Germany, the topic of smart cities has been placed on the agenda in the last decade. Political support for smart cities has also risen in recent years. As a joint effort of stakeholders from different administrative levels as well as civil society, in 2017 the Smart City Charter[38] was passed (Federal Ministry for the Environment, Nature Conservation Building and Nuclear Safety, 2017: 24). Since 2019 the German Federal Ministry of the Interior and Community ("Bundesministerium des Inneren und für Heimat"; since the 2021 elections the Federal Ministry for Housing, Urban Development and Building – "Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen") runs a smart city program equipped with 820 million euros for ten years (as of mid-2022). So far three of the planned four selection rounds have taken place (2019, 2020, and 2021) and in total 73 German cities and communities have been chosen to participate in the program. They represent the entire spectrum of living environments: 28 large cities (>100,000 inhabitants), 13 mid-sized cities (20,000-100,000 inhabitants), ten small

[38] In German „Smart City Charta"

cities and rural communities (<20,000 inhabitants) as well as 22 intercommunal cooperations and rural districts. All program participants applied with a concept and underwent a selection process. Each season of the program had a dedicated theme: "Smart Cities made in Germany" (2019), "Common welfare and city network/network of cities"[39] (2020) and "Rising from crisis together – space for future"[40] (2021). (Federal Ministry of the Interior and Community (Bundesministerium des Inneren, für Bau und Heimat) - Referat SW III 2, Smart Cities, 2020, 2021; Federal Ministry of the Interior, for Building and Community, 2019)

Commercial firms and actors in the public sector have also engaged in smart city efforts. Several studies were published. Among the most prominent in Germany is the Bitkom e.V. study which comprises an annual ranking of all German cities with more than 100,000 inhabitants (=81 cities) regarding smart city characteristics (Lange & Pfefferle, 2021). Additionally, there was an interview-based assessment of smart city implementation progress conducted on behalf of the Federal Ministry for Economy and Energy in 2020 (Skrobek, 2020). A third study by Hilbig et al. (2020) focused on smart city infrastructures and interviewed 25 city administrations, city utilities, and private sector service providers.

4.2.4 Technology selection criteria in smart cities

When cities decide to become smart cities, they need to choose which LPWAN to implement. It will be a core element in the ICT and backbone of the smart city. For such infrastructure decisions, often the MCDM process is used. It is frequently applied in complex decision-making processes where different criteria need to be incorporated or several objectives need to be met simultaneously (Kabir, 2014). This is also the case for LPWAN technology selection decision in smart cities. For example, it was used for infrastructure decisions in urban mobility (Fierek & Zak, 2012; Zapolskytė, Burinskienė, & Trépanier, 2020) and in urban waste management (Karakuş, Demiroğlu, Çoban, & Ulutaş, 2020). MCDM comprises many methods which share a common approach (Kabir, 2014): first, important criteria are identified and then, second, those are assessed for each alternative. The evaluation across criteria then leads to the choice of the best alternative. While the assessment of criteria is highly individual for each city, the criteria used are expected to be similar.

[39] In German „Gemeinwohl und Netzwerkstadt/Stadtnetzwerk"

[40] In German „Gemeinsam aus der Krise – Raum für Zukunft"

As the meta-analysis in Chapter 2 and the interview study in Chapter 3 have shown, there are several criteria cities can use to compare LPWAN technologies. It seems that practitioners consider governance-related criteria in their technology selection and subsequent adoption. Some of them value flexibility and independence: “if we have a use case internally in our waterworks, and waterworks are usually located very remote (…) then there is no mobile coverage. (…) And in our own network we simply place a gateway there and done.” (CU-1). For others it is more about being able to exert control of the network, as they “seek to provide… stability, including the guarantee that no third-party solution provider suddenly disappears…, so that we cannot offer this service to our clients anymore” (NO-1). Both draw the conclusion that providing their own network for themselves is a way out of these governance-related dilemma. In smart cities we “strongly rely on advanced technologies innovation and governance, which are essential prerequisites for developing smart, creative, innovative, and sustainable cities” (Achilleos et al.: 384). But does this view hold true beyond anecdotal evidence?

4.3 Method

4.3.1 Mixed-methods research: exploratory sequential design

Our research aims to understand and explain if and how governance-related decision criteria are relevant for smart cities in their technology selection, yet we are still lacking clarity on the governance-related influencing factors and variables we would like to measure in a potential quantitative study. Hence, we are still seeking to explore the population of smart cities in Germany and understand how they do their technology selection. This is a research setting that “require[s] both an exploration as well as an explanation drawing from different data sources” (Creswell & Plano Clark, 2011: 17). Aiming for theory development, the exploratory sequential design with the purpose to “generalize qualitative findings based on a few individuals from the first phase to a larger sample gathered during the second phase” (Creswell & Plano Clark, 2011: 86) is most suitable for our endeavors.

The exploratory sequential design follows a straightforward procedure of – as the name indicates – sequential data collection: first, researchers conduct the qualitative study and in the second step these results are used to develop a research approach for the quantitative part. In the following this quantitative approach is then implemented as a third step of the procedure. Lastly, results from both the qualitative and the quantitative study are summarized, discussed, and then put into context. The qualitative data collection was conducted between April and August 2021, the quantitative data collection took place from February to April 2022. (Creswell & Plano Clark, 2011: 88)

For the qualitative study, we analyze the verbatim transcripts of interviews with smart city stakeholders. We used a survey among German cities to collect the quantitative data. A key question we face, as other mixed-method researchers did as well, is how we connect data and results from the different methods. This goes hand in hand with the question of how to weigh each of the studies and its results.

Connecting qualitative and quantitative research methods is less of a technical challenge, but primarily a challenge of combining different paradigms (Morgan, 1998: 363) – or worldviews as some authors prefer to state (e.g., Creswell & Plano Clark, 2011: 87). Before addressing the more challenging topic of paradigms, we discuss the practical implications of connecting our qualitative interview data with the quantitative survey data. Clearly, the quantitative data collection should be informed by and building on the results from the proceeding qualitative data collection and analysis. Both methods should not only address an isolated question but need to contribute to the overarching mixed-methods research question. "[T]he meta-inferences relate to whether the follow-up quantitative strand provides a more generalized understanding of the problem than the qualitative database alone" (Creswell & Plano Clark, 2011: 238).

Turning towards the weights of both studies and the role of the underlying paradigms in mixed-methods research, we must note that the theory-developing variant of the exploratory sequential design[41] we employ, commonly assigns a higher weight to the qualitative part of the study (Creswell & Plano Clark, 2011: 87). By no means this sequence should be understood as doubt regarding the explanatory power of qualitative studies – a possible misunderstanding with the potential to result in contentious debates, which Morgan (1998: 371) sees as a key threat to this approach. In this light, we would prefer to see both studies as of equal weight: In our case, the qualitative study explores the topic and enables researchers and readers to develop an in-depth understanding of technology selection in smart cities. The following quantitative study enables us to test the observations from the qualitative study with a larger sample and hereby enrich the qualitative data with additional information allowing for more differentiated

[41] Commonly, two variants of the exploratory sequential design can be distinguished: the first one, the here-discussed theory-development variant, usually puts a stronger emphasis on qualitative data analysis. The second one called the instrument-development variant, assigns a higher weight to the quantitative part of the mixed-methods study.

interpretations. Qualitative approaches are commonly associated with a constructivist approach while the quantitative angle usually stems from a postpositivist worldview. Both paradigms, or worldviews, entail assumptions on ontology, epistemology, methodology, and rhetoric. While historically the worldviews have often been seen as mutually exclusive, more recently authors like Morgan (2007) suggest a pragmatic approach and put emphasis on transparency regarding the worldview and political agendas of researchers. The pragmatism worldview balances the extremes of qualitative and quantitative worldviews (subjective vs. objective, specific vs. generalized, inductive vs. deductive) by "rely[ing] on a version of *abductive* reasoning that moves back and forth between induction and deduction – first converting observations into theories and then assessing those theories through action" (Morgan, 2007: 71). Summarizing our approach to research we adopt the worldview of pragmatism because of "a practice-driven need to mix methods" (Denscombe, 2008: 280). While we lean towards a more constructivist mindset during the qualitative study - allowing us to explore the complexity of technology selection in the smart city context with many different stakeholders with multiple perspectives – we lean more towards a postpositivist mindset during the quantitative study. This enables us to identify, measure and interpret the collected data with statistical precision. (Creswell & Plano Clark, 2011; Denscombe, 2008)

Applying this exploratory mixed-method approach to the adoption of a novel technology is not an unknown endeavor. A similarly structured mixed-methods approach has been used by Tu (2018) to study the adoption of the IoT by Taiwanese logistics and supply chain companies as well as by Wunderlich, Veit, and Sarker (2019), who studied smart metering technologies' adoption by German households with interviews and a following survey, too. Another example close to our setting is the study by Nair, Chellasamy, and Singh (2019). They study information technology adoption among Indian small- and medium-sized companies. All three studies focus on organizations as adopting units.

4.3.2 Qualitative study design

The exploratory qualitative study aims to clarify the role of governance-related criteria in technology decisions. This also includes aspects such as the actors involved, timing, technology selection process, the resulting technical setup, and the influence of bigger targets on the LPWAN selection. Such an explorative question is inductive, aims to develop a theory, and can be captured best through semi-structured interviews (Arsel, 2017: 940). A semi-structured interview provides access to an "observer's report on the topic under study" (Weiss, 1994: 7). Hence, it allows researchers to study phenomena they did not experience themselves, either because they happened in the past, in other places, or in an organization the researcher is not part of. We as researchers were not present when cities chose their technologies for smart cities, so we decided to collect information on these decisions by interviewing the people who were there.

Population. Our unit of observation are German cities that have already debated, started to implement, or already implemented smart city. Multiple stakeholders such as city administration, a city's utilities, civil society, potentially local network operators, and – mostly in rural areas – also the district's administration is involved in the realization of smart city implementation. We aim to interview representatives of the different groups. Moreover, German cities differ enormously in size from a few thousand inhabitants to several million, hence, we also interview stakeholders from cities various sizes.

Sampling. As many other interview studies, we employ purposeful sampling to ensure our interviewees represent all stakeholder groups and come from a variety of city sizes and districts (Arsel, 2017: 944; Langley & Abdallah, 2011: 111). Based on desktop research on publications and newspaper articles on smart cities, German cities were contacted via email, and in roughly half of the cases the contacted person agreed to an interview.

Ethical considerations. Major ethical pitfalls in qualitative data collection through interviewing include revealing identities and dubious bargains, like promising support for the interviewee's agenda in turn of participation in an interview, – others, like researching vulnerable groups, are not applicable to our setting (Silverman, 2014: 141–161). Before starting the interviews, interviewers briefly introduced themselves and the research goals, granted anonymity, and asked participants for their informed consent including for recording the interview for later verbatim transcription. No financial compensation was offered to participants. Only at the end of the interview the interviewees were offered to receive updates on the research via email. Interviewees are granted anonymity in this qualitative study; hence, their cities' exact population cannot be revealed, but are only classified roughly.

Data collection. Between April and August of 2021, we conducted 19 interviews with representatives of city administrations (10), cities‘ utilities (4), civil society (1), district administration (2) and local network operators (2) via virtual meeting tools (Zoom), as shown in Table 5. We conducted the interviews of 33 to 68 minutes, totaling 15:45 hours, and produced a verbatim transcription for all of them[42].

Table 5 Overview of semi-structured interviews with smart city stakeholders

Acronym	Classification	Role of interviewee	City size (population)	Duration (hh:mm)
CA-1	City administration	Staff position smart city	>100,000	00:39
CA-2	City administration	Head of Digitization and IT	<50,000	00:44
CA-3	City administration	Head of the Bureau for Digitization	50,000-100,000	00:53
CA-4	City administration	Head of IT Applications and Digitization	>100,000	00:43
CA-5	City administration	Chief officer and Chief Technology Officer (CTO)	<50,000	00:48
CA-6	City administration	Project Manager Smart City	50,000-100,000	00:49
CA-7	City administration	Chief officer for Technology and Environment	<50,000	01:02
CA-8	City administration	Team member digitization and IT	<50,000	00:45
CA-9	City administration	Innovation manager in the IT department	>100,000	00:46
CA-10	City administration	Chief Digital Officer (CDO)	>100,000	00:57
CU-1	City utility	Team members digitization (2 people interviewed)	>100,000	00:42
CU-2	City utility (utility-affiliated company)	Project Manager	>100,000	00:45
CU-3	City utility	Head of power and business development	>100,000	00:33
CU-4	City utility	Senior Systems Engineer	>100,000	01:08
CE-1	Civil engagement - rural area	Founder of local The Things Network (TTN) community	District; >100,000	00:49
DA-1	District administration	Head of the local business development agency	District; >100,000	00:45
DA-2	District administration	Chief Information Officer (CIO) of the district	District; >100,000	01:00
NO-1	Local network operator for a district	Project Manager Smart City	District: >100,000	00:53
NO-2	Local network operator for a city	Chief Technical Officer (CTO)	50,000-100,000	01:04

Data analysis. In line with the pragmatism-approach to this mixed-methods study, we follow a grounded theory approach in the qualitative study (Corbin & Strauss, 1990: 4). This study aims to develop a novel theory on the role of governance-related criteria in technology selection based on our interview data, which is commonly achieved using the grounded theory coding procedures (Flick, 2009). We use MAXQDA during our data analysis and label the data following an open coding approach, establish connections between the different elements using

[42] 7 out of the 19 interviews were already used for the LPWAN study presented in Chapter 3. For this study in Chapter 4 they were re-coded with a specific focus on smart cities. Namely, these interviews are CA-1, CA-10, CE-1, CU-1, CU-4, DA-11, NO-2.

axial coding, and use selective coding to sharpen and condense our findings – all three coding approaches are used in an iterative way, even influencing further data collection (Corbin & Strauss, 1990: 4). This "continual movement between data … and theory … [ensures] that data analysis is theoretically based and theory is grounded in data" (Silverman, 2014: 123). In our case, we coded 599 text excerpts, organized them in up to four levels of detail, and structured the findings along technology selection context, process, and outcome. The iterative process was concluded once theoretical saturation was achieved, meaning additional data did not yield novel insights anymore.

Validity. In qualitative research, validity can be assessed by evaluating various criteria: "credibility, authenticity, criticality, and integrity" (Whittemore, Chase, & Mandle, 2001: 529). Cautious interpretation (credibility), remaining true to the phenomenon (authenticity), an open mind, and high awareness of potential own biases and influences of the researchers (criticality), as well as their integrity when it comes to data collection and processing, are needed (Creswell, 2016: 208; Whittemore et al., 2001: 530). In our study, we aim to establish credibility by making our sampling, data collection, and coding process very transparent. Verbatim transcriptions and voice recordings allow us to interpret the interviews diligently, and we present excerpts from the interviews in our Findings section (4.4) to show the relationship between the primary data and our interpretation. By dedicating several paragraphs to our research approach and its limitations, including subjectivity, later in the discussion, we aim to satisfy the criterion of criticality and integrity. Additionally, the survey serves as a tool for data triangulation, and this contributes to our study's validity (Creswell, 2016: 208; Langley & Abdallah, 2011: 112; Reeves et al., 2013: 1369).

Reliability. Reliability refers to the replicability or reproducibility of the results. Recordings of the interviews and verbatim transcriptions also help here to collect researcher-independent data for the following analyses and, as a result of this, contribute to reliability. (Creswell, 2016: 209; Silverman, 2014: 83)

4.3.3 Quantitative study design

The second, the quantitative part of our exploratory sequential mixed-methods design, aims to generalize the findings generated through the first method. Shifting gears from the rather constructivist to a postpositivist mindset, our focus now lies on generating a representative dataset. If there is no data available yet meeting the analysis needs – as it is in our case – a survey is well-suited to collect this data (Fowler, 2010: 3). For data collection, we opted for an online self-administered study for three reasons: First, a large data set is needed for statistical analysis and hence calls for a standardized questionnaire with – as a second reason – manageable effort in execution; a survey leaves participants the choice at what time of day to respond; and third, as we could not always identify and contact the most suitable respondent within a city's administration the online survey offered the advantage that it could easily be forwarded when required. The ongoing Covid-19 pandemic and remote working made it seem unlikely that a paper-based solution would reach participants in time and be returned, so a web-based solution seemed most promising (Creswell & Plano Clark, 2011: 7–8).

Population. The target population or sampling frame consists of German cities and communities with more than 20,000 inhabitants and accounting for more than 60% of the German population, which I considered potential smart city implementers. In total, 10,796 communities existed in Germany as of December 31st, 2020. In line with existing smart city studies in Germany and their findings, we defined a minimum size of 20,000 inhabitants for a city to be considered in our study. This number results from Skrobek's study (2020), which found German cities with more than 20,000 inhabitants to be much more likely to have a digitization strategy than the smaller ones, where not even every fifth community has developed a digitization strategy yet. Hilbig et al.'s (2020) interview study on smart cities in Germany supports this number implicitly: their smart city examples are from cities with roughly 20,000 inhabitants or more, even though a clear cutoff was not mentioned. The six cities with which the authors conducted interviews are described as "heterogeneous" with regards to their size and location (Hilbig et al., 2020: 23). A third study, the Bitkom e.V. Smart City index, set the cutoff higher and considers only large German cities with more than 100,000 inhabitants (Lange & Pfefferle, 2021). As we aim to gather a more extensive sample beyond the 81 cities addressed by the Bitkom e.V. Smart City index and expect to see the association of city size with its LPWAN infrastructure details, we opt for the cutoff at 20,000 inhabitants. This gives us a sampling frame of 666 German cities representing almost 59% of the inhabitants of the country (~50 million) (Destatis - Federal Statistical Office, 2021d).

Despite being the unit of analysis, cities as institutions will be represented by a single person providing these answers. Other authors have used this approach (e.g., Zhu et al., 2006). It's not a risk-free approach: Hilbig et al. (2020) found that a city's administration focuses on digitizing processes, whereas the city's utility is generally more interested in infrastructure and network aspects. As either of them could be our survey respondents, we included a question regarding the respondents' roles and positions in the city.

Sampling. Traditionally, hypothesis-testing studies employ statistical sampling, which later allows for statistical analysis (Eisenhardt, 1989: 537). We also aim to draw a representative sample from the 666 cities in the sampling frame. We relied on several channels to contact these cities: the association of German cities and towns[43], a list of all German cities in the sampling frame, specialized LinkedIn groups, and interview partners of the qualitative part of this study. The association of German cities and towns distributed the survey to its direct and indirect members, representing more than 60% of the German population (53 million inhabitants). In addition, we used a list of all German cities in the sampling frame with manually collected email contact details of the Chief Digital Officer (CDO), head of IT, or a similar position from publicly available online sources. In around ten percent of the cases, it was not possible to find such a person within ten minutes of online research; those were excluded from the mailing list. Cities' representatives were approached via a personalized email and received a reminder to complete the survey roughly one week after the first contact. Moreover, contacts from previous qualitative interviews were invited to answer the survey, and two German-speaking LinkedIn groups of city representatives working with smart cities.

Ethical considerations. The survey was anonymous, and as respondents were expected to be civil servants, no monetary reward could be paid. As an incentive, we offered participants to receive the study results, including a customized evaluation of the respective city's position relative to the sample.[44]

Survey design. The survey was conducted in German to remove language barriers and avoid misunderstandings; both the original German survey and the English translation can be found in Appendix D. All pretest participants, and the authors of this survey, are native speakers of German. The careful wording of questions is essential in self-administered surveys yet does not follow codified rules (Bradburn et al., 2004) – or in other words: "There is no one correct way to formulate questions" (ibid. 2004: 136). We followed an iterative process for the survey design and received feedback from two representatives of the association of German cities and towns. For standard questions on education or alike, we used the Leibniz Open Access Repository for Measurement Instruments (Leibniz Institute for the Social Sciences, 2022).

[43] The association directly represents 195 cities as of October 31st, 2020, and as of December 31st, 2020, additional 2,992 cities are indirect members through other umbrella organizations Deutscher Städtetag (2021: 93).

[44] The document sent out to survey participants afterwards was in German. It was compiled as part of a project study conducted by Niklas Karlin and Valentin Mayer under our supervision in 2022. The customization was done by highlighting the given responses in the graphics. The non-customized report is available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4245680.

Moreover, we screened the existing smart city studies in Germany to replicate wording and ensure the completeness of answer options. The survey was implemented using the SoSci tool.

Survey pretests. A survey must undergo pretesting before being distributed as part of the quality assurance. In addition to careful reviews by the survey designers, this must include exposure to the real world (Bradburn et al., 2004). We conducted three types of pretests: an online pretest with feedback, an online pretest, and a cognitive think-aloud test addressing the quality perception, duration, and understandability of the questionnaire, respectively. The *online pretest with feedback* addresses the clarity of instructions and options as well as the usability features of the survey. Feedback provided by testers can, for example, point out difficulties with questions and gives researchers a chance to improve the survey questions and design iteratively (Bradburn et al., 2004: 129; Weisberg, Krosnick, & Bowen, 1996: 100). Ten testers answered the survey in a pretest and commented their observations regarding wording, layout, instructions, and answer options directly next to each question in the SoSci tool. The *online pretest* aims to assess the duration to complete the survey. Since the drop-out rate of a survey correlates with the length of the survey (Ganassali, 2008), this is a crucial consideration for successful data collection via a survey and is commonly tested with survey *pretests* (Weisberg et al., 1996). The smart city survey aimed for around 15 minutes to complete, but as the number of pages shown depended on the selection of technologies used in the city, it was clear that execution times would differ significantly. Nine testers participated in the online survey pretest, on average taking 13:32 minutes to complete the survey. This was considered an appropriate duration for the survey. Lastly, in the *cognitive think-aloud test*, five testers took the survey and simultaneously verbalized their thoughts aloud. This testing technique allows to unveil misunderstandings and unclear questions (Weisberg et al., 1996: 100). These potential misunderstandings can – among others – be caused by inconsistent wording, complicated questionnaire design, or layout (Collins, 2003: 235). Additional observations by the interviewer can help to identify confusing points or misunderstandings, e.g., if "respondents take a long time to answer a question, it may suggest the question is either confusing or difficult to answer" (Fowler, 1995: 131). As a "self-administered questionnaire … must depend entirely on the questions and written instruction to elicit accurate responses" (Bradburn et al., 2004: 12), unambiguous wording is essential and was ensured by this third pretest type.

Data collection. The survey data was collected between the 1st of February and the 1st of April 2022 through different channels, as listed in Table 6. 562 clicks on the survey links resulted in 252 attempts to fill out the survey questionnaire with 118 (equivalent to 21 percent or 45 percent, respectively) completing the survey. Of those 118, three participants disagreed with the privacy conditions, and thus, the survey finished after the first page for them. Subtracting those, 115 complete and usable responses remain as the data for further analyses. As expected, participants in earlier interviews were much more likely to complete the questionnaire (group “Interview partners” where five out of six completed the survey), whereas in most other groups, around half of the people starting the survey then completed it. Most respondents who did not finish the survey left it before or on page four (out of 15), which suggests they did not stop for length but for other reasons. For seven cities, two or more respondents from the same city answered the questionnaire. Accounting for these duplicates there remains a total of 107 cities in the dataset.

Table 6 Channels for survey distribution and responses

Medium/Target group		**Clicks on the link**	**Number of complete, usable responses (total attempts)**
List of German cities via personalized email	Wave 1	129	8 (18)
	Wave 2	53	14 (29)
	Wave 3	41	9 (24)
	Wave 4	93	29 (58)
Others	Association of German cities and towns	210	48 (109)
	Smart city LinkedIn-groups	29	2 (8)
	Interview partners (from qual. interviews)	7	5 (6)
Sum		562	115 (252)

Validity. Internal validity, which includes the validity of instruments and constructs used in the survey, must be distinguished from external validity, which aims to ensure that survey results and research outcomes contribute to the existing knowledge base and are consistent. As “[i]t’s pointless to ask questions about external validity until you establish internal validity” (Bernard, 2013: 95), we first discuss internal validity aspects before we move on to external validity.

Internal validity. Instrument validity is a critical component of internal validity. It ensures the instrument is actually measuring what it is intended to measure and with this also is the basis for data validity after conducting the survey, as Weisberg phrases it: “they [questions; authors’ note] should measure the concepts they are intended to measure”

(Weisberg et al., 1996: 94). For a start, six researchers where only two were familiar with the subject, read the survey and ensured it is well understood. Additionally, two members of the association of German cities and towns reviewed the questionnaire. With this we established what is often being referred to as “face validity”: consensus among researchers and an expanded group of non-participants. In addition, the iterative testing included think-aloud tests as a form of cognitive tests – a well-established method to ensure instrument validity – and hereby also ensured instrument validity for the survey (Bernard, 2013: 45–46; Bradburn et al., 2004: 120).

Out of Bernard’s (2013: 95–98) seven threats to internal validity, six are much more critical to longitudinal studies desiring a stable respondent group. Selection bias, however, clearly needs to be discussed for this survey. During data collection we decided to focus on cities larger than 20,000 inhabitants. From an interpretation angle, this focus on cities above 20,000 inhabitants in an urban structure makes very much sense: Hilbig et al. (2020) pointed out in their study, the requirements between urban and rural areas with regards to smart city concepts differ and our study targets the urban spaces. Thus, we expect to be able to contribute to expand existing knowledge around Smart City, but conclusions cannot be extended to the rural areas without further research.

External validity. To allow for generalizations beyond the sample of this survey external validity needs to be established. A first aspect – validity of the data – can be derived from instrument validity. However, data alone does not yet establish external validity, a potential non-response bias can pose a serious threat to external validity and finding validity needs to be evaluated in the context of existing domain knowledge. (Bernard, 2013: 94) There are good reasons to assume a nonresponse bias in our survey: cities which are currently not pursuing a smart city strategy, might be less likely to answer a 10-15 min survey on smart city. They may feel as if they cannot contribute. The share of those cities could be around 20%, as Skrobek (2020: 8) found that 78% of the cities and municipalities were in conceptualization or implementation phase of smart cities in 2019 and this number has only increased in the past three years. This led us to conclude that the non-response bias is relatively small in our survey. The challenge with nonresponse is that “with a lot of nonresponse, all you know is that you’ve got bias but you don’t know how to take it into account” (Bernard, 2013: 241). Hence, for discussion and conclusion of this survey’s results we limit our generalization for smart cities, but implications for cities which are not yet undertaking efforts to become a smart city need to be discussed with great caution. Support for external validity can be collected through a comparison of our results with the existing knowledge. Comparing our survey data to existing smart city studies, we find a good overlap between the cities' self-assessment regarding their smart city maturity in our survey with the rankings from the Bitkom e.V. study (2021). Both have 33 cities in common and we can see a notable, highly significant correlation between the Bitkom e.V. ranking in the category "IT and communication" and the cities' self-assessment in our survey, as Table 7 shows.

Table 7 External validity: survey and Bitkom e.V. study correlation

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Bitkom rank	1.000							
(2) Bitkom score ***total***	-0.976 (0.000)	1.000						
(3) Bitkom score ***administration***	-0.736 (0.000)	0.739 (0.000)	1.000					
(4) Bitkom score ***IT & communication***	-0.813 (0.000)	0.860 (0.000)	0.516 (0.002)	1.000				
(5) Bitkom score ***energy* & environment**	-0.775 (0.000)	0.793 (0.000)	0.519 (0.002)	0.670 (0.000)	1.000			
(6) Bitkom score ***mobility***	-0.829 (0.000)	0.852 (0.000)	0.590 (0.000)	0.728 (0.000)	0.537 (0.001)	1.000		
(7) Bitkom score ***society***	-0.830 (0.000)	0.835 (0.000)	0.575 (0.000)	0.600 (0.000)	0.528 (0.001)	0.608 (0.000)	1.000	
(8) ***Survey*** self-assessed smart city maturity	-0.390 (0.025)	0.405 (0.019)	0.191 (0.286)	0.473 (0.005)	0.317 (0.072)	0.384 (0.028)	0.272 (0.125)	1.000

n=33; spearman=0.4021; p=0.0204

Reliability. Reliability is "whether or not you get the same answer by using an instrument to measure something more than once" (Bernard, 2013: 46). To test this survey for reliability, we adapt the common test-retest approach, where usually one respondent is asked to complete the same questionnaire a week later or so again. (ibid. 2013: 47–48) For this survey we exploit the fact that respondents of the survey are not the same as the unit of analysis: for six cities two respondents submitted a complete questionnaire and for one city even three respondents did so. This provided an opportunity for the assessment of reliability. Moreover, as the unit of analysis in this research is the city, this meant that the information had to be aggregated on that level for further analyses.[45] Thus, for all cities with more than one response,

[45] Alternatives are (1) to select one response as the leading one and discard all others, (2) to exclude the city completely from the data set or (3) to keep all responses. These three alternatives did not seem appropriate for the following reasons: (1) would rely on the researchers outside-in assessment of the quality of the answers. The questions on qualification of the respondents could be leveraged, but would favor those respondents, who overestimate their own qualification. (2) would have removed in total 15 answers from the data set and reduced it

the answers were integrated into one harmonized response. We reviewed and harmonized the data manually[46]; only minor deviations were observed between respondents from the same city and thus reliability of the answers was supported.

Survey data post processing. The survey data was enriched with information on municipal debt, population, and political power situation (mayor's party, share of political parties in the city parliament). The postal code provided by survey respondents was first mapped to the cities' names, federal state, and population using a comprehensive database (containing all German communities provided by Destatis - Federal Statistical Office (2021a)). In a second step, this information was then used to find debt figures for these cities in the data of each federal state's statistical office (Bavarian Statistical Office, 2021; Information and Technology North Rhine-Westphalia Statistical Office, 2022; Office for Statistics Berlin-Brandenburg, 2021; Statistical Office for Baden-Wuerttemberg, 2022; Statistical Office for Hamburg and Schleswig Holstein, 2021; Statistical Office for Hesse, 2021; Statistical Office for Lower Saxony, 2021; Statistical Office for Mecklenburg Western Pomerania, 2021; Statistical Office for Rhineland Palatinate, 2022; Statistical Office for the Free State of Saxony, 2021; Statistical Office for Thuringia, 2022). The most recent available closing date from most of the federal statistical offices was December 31st, 2020. Mapping at this stage was executed manually as different structures of the databases did not allow for automation. In a third step, the data was manually enriched with desktop research information. These included the party of the mayor in office and the political parties in the city parliament, as they were during most of the year when the city started its smart city efforts.

Analyses. To see if political parties do have any influence on the advancement of smart city concepts, we will conduct Mann-Wilcoxon-Tests. For the broader topic of governance-related criteria, we run a set of analyses: first, we examine the relationship between the city and its citizens – in classic principal-agent-thinking, the city can be seen as a representative of the citizens' interests – in factor analysis. We then investigate the influence of the identified factor,

to an n=100. This was seen as very disadvantageous for further analyses. (3) would imply to count cities with more than one response in the survey double or triple, respectively. Moreover, analyses would rely on inconsistent data or conflicting data for the same city.

[46] For reasons of transparency we lay out the guidance we followed for creating these harmonized responses: (1) Maximum principle: in binary we used the maximum value. The underlying assumption is that respondents might be unaware of some activities in their own city. Thus, as soon as one respondent explicitly states that something exists in the city, the harmonized data for this city reflects this response. (2) Average for scaled questions: in questions with scales, mostly Likert-scales, the average of the responses is used. (3) Consistency for count-values: some variables are counts. They summarize factors within a question, for example, they count how many factors (being binary variables) were selected. In the harmonized data we simply calculated the count values accordingly.

as well as further criteria (the city's debt, city size, etc.), on the actual self-provisioning of a city through a probit regression.

Response demographics. The large majority (103, 90%) of the 115 respondents who completed the survey were city employees, which is not surprising considering the chosen distribution channels. The remaining respondents were either employed at one of the cities' utilities (9, 8%), worked for external IT service providers (3, 3%), or worked in the district administration (1, 1%). Respondents were asked two questions about their self-perceived qualification for their work with smart cities in line with the 6-level Likert-scale competency assessment proposed by Fischer, Schwemmle, Johannsen, and Schmid (2018). The statements, items two and six from Fischer et al.'s (2018) scale, assess perceived familiarity with required concepts and technology[47] and topicality of the own knowledge[48]. Almost 90% of the respondents consider themselves at least partially familiar with the relevant concepts and technologies. Slightly fewer, around 75%, at least "partially agree" that their knowledge is topical. The items are strongly correlated (Spearman rank correlation $\rho=0.60$, $p=0.00$), and the contingency table (Table 8) shows that the level of agreement with the familiarity question is nearly always higher than or equal to the level of agreement with the topicality question, which is plausible.

[47] Question in German phrased as: "Uns interessiert Ihre persönlich wahrgenommene fachliche Kompetenz für die Arbeit im Kontext der Smart City. Es keine richtigen oder falschen Antworten – es zählt Ihr persönliches Empfinden. Wie sehr stimmen Sie diesen Aussagen zu? (1) Bezüglich des benötigten Wissens bin ich auf dem Laufenden." English translation: "We are interested in your personally perceived professional competence for the work in context of smart city. There are no right or wrong answers – your personal assessment counts. How much do you agree with following statements? (1) With regards to the required knowledge I am up to date."

[48] Question in German phrased as: "Die für meine Arbeit bedeutsamen Konzepte und Technologien verstehe ich." English translation: "I understand the concepts and technologies which are relevant for my work."

Table 8 Contingency table of competency assessment

n=115 *Numbers are absolute values.*		"I understand the concepts and technologies which are relevant to my work" Don't know	Fully agree	Mostly agree	Partially agree	Still agree	Rather don't agree	Don't agree at all	Total
"With regards to the required knowledge, I am up-to-date"	Don't know	2	0	0	0	0	0	0	2
	Fully agree	0	12	2	0	0	0	0	14
	Mostly agree	0	7	22	7	0	0	0	36
	Partially agree	0	2	22	11	0	0	0	35
	Still agree	0	1	2	3	3	3	0	12
	Rather don't agree	1	1	1	3	7	2	1	15
	Don't agree at all	0	0	0	0	0	0	1	1
	Total	3	23	51	28	5	4	1	115

Asked about sources of their general knowledge on the topic of smart cities (

Figure 8), the option *freely accessible (online-) media* was ticked most frequently (by 77% of respondents), followed by an *exchange with other cities* (64%), and *conferences and symposia* (52%). While the option *other, e.g., studies, external training* was ticked least frequently, 87% of respondents (100 out of 118) left their email address to receive the survey results.

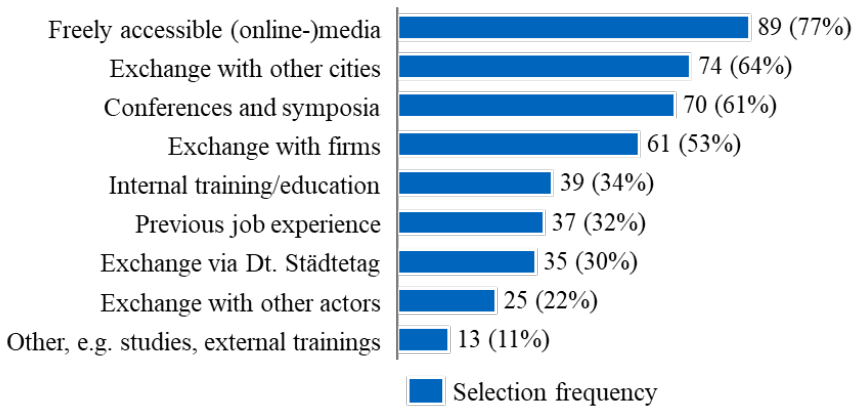

Figure 8 Sources of respondents' knowledge on smart city – "Knowledge acquisition via..." (n=115, three respondents didn't provide an answer; number of selected items and)

We assess the representativeness of the sample regarding size distribution and geographical location (federal states in Germany differ significantly with respect to wealth and digitization) (Destatis - Federal Statistical Office, 2020). Regarding geographical representation, the sampling has worked well: 107 cities from 14 federal states (out of 16) participated in the survey. Only Berlin and Saxony-Anhalt, which jointly account for 7.0% of the German population, are not represented in the sample. The top three federal states in terms of population (North Rhine-Westphalia, Bavaria, and Baden-Wuerttemberg) are also the top three federal states in the sample, as Figure 9 shows.

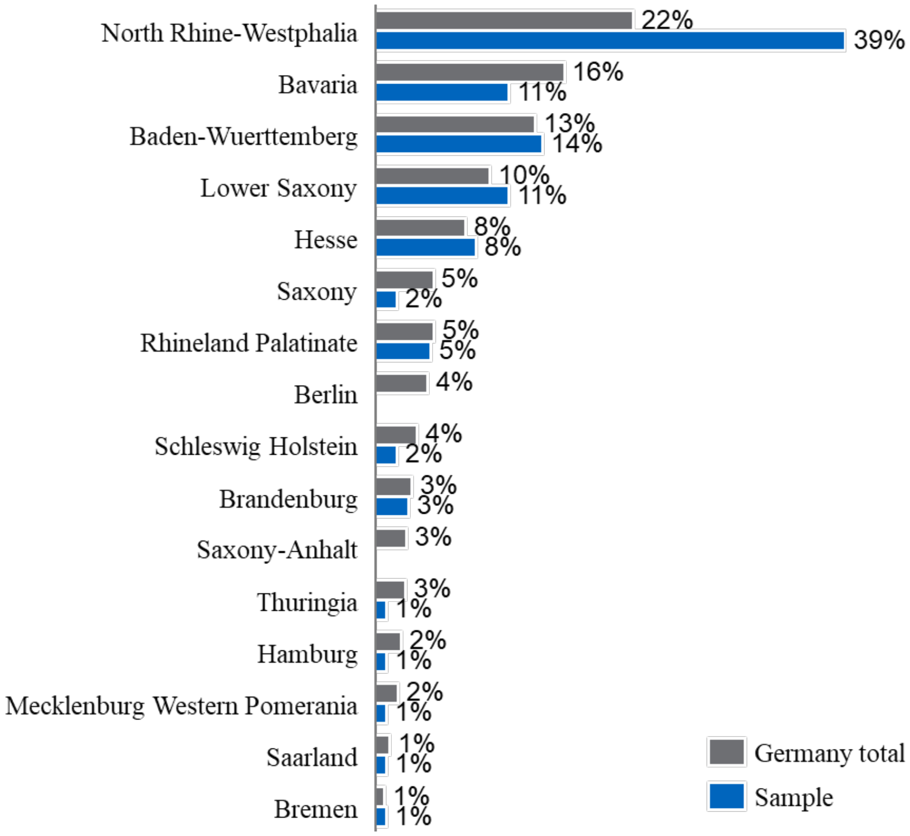

Figure 9 Distribution of population across federal states in the sample and in Germany in total (Destatis - Federal Statistical Office, 2021c; own survey data)

The sample represents 16.1% of the cities in the sampling frame and 1% of all communities in Germany (10,796). At the same time, the cities in the sample are home to 19.2% of the German population (15.97 million people). Also, descriptive statistics (Table 9) show that cities in the sample are larger on average than the cities in the sampling frame (Destatis - Federal Statistical Office, 2021c, 2021d). Two cities in the sample have less than 20,000 inhabitants; we decided to keep them in the sample, nevertheless.

Table 9 Descriptive statistics of sampling frame and sample (Destatis - Federal Statistical Office, 2021d; own survey data)

Population [inhabitants]	N	Average	Median	Maximum	Minimum
Sampling frame (cities with more than 20,000 inhabitants)	666	73,047	34,629	3,664,088	20,003
Sample (all cities in the dataset)	107	150,346	59,282	1,852,478	14,213

4.4 Findings

4.4.1 Findings from the qualitative study

In the following, we report our key findings with regards to the "how" of the technology decision in smart cities, organized along the following dimensions: (1) decision context and motivation to engage in smart city, (2) technology decision process and criteria applied in the decision making and finally (3) the resulting smart city LPWAN setup.

(1a) Smart city contributes to sustainability and democracy in urban and regional development.

The smart city is frequently mentioned as a key element in the city's strategy or as a key element in the regional development agenda. The goals of these strategies and agendas are democracy, resilience or independence, and sustainability. Frequently, interviewees also mention the imperative to create value for citizens, be it through innovations, jobs, or improved living conditions in the city.

> *"I would say we understand the smart city as a process which we, as a city, shape so that digitization supports our urban development."*[49] *(CU-1)*
>
> *"Again and again, we care about new jobs, new innovations, and value creation."*[50] *(DA-1)*
>
> *"[I] have the impression that actually people with a very sustainable mindset gather in this movement [smart city; authors' note], and for that reason, they bring a lot of innovation – a lot – and good ideas into the municipalities. So, my wish is that in the*

[49] Translation of the German statement: „also würde ich sagen, dass wir Smart City verstehen als einen Prozess, den wir als Stadt gestalten, [so] dass Digitalisierung uns bei der Stadtentwicklung hilft."

[50] Translation of the German statement: „Uns geht es ja immer wieder um neue Arbeitsplätze, neue Innovationen, neue Wertschöpfungen."

end, we manage to develop a sustainable city and ecologically sensible city, too. And that, if we need data, we have the possibility to collect it but not at all costs(…) in principle, I can digitalize everything. But the question is: what do I want to achieve?"[51] *(CA-6)*

Some see smart cities as one component of "digital services of general interest":

"For us, from a city's viewpoint, accessibility is the critical point. Can we offer our city's citizens that [LoRaWAN connectivity; authors' note] as a freely accessible medium as part of the digital infrastructure or services of general interest, just like streets and lightning?"[52] *(CA-2)*

Interviewee CA-6 also point out the connotation of surveillance and the transparent man that the term "smart city" might carry for some people and emphasizes the importance of sustainability.

(1b) Citizens are principals, a key stakeholder in the adoption process, and a source of innovation for cities.

Cities perceive a moral imperative to engage with their citizens and to ensure their participation in smart city endeavors. One reason for that is the fact that cities receive their money as taxes from their citizens and hereby feel a moral obligation to ensure public access to the network – in classic stewardship theory terms, one would say "the city acts as the steward of the citizens."

"The community thought has caught me. And we are a participatory city (in German, the term 'Mitmach-Stadt' is rather colloquial and has the connotation of low barriers; authors' note). We, [city name], have that in our claim. We do a lot with citizen participation. We have hardly any processes in which citizens are not involved, in one way or the other." (CA-7)

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[51] Translation of the German statement: „Aber er ist eigentlich zweitrangig, weil was dahintersteht, das deckt sich vielerorts und ich habe das Bild, ja, einfach den Eindruck, dass da hinter dieser Bewegung versammeln sich eigentlich Menschen, die eine sehr nachhaltige Wertevorstellung haben und deswegen auch viele Innovationen, viel Innovation und gute Ideen eigentlich auch in Kommunen reinbringen. Und deswegen ist meine Wunschvorstellung eigentlich, dass wir. Im Endeffekt eigentlich schaffen, eine nachhaltige Stadt zu entwickeln und auch eine ökologisch sinnvolle Stadt zu entwickeln. Wenn wir Daten brauchen, haben wir die Möglichkeit, sie zu erheben, aber nicht um jeden Preis. Im Prinzip, (…) ich kann im Grunde alles digitalisieren. Die Frage ist halt immer nur, was möchte ich erreichen?"

[52] Translation of the German statement: „Für uns aus Stadtsicht ist denke ich der entscheidende Punkt die Zugänglichkeit. Können wir unserer Stadtgesellschaft das im Rahmen der digitalen Infrastruktur oder Daseinsvorsorge so wie Straßen oder Beleuchtung anbieten als frei zugängliches Medium."

> *"We as a city realized that if we buy a gateway with tax money, we also want to provide it to the community, of course."*[53] *(CA-2)*

Besides that, cities emphasize the importance of open networks for the participation of their citizens. They view participation enabled by an open network to accelerate the acceptance of smart cities among their population. Moreover, they see a chance in that to benefit from collaboration in terms of innovative ideas developed by makers in their population.

> *"…so, we decided to offer this basic infrastructure so that every citizen can use it, and hereby we increase acceptance of such topics [i.e., digitalization and smart city] and enhance the understanding of it. But also, to create that community spirit of the digital transformation … to finally increase the acceptance."*[54]*.(CA-9)*

> *"But it [the LoRaWAN] is open and free of charge. And this is important because we have a large maker scene on this level, especially around LoRa, and they drive innovations, and you don't learn about that if you establish a paywall."*[55] *(CA-7)*

Cities have found a variety of settings to engage with and involve citizens in their smart city efforts, ranging from information meetings, hackathons, competitions, and open workshops where citizens can learn and co-create to an institutionalized digitization council that serves as an advisory board to the city council. Two exceptions were mentioned as a threat to citizen involvement: time pressure during the implementation of an LPWAN kept one district from involving citizens from the beginning (DA-2), and another city lost its close ties with its citizens during the Covid pandemic and struggled to re-establish regular exchange (CA-4).

Going forward, many cities (CA-1, CA-2, CA-5, CA-9, DA-2) aim to follow an open data approach to make the non-security-critical data collected by the city's sensors available to the citizens. Again, this is justified by considerations around financing through tax money (CA-5), data sovereignty (CA-5), and an overall strategy with the thought "the city belongs to all"

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[53] Translation of the German statement: „Also wir als Kommune haben festgestellt, dass wenn wir ein Gateway kaufen aus Steuergeldern, möchten wir es natürlich auch der Allgemeinheit zu Verfügung stellen."

[54] Translation of the German statement: „… wir uns dazu entschieden haben, diese Basisinfrastruktur zur Verfügung zu stellen, damit eben jeder Bürger oder jede Bürgerin entsprechend das dann auch nutzen kann und dadurch dann aber auch die Akzeptanz für solche Themen zu erhöhen, um eben auch das Verständnis für solche Dinge zu erhöhen. Und aber auch um irgendwie dieses Gemeinschaftsgefühl des digitalen Wandels zu schaffen, … dann entsprechend die Akzeptanz zu fördern."

[55] Translation of the German statement: „Aber es ist offen und es kostet nichts. Und das ist wichtig, weil wir haben eine Maker Szene auf der Ebene gerade auch bei Lora, wo halt unheimlich viel Innovation treibt und die kriegst du nicht, wenn du da eine Paywall ziehst."

at its heart (CA-1, CA-5, DA-2). In doing so, cities see several challenges, such as visualization and format of high usability, as one interviewee also pointed out (CA-10).

> *"Here we refer to this paper of the digital summit ... and follow the approach of interlaced open data and open infrastructure resulting in an open region. That means we, as a city, provide infrastructure as well as data openly. Currently, we're just at the point to build up the infrastructure, but there are already discussions ongoing to establish an open data structure in the region, too."*[56] *(CA-2)*

(2a) There are a variety of approaches towards technology selection: conscious or by chance, use case-driven or technology first.

There is no single path apparent by which cities select an LPWAN technology and develop their use cases. Some interviewees described it as a "hen-egg-paradox" (CA-7) or more explicitly stated that "use cases expect a nice network, and a nice network expects use cases" (CU-4). This is also reflected in the fact that several cities first chose an LPWAN technology, set up the network, and then started looking for use cases (e.g., CA-3, CA-5, CA-6, CA-10, CU-1, CU-3), whereas others did it the opposite way around, starting from a specific application and identifying the most suitable network technology (e.g., CA-7, CA-8, CU-2, DA-1, NO-1). Several cities were simply inspired by the implementation of LoRaWAN in other cities and did follow their example without having a conscious technology selection:

> *"We simply had that idea of LoRaWAN from [name of another city], and then it quickly became obvious for us as [organization's name] that this is the technology on which we want to build upon and that we do not need to look into other technologies."*[57] *(CA-2)*

Also, implementation of the network in cities does not always start at scale but might initially also work rather as a startup-like project within a larger organization and, as CU-4

[56] Translation of the German statement: „Da beziehen wir uns auf dieses Paper des Digitalgipfels … und haben eben diesen Ansatz diese Verwebung aus offenen Daten und offener Infrastruktur, bildet für uns dann diese Open Region. Das heißt wir als Kommune stellen die Infrastruktur aber auch die Daten offen zur Verfügung. Wir sind gerade erstmal an dem Punkt die Infrastruktur aufzubauen, aber es gibt schon Überlegungen, auch eine Open Data Struktur in der Region aufzubauen."

[57] Translation of the German statement: „Das lag einfach daran, dass wir diese Vorstellung über LoRaWAN von [Name einer anderen Stadt] hatten, und da war für uns als [Name des regionalen Verbunds] dann eigentlich klar, dass das die Technologie ist, auf der wir aufbauen wollen und wir müssen uns jetzt andere Technologien gar nicht ansehen."

describes, "operate outside the line [organization] and build a small network with a hand full of gateways in the city."

(2b) In their technology selection, cities consider criteria related to the technology itself, maturity, and accessibility; they prioritize self-provisioning, a governance-related criterion.

Cities mention a range of criteria they consider important when selecting a suitable LPWAN technology. We categorize them into four groups: technology-related, maturity-related, accessibility-related, and governance-related.

The first category, **technology-related**, includes criteria that are common to all LPWAN technologies, such as "low power use" and "low data rate," but also a very frequently mentioned criterion: data and cyber security. The latter involved discussions on whether the LoRaWAN built-in encryption was strong enough (yes, but some disagree for TTN), where servers are to be hosted (legally binding: Germany or EU), and indications that after previous doubts, cities and, in particular, their utilities are now opening up towards cloud services. Especially access to all data rather than simply some dashboards and data ownership were also a concern expressed by cities:

> *"In the future, because on a municipal level, we simply observe the topic data as a large blind spot – well, we at least identified in our city that we need to be very careful with that. So, alongside data protection, which we comply with anyways – obviously – it is all about who has which rights in the end, depending on which provider you involve. And we simply want to have some sovereignty."*[58] *(CA-6)*

The **maturity-related** criteria mentioned in the interviews are the availability of gateways and devices, wide adoption of the technology seen as a positive signal, and good existing coverage of the network. With regards to the device availability, after some initial issues with LoRaWAN sensors, they are now well available (e.g., CA-2, CU-3, CU-4), whereas the critical view on Sigfox persisted with the interviewee NO-2, who previously had investigated Sigfox: "Sigfox…originally has been a very limited network. In the beginning you had to take the Sigfox-certified sensors, that would have limited us." With regard to coverage,

[58] Translation of the German statement: „Perspektivisch, weil wir sehen einfach das Thema Daten generell als großen blinden Fleck eigentlich erfasst, auch noch auf kommunaler Ebene -.und wir haben das zumindest bei uns in der Stadt erkannt, dass wir sehr sorgsam damit umgehen müssen. Also, neben Datenschutz, den wir natürlich sowieso einhalten, geht es einfach darum, wer hat nachher welche Rechte? - Je nachdem, welchen Anbieter man einbindet… Und da wollen wir einfach eine Hoheit irgendwie bekommen."

the picture is very mixed: while some interviewees acknowledge the fact that once use cases grow bigger than one city's area, national networks like Sigfox and NB-IoT might be more suitable (e.g., CU-.4, NO-1), they also point out that right now their use cases are within their cities and thus this does not play a major role in their decisions. They rather see several strengths of LoRaWAN: specifically in the hard-to-reach areas in a city like district heating shafts, LoRaWAN outperforms other technologies (CA-5, NO-1), and in some regions, the LoRaWAN coverage is already very good, making it easy for cities to join and enjoy a good coverage from the beginning (CA-3). Some cities also value the possibility of testing LoRaWAN easily upfront (CU-3).

There are two accessibility-related criteria mentioned by the interviewees: relatively low cost and testing possibility. Cities consider both setup and operational costs and see LoRaWAN as performing well on both dimensions.

> *"LoRaWAN…is a low threshold to start with. Costs are almost non-existent, and it is a well-established technology which has been in use globally for a few years."*[59] *(DA-1)*

> *"And for such a cheap network as LoRa – this is really – …well, I didn't even have to apply for budgets to set it up."*[60] *(CA-7)*

> *"What I don't have [with LoRaWAN] are, so to speak, the running costs, which I have with Narrowband-IoT. This was the actual reason to say: 'No, we don't do that.'- Because you don't have a [business] case. And if I then have something which continuously costs money, then you are careful… this deters. And the other is rather: 'I once spend the money because investments are often easier (...) than the operations. And operations often carry one after another: I can hardly calculate them, and so on and so forth. And this additionally deters [from Narrowband-IoT]."*[61] *(CA-9)*

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[59] Translation of the German statement: „LoRaWAN…weil niederschwellig im Einstieg. Kosten sind eigentlich so gut wie keine vorhanden und es ist eine bewährte Technik, die weltweit schon seit Jahren läuft."

[60] Translation of the German statement: „Und bei so einem billigen Netz wie Lora, das ist ja wirklich - ich hab' da nicht mal Haushaltsmittel einstellen müssen, um das aufzubauen."

[61] Translation of the German statement: „Was ich aber nicht habe [bei LoRaWAN], sind sozusagen die laufenden Kosten, die ich bei Narrowband-IoT habe. …. Das war eigentlich der Grund zu sagen: ‚Ne machen wir nicht,' Weil man eben keinen [Business] Case irgendwie hat. Und wenn ich dann sozusagen etwas habe, was kontinuierlich, wenn man so will, Geld kostet, da ist man dann vorsichtig … das schreckt ab. Das andere ist eher ‚Ich habe das einmal ausgegeben', denn Investitionen sind oft auch einfacher als (…) der Betrieb, ... Und Betrieb

> *"Yes, this [cost] was a decisive reason for us, that here we can build a powerful …network at relatively low-cost and also with low material expenditures, where we can also decide ourselves- which is also in our area of responsibility, that was very important for us."*[62] *(CA-6)*

The last quote already points towards the fourth and last category of decision criteria, the **governance-related** ones. We observe three different governance-related criteria; the first one relates to openness and collaborative aspects of networks which are valued highly by several interviewees. They see citizens as beneficiaries of this architecture and cherish the community aspect.

> *"Actually, we are really trying to emphasize this openness and to say: 'There is this network, and it shall be used by each citizen.' Logically, only by the technically more affine ones… but, yes. "*[63] *(CA-1)*

> *"Also, private persons can add their gateways and hereby support the entire network. This is the nice thing when you use the community because you can equip a city or municipality or a district with solid basic equipment, but all others can also privately and selectively add to it."*[64] *(CA-7)*

The second governance-related criterion is comprised of service level agreements and network availability 24 hours, seven days a week. Depending on the maturity of the city's smart city endeavors and whether the network is primarily for commercial purposes or just for anyone who is interested, they see this criterion's importance very differently.

(…) ja da hängt ein Rattenschwanz irgendwie hinter: kann ich schlecht kalkulieren und so weiter und sofort. Und das schreckt dann auch nochmal zusätzlich ab [vom Narrowband-IoT]."

[62] Translation of the German statement: „Ja das [d.h. Kosten] war ein ausschlaggebender Grund für uns, dass wir da relativ kostengünstig oder auch mit wenig wenig Materialaufwand eigentlich dann … ein Netz aufbauen, wo wir selber drüber entscheiden können, was also in unserem Verantwortungsbereich liegt, was auch für uns sehr wichtig war."

[63] Translation of the German statement: „Aber eigentlich probieren wir schon eben gerade diese Offenheit sehr groß zu schreiben. Und zu sagen: "Es gibt dieses Netz und es soll durch jeden Bürger und Bürgerin genutzt werden." Logischerweise nur die etwas technisch-affineren... aber ja, genau."

[64] Translation of the German statement: „Auch Private können ihre Gateways mit reinhängen und unterstützen somit wieder das gesamte Netz. Das ist halt das schöne dran, wenn man über die Community geht, weil man halt Netze ausbauen kann, eine Stadt oder eine Kommune oder Landkreis, kann man mit einer ordentlichen Grundausstattung ausrüsten, aber alle anderen können auch privat oder auch punktuell nochmal nachsteuern."

"Well, if it [i.e., the local LPWAN] is off for two days, this is not a big deal in this case. This is an experimental field, and not and not a fully operational area in this sense, and therefore it [i.e., reliability] is not relevant."[65] *(CA-10)*

"…we get access to their closed network… and we can realize business-critical and more sensitive data with it, where we simply need this reliability. On the TTN side, we have a problem: if it doesn't work, it doesn't work. So, in parallel, we have this closed network TTI [commercial product from the TTN issuing company The Things Industries, TTI has an SLA in place; authors' note] where I have the reliability, SLAs, and support."[66] *(CA-2)*

"A firm, so, for example, a utility, shouldn't use it [i.e., an open network with unrestricted access]. They should rather pay someone, who then also takes care of it… or even operate it themselves."[67] *(CE-1)*

The last quote already points towards the third criterion: self-provisioning. Are cities able to build the network as they like it, or are they dependent on a third party installing additional gateways to achieve satisfactory coverage? It is the most frequently mentioned technology selection criterion in the interviews, not commonly discussed in the literature, and hence deserves further exploration.

(2c) The importance of self-provisioning stems from an urge for independence and a need to access hard-to-reach locations, resulting in a clear preference for LoRaWAN.

Exploring the roots of the importance of the self-provisioning criterion, we find a historical tendency of utilities for self-provisioning in several interviews. Utilities themselves call it the "classic utility mindset" (CU-3), and one interviewee from a utility (CU-1) explains

[65] Translation of the German statement: „Ja gut, wenn das dann zwei Tage ausfällt, ist nicht so schlimm, an der Stelle. Das ist ja Experimentierfeld, das ist ja kein Wirkbetrieb in dem Sinne und damit ist das dann nicht relevant."

[66] Translation of the German statement: „…bekommen Zugang zu ihrem geschlossenen Netzwerk, …, und da können wir eben geschäftskritische und auch sensiblere Daten, darüber realisieren, wo wir eben einfach diese Ausfallsicherheit brauchen. Wir haben auf der TTN-Seite natürlich das Problem, wenn's mal nicht geht, dann geht es eben nicht, parallel dazu haben wir eben dazu dieses geschlossene Netzwerk, TTI, wo wir dann einfach die Ausfallsicherheit, SLAs bzw. Support habe."

[67] Translation of the German statement: „Aber eine Firma, also Stadtwerke zum Beispiel, sollten das also nicht benutzen. Die sollten entweder jemanden dafür bezahlen, der dann auch dafür sorgt…oder es sogar selbst betreiben."

that "we have always had the strategy in the utility to build the telecommunications networks ourselves… we don't like to rely on third parties"[68].

A second reason for the importance of the self-provisioning criterion lies in physical accessibility: cities have some hard-to-reach locations, such as district heating shafts, waterworks, or other assets in very rural and remote areas (CA-7, CU-1). They see it as an advantage to be able to set up their network wherever they need it:

> *"We don't have any influence on the network [provided by a third party]. That means if we, for example, have a use case internally in our waterworks – and they ... are not located in the middle of the city but far outside the city gates, there is no mobile coverage. ... In our own network, we simply place a gateway there and done. The same goes for the district heating shafts, for example, they are located two and a half meters underground and are protected by a meter of reinforced concrete - we don't get any Vodafone and Telekom convinced to place a base station there just because we'd like them to."*[69] *(CU-1)*

This need to be independent of third parties may not only be led by practical considerations, as just expressed, but other interviewees also express a strong urge for independence from network providers and add the economic dimension of avoiding vendor lock-in (e.g., CA-2, CA-7).

> *„Building a closed network from tax money with the risk of having a vendor-lock-in-effect means I am then fully dependent on [name of a local external network operator]. And how they then setup, supervise the network, and so on, is not in our hands as a city anymore."*[70] *(CA-2)*

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[68] Translation of the German statement: „wir seit jeher die Strategie bei den Stadtwerken fahren, die Telekommunikationsnetze selbst zu bauen. … da verlassen wir uns sehr ungerne auf Drittnetze."

[69] Translation of the German statement: „…wir haben einfach keinen Einfluss auf das Netz. Das heißt wir können auch, wenn wir zum Beispiel einen Use Case haben bei uns intern im Wasserwerk, … die liegen nicht mitten in der Stadt, sondern die sind irgendwo vor den Toren der Stadt, da gibt es keinen Mobilfunkempfang. ... Und in unserer eigenen Struktur setzen wir da einfach ein Gateway hin und fertig. Dasselbe ist für Fernwärmeschächte, zum Beispiel. Die liegen nun mal zweieinhalb Meter unter der Erde und sind von einem Meter Stahlbeton abgeschottet - da kriegen wir keine Vodafone und keine Telekom dazu, da mal einen Mast hinzusetzen, nur weil wir das jetzt gerne hätten."

[70] Translation of the German statement. „Eben aus Steuergeldern ein geschlossenes Netzwerk aufzubauen, mit der Gefahr dann eben diesen Vendor Lock In Effekt zu haben, heißt, ich bin dann völlig abhängig von [Name des lokalen externen Netzwerkanbieters] und wie die dann das Netzwerk betreuen, aufbauen usw., liegt dann nicht mehr in unserer Hand als Kommune."

In addition to the vendor lock-in, another interviewee mentions concerns around data ownership and security (CA-10). With regards to the self-provisioning feature, cities and their utilities see LoRaWAN as superior to NB-IoT and Sigfox (e.g., CA-6, CU-4, NO-1). Local network providers prefer LoRaWAN because it allows them to ensure availability and security for their own clients (NO-2). One city utility explicitly explains that they excluded Sigfox because it didn't meet their expectations with regard to self-provisioning: "We discarded Sigfox because it didn't conform to this 'we do all or very much ourselves'".[71] (CU-4). Interviewee CA-6 summarizes the importance of the self-provisioning criterion:

> *"Yes, it was a decisive reason for us, that we… built a network, where we ourselves can decide, i.e., which is in our area of responsibility, that was very important to us."*[72] *(CA-6)*

(3a) LoRaWAN is the most popular LPWAN among interviewed cities and districts.

Across interviewees, the vast majority already had a minimum of one LoRaWAN implemented, and some were planning to build a second parallel network soon. Among the 19 interviewees, it was by far the most common LPWAN. In fact, no interviewee was primarily using Sigfox or NB-IoT. In one case, the city opted to monitor a remote gas tank with a Sigfox sensor because, at the time when they decided to monitor the asset, there was no suitable LoRaWAN sensor available yet (CA-8).

However, several interviewees point out that despite the current dominance of LoRaWAN, a variety of LPWAN may co-exist in the future (CU-2, CU-3, NO-1) and that they remain open to testing others as well (CU-1). It is only one communication technology in the smart city, and others, like 5G, are expected to play an important role as well (CA-5, CU-5).

(3b) Parallel open and closed LoRaWANs appear to be the most popular setup.

Interviewees from many cities explain their network setup the following way: one closed network primarily serving internal, sensitive use cases and one parallel open network, often TTN, for general use and free access, for example, for citizens.

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[71] Translation of the German statement: „Sigfox haben wir verworfen, weil es diesem, ja "Wir machen alles oder vieles selber" nicht gehorcht hat."

[72] Translation of the German statement: a das war ein ausschlaggebender Grund für uns, dass wir … ein Netz aufbauen, wo wir selber drüber entscheiden können, was also in unserem Verantwortungsbereich liegt, was auch für uns sehr wichtig war."

> *"Yes, the reason for the open network lies in the fact that there are many hobbyists and – I'd say – fellow citizens who like to see their data somewhere. That is simply the open network. But the closed network does also have a commercial background."*[73] *(NO-2)*

> *"We [as the city administration] are using the network of our utility, and with regards to participation, we think it is good and absolutely right that this is completely open via the TTN network. (...) In principle, we try to emphasize this openness and to say, 'There is this network, and it should be used by each citizen.' obviously only by the more tech-savvy ones, but… well, yes."*[74] *(CA-1)*

The closed networks are frequently operated by city utilities, often related to security concerns and a perceived need to protect their data transmission as well as a legacy of operating their own closed networks.

Some utilities also have their own commercial offerings and hence need to fulfill SLAs (e.g., CA-5, CA-9, NO-2). This is possible in a closed network but not in a public one where servers might be operated by a third party and not accessible for the utility for maintenance, or a spammer may block the network for some time. The following quote illustrates the considerations several cities share:

> *"Our utility… they operate a closed network. They have equipped all gas, water, and electricity meters with LoRa modules, for example, and they read them, and they say these are system-relevant components, they cannot be run with an open network, that's why they operate a parallel, closed network."*[75] *(CA-3)*

This opinion is not shared by all interviewees, as the following statements from an interviewee from a small city who also operates the network there illustrate:

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[73] Translation of the German statement: „Ja, also der Grund sage ich mal des offenen Netzes liegt einfach daran, dass ist ja auch sehr viele Hobbyamateure und sage ich mal Mitbürger gibt, die gerne einfach ihre Daten irgendwo sehen wollen. Das ist einfach nur das offene Netz. Aber das geschlossene Netz hat eigentlich auch einen wirtschaftlichen Hintergrund. "

[74] Translation of the German statement: „Genau, ja, also wir nutzen das Netz der Stadtwerke und was Beteiligung angeht, finden wir es auch gut und richtig, dass das auch komplett offen ist über dieses TTN-Netz. (…) Aber eigentlich probieren wir schon eben gerade diese Offenheit sehr groß zu schreiben. Und zu sagen: ‚Es gibt dieses Netz und es soll durch jeden Bürger und Bürgerin genutzt werden.' Logischerweise nur die etwas technisch-affineren... aber ja, genau."

[75] Translation of the German statement: „Unsere Stadtwerke, die haben ein geschlossenes Netz. und die haben zum Beispiel die ganzen Gas-, Wasser- und Stromzähler mit LoRa-Modulen versehen, die lesen diese aus und sagen, dass sind systemrelevante Sachen, die können nicht über ein öffentliches Netz laufen, deshalb betreiben die parallel ein geschlossenes Netz."

“Utilities are a special topic because they always want closed networks. They always operate very, very critical infrastructure.”[76] *(CA-7; with ironic undertone)*

“With utilities, it’s always about this critical infrastructure, what we just discussed. You can actually do that with an open network, but it’s their DNA to seal themselves off; yeah, they always want everything [protected. And scream:] ’Critical! Critical! – Water, power, gas… you’ve got to be careful there!’ – True, one must be careful… That’s how they are socialized.”[77] *(CA-7)*

The interviews were able to elucidate the context of the technology selection, the decision process with a variety of decision criteria considered by cities, and the different outcomes in terms of network setups. While these semi-structured qualitative interviews provide rich insights into how the technology selection process works, they do not allow us to quantify and generalize the findings. This is where the following quantitative study comes in.

4.4.2 Findings from the quantitative study

The quantitative insights from the survey follow the structure of the qualitative findings and are organized around three aspects: first, to explore the context, we investigate why and when cities got engaged in smart city efforts. Thereafter, we analyze the importance of different criteria in the technology decision process and the evaluation of the LPWAN technology with regard to those technologies. Lastly, we turn toward the resulting setup of LPWAN and investigate which factors favor one or another.

4.4.2.1 Reputational benefits from implementing smart city

Figure 10 illustrates that most cities in the sample started their smart city efforts only in the last decade, slightly before or in parallel with the aforementioned governmental programs and efforts, such as the “Smart City Charter” in 2017 and the “Modellprojekte Smart City” after 2019 (see 4.2.1). With regards to municipal debt, cities in the sample are slightly above the national average at the end of 2020: cities in the sample have, on average, 2,079€ per capita

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[76] Translation of the German statement: „Stadtwerke sind schon ein besonderes Thema, weil die wollen immer geschlossene Netze, weil die immer ganz, ganz kritische Infrastruktur haben.”

[77] Translation of the German statement: „Bei den Stadtwerken ist diese kritische Infrastruktur, aber das haben wir ja auch schon besprochen. Das kann man sehr wohl mit einem offenen Netz betreiben, aber das ist deren DNA, sich abzuschotten, ja, die wollen ja immer alles irgendwie [geschützt und rufen:] ‘Kritisch!, Kritisch!. Wasser, Strom, Gas - .na, da muss man aufpassen!’ - Muss man ja auch. So sind die sozialisiert.”

debts with a standard deviation of 1,709, while the national average is 1,733€ (Destatis - Federal Statistical Office, 2021b). As municipal debt in Germany largely depends on the federal state a city is in, with North Rhine-Westphalia, Saarland, Rhineland-Palatinate, and Hesse being among those with the highest municipal debts, this higher average could also stem from the overrepresentation of North Rhine-Westphalia in the sample (Beznoska & Hentze, 2019).

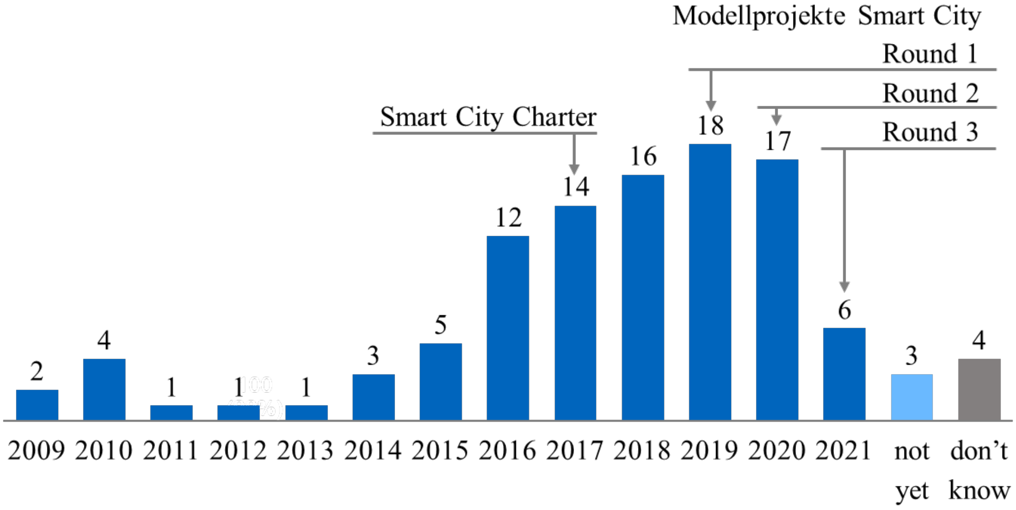


Figure 10 Start of smart city efforts in the cities of the sample (n=115)

Regarding the perceived benefits of implementing smart cities, cities particularly agree with reputational benefits and expect improved execution of their own services (see Figure 11). Reputational benefits are particularly expected from the relationship with citizens, but also the city's attractiveness towards companies is seen as an important benefit. Most believe that smart city can also improve their economic situation, mostly through cost savings and less through additional revenues.

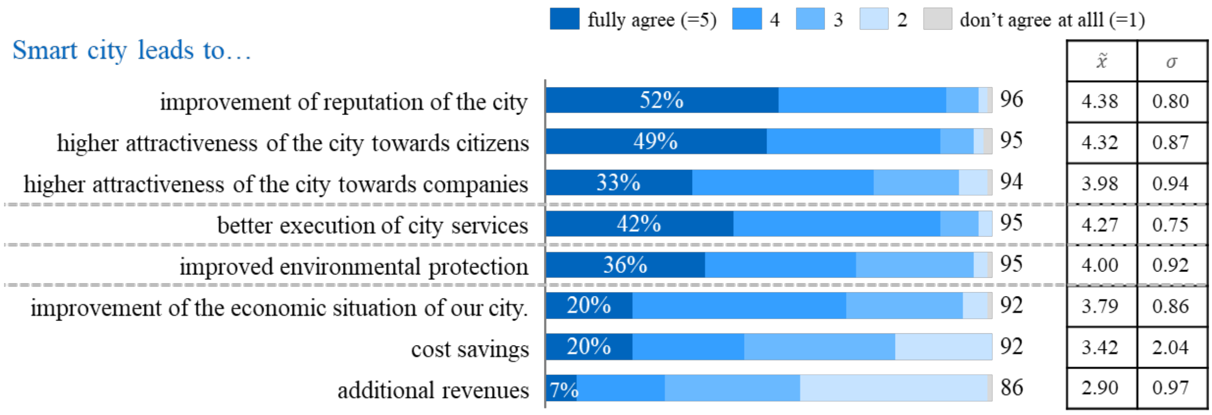


Figure 11 Agreement to advantages of smart city implementation

4.4.2.2 City administration and utilities as drivers of smart city efforts

In most cities, the city administration and utilities are considered the driving forces, as can be seen in Figure 12. One must keep in mind that these results may be biased, as these groups are also the main respondents of this survey. The civic society, the citizens, are rarely considered driving forces, as the numbers for both civic initiatives (22) and democratically elected representatives of the citizens (23), for example, the city council, show.

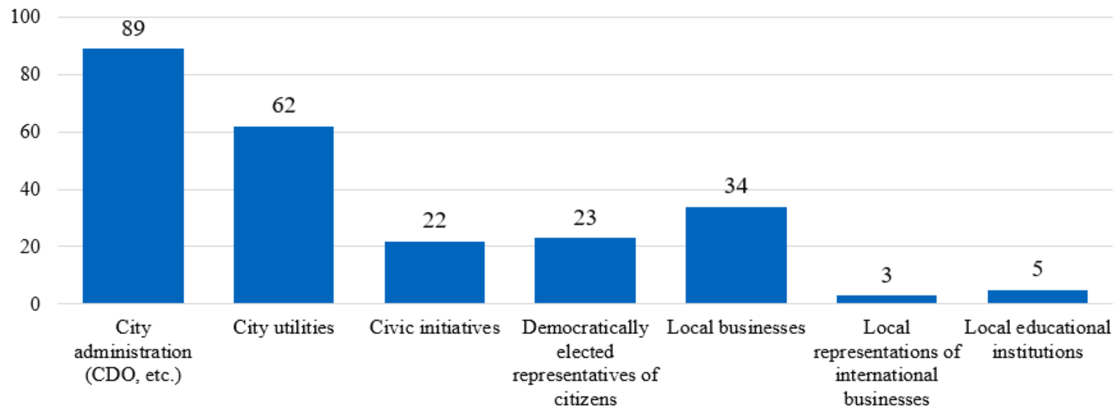


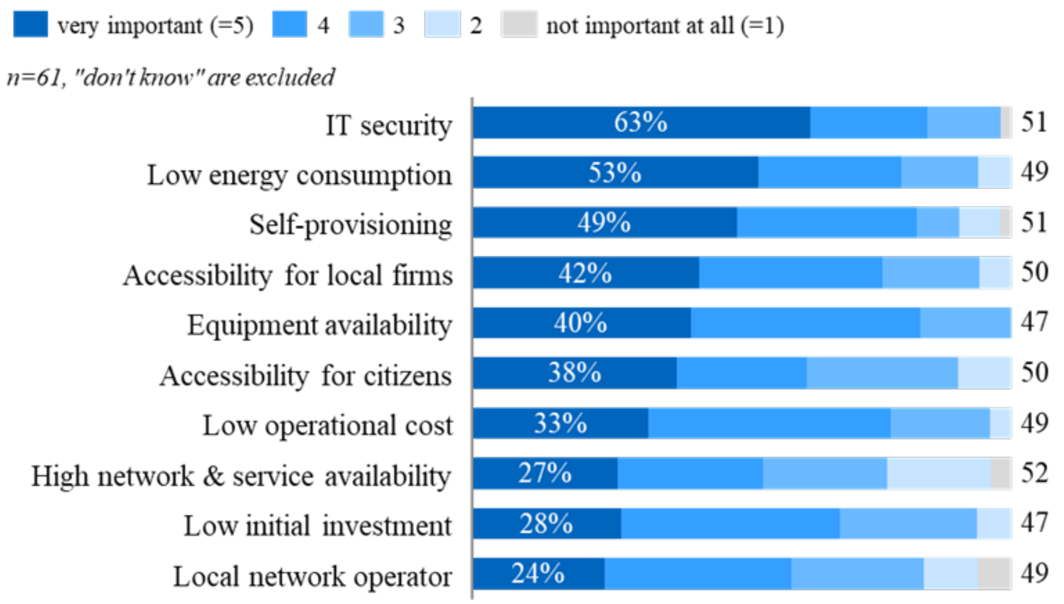
Figure 12 Driving forces for smart city (multiple selection possible; n=107)

Narrowing down the focus to IT-related initiatives and clubs, where technology-savvy citizens often come together and often are also willing to share their knowledge, the impression of weak exchange with citizens is further strengthened. Some cities collaborate with a local TTN group (20), the local section of the Chaos Computer Club (10), a local group from Code for Germany (10), or others (27), e.g., free casters. However, it is remarkable that more than half of the cities, namely 58% (62), do not collaborate with any IT-related civic initiative so far.

4.4.2.3 Technology selection: process, criteria, and assessment

In the survey, 69 cities provided information on the order of their technology selection process. Based on what we learned from the interviews, we gave them two answer options as well as a free text field. 38% (26 of 69 cities) state that they first had a use case and then identified a suitable technology. Almost half of the cities (34 out of 69, 49%) did it the other way around: they started with the selection of a suitable LPWAN technology and then looked for use cases. Nine cities provided answers in the free text field, mostly being an expression of „don't know. " In one case, the district and not the city followed the second approach.

Figure 13 shows the importance that respondents attribute to the various decision criteria in their LPWAN technology choice. In most cities, IT security (61%) and low energy consumption (53%) are seen as very important technology decision criteria. Alongside equipment availability, these can be seen as hygiene factors for any kind of IoT infrastructure (in the case of IT security and equipment availability) or, even more specifically, in the LPWAN application area (in the case of low energy consumption). Interestingly, self-provisioning, as a governance-related decision criterion, is mentioned third already. Also, accessibility for local firms seems to be of relevance. Cost, however, seems to be far less important than some authors, such as Mohanty et al. (2016), have postulated.



$\tilde{x}$	σ
3.54	2.18
3.23	2.27
3.34	2.15
3.20	2.15
3.03	2.31
3.01	2.11
3.07	2.16
2.87	1.96
2.77	2.21
2.70	2.11

Figure 13 Ranking of decision criteria for LPWAN technology selection

The second step in the technology choice, the assessment of the alternative technologies regarding the decision criteria, shows a clear preference for LoRaWAN (Figure 14). Also, with respect to all other criteria, LoRaWAN emerges as the favored LPWAN technology.

Combining these two figures, they reflect the two steps of the MCDM technology choice and show that the governance-related decision criterion "self-provisioning" is highly relevant in cities' decisions for LPWAN technologies. Across decision criteria, LoRaWAN seems to be the preferred LPWAN technology.

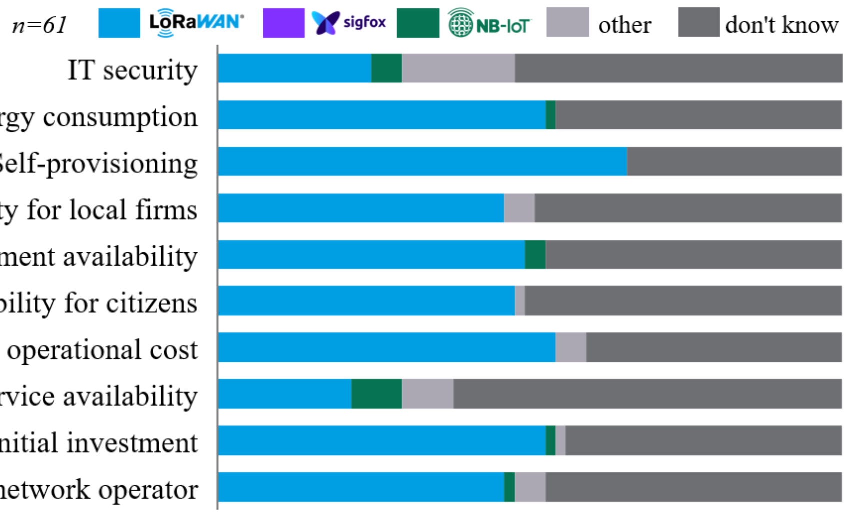


Figure 14 Assessment of LPWAN technologies regarding the decision criteria

4.4.2.4 LPWAN implementation and setup

Thus, it is not surprising to find LoRaWAN as the most frequently implemented LPWAN technology. Around half of the cities in the sample (53 out of 107) had implemented an LPWAN at the time of the survey, and 11 additional cities had planned to do so. LPWAN are thus not a peripheral phenomenon but are as frequently part of the smart city infrastructure as cellular technologies (used by 52 out of 107 cities). As Figure 15 shows, especially among the existing (i.e., where implementation was completed) LPWAN, LoRaWAN clearly dominates. Among those who are still deciding which network to implement, NB-IoT is also frequently being discussed. Among those who are more advanced in the LPWAN implementation (implementation ongoing, in last six months or longer than six months ago), LoRaWAN clearly dominates. This, of course, begs the question of whether the dominance of LoRaWAN is purely transient due to the non-availability of NB-IoT before the end of 2018. Looking at all cities that started to implement smart city 2019 or later (Figure 16), when coverage for all three LPWAN technologies was available, no pattern of NB-IoT rise can be observed.

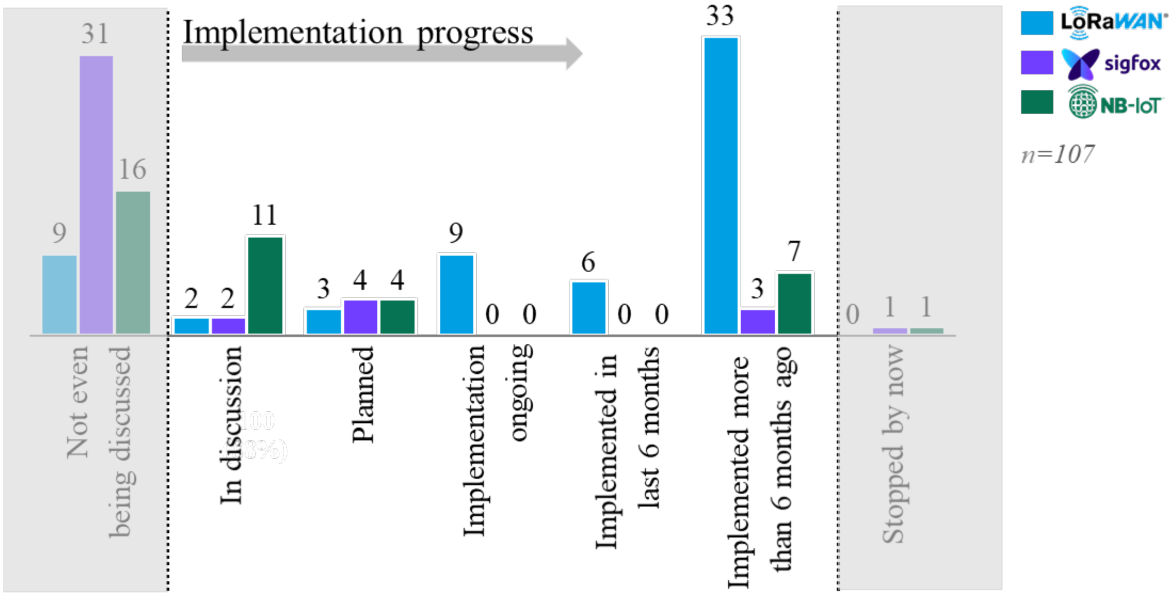


Figure 15 LPWAN implementation progress in the cities in the sample

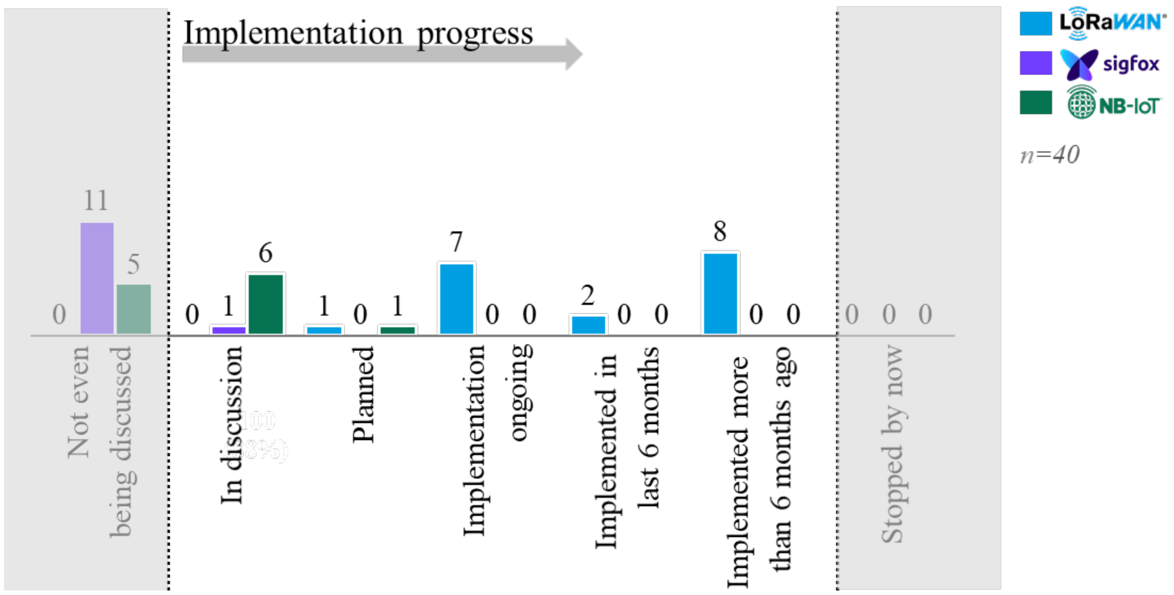


Figure 16 LPWAN implementation progress in the cities that started their smart city efforts in 2019 and later

What remains unclear at this stage is whether LoRaWAN is implemented so frequently because the self-provisioning feature is so important to the cities or because it is seen as superior in a wide range of decision criteria. The actual network setups provide further evidence that self-provisioning matters: Of the 47 cities which provided detailed information on their LoRaWAN network setup, only 7 (14.9%) had their network provided by an external network operator. So apparently, it is not only about the advantages of the LoRaWAN as technology, but 85.1% of the cities that deployed it make use of the self-provisioning feature. Those who operate their own LoRaWAN network do so in a variety of setups (Figure 17): self-provisioning for their own use is the most popular setup, but also a contribution to open networks which can be used free of charge is very popular either via their own networks (13) or even more popular by connecting the city's gateways to the TTN (21). Several of these setups can technically be run in parallel on the same gateways by splitting them virtually. Nevertheless, a large share of cities is also aiming to commercialize their networks (23 cities indicated that). Being asked more specific questions about whom to offer connectivity for free and whom to charge for it, cities show a clear pattern: for their own use (i.e., for the providing unit itself), it is always intended to be free of charge. However, some cities even consider charging their own utilities for the use of their network (10 out of 39), less are willing to charge their own citizens (6 out of 26). A majority (18 of 31) would hope to be able to charge companies in the future for the provided connectivity.

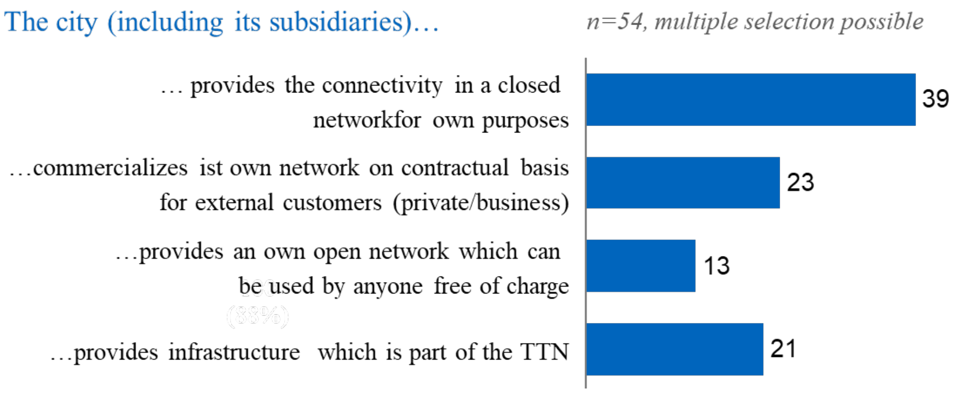


Figure 17 Setups of self-provisioned LoRaWAN networks

This detailed assessment of the network setups points to the fact that cities prefer self-provisioning their LPWAN. Interestingly, cities often provide connectivity free of charge for their citizens by providing an open, free-of-charge network or by contributing to the TTN network.

Turning towards the role of political parties in the cities, they don't seem to be decisive in most of the cases: no association between the year smart city efforts started and the respective party of the mayor could be confirmed[78]. Also, the share of parties in the city parliament at that time did not have any significant with the weight assigned to the self-provisioning feature or with the number of parallel networks installed in a city. An exception to this is Table 10, where

[78] For completeness these analyses are provided in Appendix E.

we investigate the contingency of the two categorical variables “Follower or leader” (self-assessment of the city; 1 as follower and 5 as leader[79]) and “Mayor’s party in the year smart city started”. At a 7% significance level (p=0.0683) we can confirm an association of the two variables.

Table 10 Contingency of “Follower or leader” and the mayor’s party in the year smart city started

Follower or leader	Mayor's party in the year smart city started							
	CDU	CSU	FDP	Grüne	SPD	others	no party	Total
Don’t know	1	0	0	0	1	0	0	2
1	4	0	2	0	0	0	0	6
2	6	5	0	0	9	1	4	25
2.5	0	0	0	0	1	0	0	1
3	13	1	1	0	18	0	2	35
3.5	1	0	0	0	0	0	1	2
4	10	0	1	1	8	0	4	24
5	2	0	0	1	1	0	0	4
Total	37	6	4	2	38	1	11	99

Pearson Chi2 = 56.37 Prob = 0.0683

Calculating the Mann-Wilcoxon two-sample statistic (Mann & Whitney, 1947), also known as the Wilcoxon rank-sum test, for the mayors of the CDU and CSU[80] on the one hand and all other parties on the other hand, we find that these groups differ at a significance level of 9% (p=0.0875), as Table 11 shows. It seems that on average CDU or CSU led cities introduced smart city concepts later than those led by other parties. Conducting the same test for other parties, no significant results could be found. However, that might also be given due to small sample size for several parties (e.g., FDP (4), Grüne (2), others (1)) or in case of the mayors without any party (11) it might be simply given to the fact that this is not a group with a shared agenda, they only share the fact that they do not belong to a party. For SPD, which also has 38 mayors in the sample, the Mann-Wilcoxon two-sample statistic did not find any significance difference compared to all other parties.

[79] The values of 2.5 and 3.5 are from the harmonized data of a city with multiple respondents. It is the average of their individual answers. E.g., if the respondents reported 2 and 3, this is now reported as a 2.5 in this table.

[80] Christian Democratic Union (CDU; in German: Christlich Demokratische Union) and Christian Social Union (CSU; in German: Christlich Soziale Union), both are one parliamentary group on national level and depending on the German region either CDU or CSU takes part in the election, but they are never competing for the same voters and hence are never in competition with one another.

Table 11 Mann-Wilcoxon two-sample statistic for mayor of CDU and CSU vs. other parties for the years when their cities got involved in smart city (based on enriched survey data)

Mayor is CDU or CSU	Observations	Rank sum	Expected
0 (=no)	56	2560	2800
1 (=yes)	43	2390	2150
Combined	99	4950	4950

Unadjusted variance 20066.67
Adjustment for ties -389.67
Adjusted variance 19677.00
H0: StartYear(Mayor is CDU or CSU ==0) = StartYear(Mayor is CDU or CSU==1)
z = -1.711
Prob > z = 0.0871
Exact prob = 0.0875

From political actors we turn towards citizens: To characterize the relationship between cities and their citizens, respondents were asked for their degree of agreement to seven statements referring to various aspects of the relationship. The items covered aspects such as whether citizens profit directly or indirectly (e.g., through the creation of new employment opportunities) from smart city, whether citizens were informed about and even involved in the development of smart city, the importance of the open data approach, and if the city perceives connectivity as public good. As independence of the observations and sufficient correlation among the variables are given and 91 observations are available, a principal component analysis to reduce complexity is possible. Two factors can be identified following the latent root criterion (see Table 12).

Table 12 Principal-component factor analysis for items characterizing the relationship between the city and citizens (based on survey data)

Factor	Eigenvalue	Difference	Proportion	Cumulative
Factor1	2.376	0.680	0.339	0.339
Factor2	1.696	0.822	0.242	0.582
Factor3	0.874	0.084	0.125	0.707
Factor4	0.790	0.098	0.113	0.819
Factor5	0.692	0.303	0.099	0.918
Factor6	0.388	0.204	0.056	0.974
Factor7	0.185	.	0.026	1.000

LR test: independent vs. saturated: chi2(21) = 146.27 Prob>chi2 = 0.0000, n=91

After oblimin-oblique factor rotation (Table 13), two items – direct and indirect benefits for citizens – still cannot be explained satisfactorily, their uniqueness remaining clearly above 50%. From the factor loadings we can interpret that Factor 1 denotes the *offer from the city* towards the citizens (information on the smart city project, involvement in the smart city development, provision of open data) whereas factor 2 represents the *citizens' rights* towards the city (access via open data, connectivity as public good, tax money as legitimation for open networks). The direct and indirect benefits from smart city implementation load on both factors. These two factors characterize the relationship between the city and its citizens as it is perceived by the city and are, as such, used in the next analysis.

Table 13 Factor ladings and unique variances after oblimin-oblique factor rotation for items characterizing the relationship between the city and citizens

Variable	Factor1	Factor2	Uniqueness
Direct	0.432	0.348	0.693
Indirect	0.581	-0.033	0.662
Informed	0.776	-0.435	0.209
Involved	0.815	-0.398	0.178
OpenData	0.665	0.243	0.498
PublicGood	0.362	0.794	0.238
Taxes	0.111	0.733	0.451

In order to understand which characteristics of a city go hand in hand with self-provisioning a LoRaWAN in the city, we run a probit analysis for a binary variable (*HasSelfProvisionedNetwork*), constructed based on the cities' responses as displayed in Figure 17. The results of this probit regression are shown in Table 14. It achieves a McFadden pseudo-R-squared of 0.478, which can be considered a good fit.

Table 14 Probit regression for self-provisioned LPWAN in cities

HasSelfProvisionedNetwork	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
Decision_SelfProvisioning	.128	.327	0.39	.694	-.512	.768	
TotalPopulationDec2020	0	0	-0.47	.64	0	0	
Offer from the city	1.132	.62	1.82	.068	-.084	2.348	*
Citizens' rights	.374	.5	0.75	.455	-.606	1.354	
DebtPerInhabitant	.001	.001	1.70	.089	0	.002	*
FinancialAid	1.581	1.764	0.90	.37	-1.876	5.039	
Local TTN Community	-.878	1.001	-0.88	.381	-2.841	1.085	
Constant	-1.801	2.353	-0.77	.444	-6.413	2.812	

Mean dependent var	0.842	SD dependent var	0.370
Pseudo r-squared	0.478	Number of observations	38
Chi-square	15.856	Prob > chi2	0.026
Akaike crit. (AIC)	33.293	Bayesian crit. (BIC)	46.393

*** *p<.01*, ** *p<.05*, * *p<.1*

We expect that cities which initially named "self-provisioning" as a very important technology decision criterion are more likely to then also self-provision such a network. However, the probit regression does not confirm that. We included the city size by the number of inhabitants end of December 2020 in the model, as smaller cities might have fewer resources and, for that reason, opt against setting up their own network and rather join the TTN or opt for a solution by an external network provider (e.g., Sigfox Germany/ Heliot or Telekom or Vodafone). Again, here we cannot observe a significant effect, though. Moreover, we hypothesize that the attitude that a city has towards its citizens – namely, the strength of the two above-derived factors – is also assumed to be reflected in the chosen network setup. If cities have a higher awareness of the fact that they are acting as the agent of their citizens and using their tax money to set up an IoT network, they may feel a stronger obligation to self-provision the network rather than passing the money to an external network provider. Similar reasoning holds for complying with the "rights" of citizens: if a city aims to inform and involve citizens strongly, they might rather opt for a free-of-charge network to remove entry barriers for citizens. In the model, we see a significant positive association between the "offer for citizens" and having a self-provisioned network. The other significant positive association we find is between the city's relative debt and having a self-provisioned network. In a city with a difficult financial situation, i.e., higher relative debt, self-provisioning a network might give them a feeling of cost control and transparency. Another aspect of the financial situation of a city is its available external sources of financial aid (federal programs, federal states' programs, EU funding, etc.). Cities with many governmental funding sources might have more money available to set up their own infrastructure and, eventually, even a moral imperative to build open, free-of-charge network infrastructure as they are using governmental and, thus, indirectly, taxpayers' money. However, such an assumed positive association is not significant in the model.

4.5 Discussion

4.5.1 Smart cities as part of a larger development strategy in cities

Most cities that have already started their smart city journey did so in the second half of the 2010s. This coincides with the time when also governmental awareness and support for the smart city topic rose, for example, the publication of the Smart City Charter (2017) or the start of the smart city program (2019, still ongoing). Insights discussed in this section need to be seen in the light of the previously discussed non-response bias, so while we cannot conclude which percentage of German cities have already embarked on a smart city transition, we can conclude that the majority of those who is on the smart city journey, embarked on in the past ten years. The transition is ongoing and still of experimental nature, as also interviewees illustrated regarding technology selection and smart city use cases.

Embarking on the smart city journey is not a value by itself, but as our qualitative study reveals, cities see smart city as a contribution to city and regional development. The connotation of being an innovative and livable city for the sake of its own citizens was mentioned by various interviewees. It is supported by the survey results, according to which cities perceive reputational benefits – in particular, with regards to citizens and slightly less with regards to companies – from implementing smart city as a far stronger advantage than potential financial benefits. Our findings here do not stand alone; already, Hilbig et al.'s study (2020: 20) mentioned these reputational benefits for a city towards citizens and companies. Our study adds the insight that German cities see this as the most important benefit. Attracting a skilled workforce and prospering companies is an asset for cities, and in the end, it might then also result in higher tax income from firms and thus financial benefits for the city as well. More than half of the cities also see ecological advantages, an ambition that was also formulated in the Smart City Charter in 2017 (Federal Ministry for the Environment, Nature Conservation Building and Nuclear Safety, 2017: 24), so also national ambitions overlap here with the cities' goals. However, a smart city is not automatically a warrantor for achieving sustainability goals and livable cities: production of sensing equipment, chips, and other devices can contribute to pollution, and collecting data from the environment does not automatically imply that this data is being used, conclusions are drawn and that these conclusions improve the carbon footprint of the city. Hence, the link between smart city and sustainability can be drawn, as many interviewees did, but it is not an effortless and automatic one.

Summarizing these observations, the context of the smart city technology selection is one where reputational and ecological considerations mainly have one addressee: citizens. This is consistent with many descriptions and characterizations of smart cities in literature, such as Dameri (2013) or Stübinger and Schneider (2020), where citizens are at the core of the concept and are also involved in the advancement of smart city. This can also be observed in practice, for example, through living labs in Barcelona (Bakıcı, Almirall, & Wareham, 2013: 142).

4.5.2 Heterogeneous technology selection processes all benefit from increased knowledge exchange

During the qualitative analysis, we observed that some cities start with a structured technology selection to later select use cases, while others start with an immediate need and then select a suitable technology to solve it. Some rely on recommendations from other cities or districts, and others see low initial investments as an invitation for experimentation.

Considering the heterogeneity of cities in Germany with regard to size, demographics, financial means, degree of industrialization, and many more aspects, a "one-size-fits-all" approach with a standardized process likely does not yield success. Nevertheless, we as a community interested in smart cities should discuss how cities can be supported in their technology decision, regardless of the process they follow. In the survey discussed, we saw that depending on the decision criterion, 40% to 60% of the respondents did not know which LPWAN technology performed best with regard to it. This is a matter of knowledge and expertise, and while the weighting of these criteria might differ from city to city, the assessment of the technologies should not. Cities, and especially those with limited resources, need access to this knowledge and then can combine it with their local expertise to find the best solution for themselves.

During the interviews, we learned that cities are already engaging in knowledge sharing, knowledge exchange, and collaborations: within associations like the association of German cities and towns, and informally with colleagues from other cities and utilities they know. They also do excursions to more advanced smart cities, form regional collaborations, or even find a regional smart city association with other cities to institutionalize knowledge transfer are other expressions of this search for knowledge and call for exchange.

Research institutions and national governmental bodies can support this by generating and providing knowledge and fostering knowledge exchange. The current smart city initiative (Modellprojekte Smart Cities) is a good starting point: the projects selected for the program represent cities of all sizes, different use cases, and approaches. This enables broad learning. A database with all cities and projects, progress reports, and filters to enable structured searches and a sharing of lessons learned from each of the participating cities with their projects could foster further knowledge exchange. This is fully in line with the ambition of the project to promote "knowledge and experience sharing within the model projects as well as with other non-promoted cities, as long as they have similar goals and challenges"[81] (Federal Ministry of the Interior, for Building and Community, 2019: 6). As smart city is evolving quickly it would be beneficial to share knowledge timely and in an iterative manner. In addition, regional and

[81] Translation of the German statement: „Der Wissens- und Erfahrungsaustausch soll sowohl innerhalb der Modellprojekte als auch mit anderen nicht-geförderten Kommunen stattfinden - soweit diese ähnliche Ziele und Herausforderungen haben."

national meetings can help to spread knowledge more quickly. One example is the yearly smart country convention.

4.5.3 The possibility of self-provisioning as a key technology selection criterion embedded in the broader context of citizen involvement and innovation

Governance-related considerations play a role in the smart city technology choice. We found the possibility of self-provisioning to be both a stated selection criterion and, consistently, an observable outcome in cities' LPWAN setup. This adds a new perspective to the existing comparisons of LPWAN technologies (e.g., Ayoub et al., 2019b; Hossain & Markendahl, 2021; Kasujee & Mackenzie, 2022; Mekki et al., 2018), as discussed in Section 2.2.

Cities use criteria to assess technologies. The emphasis on self-provisioning in the LPWAN context that could already be observed in the interviews has been confirmed by the survey (recall Figure 13). The interviews revealed that perceived security, independence from large telecommunication operators, cost transparency and control, as well as the possibility to reach all own assets wherever they are located, are appealing and important to cities. Potential challenges associated with self-provisioning a network might be the acquisition and training of qualified personnel. Self-provisioning an LPWAN is a decision with future impact and hence should be aligned with the smart city strategy and the broader strategic ambitions in the city. While interviewees broadly agreed on the historic self-image of utilities to be network operators, interviewee CU-4[82] reported an increasing openness towards cloud-based solutions in his utility. It will be interesting to see in the future to which degree cities remain or even expand their own footprint as network operators and how much they rely on telecommunication channels operated by national telecommunication providers. In a democracy, this should not only be determined by the administration alone but with the involvement of citizens – an idea that already the German smart city charter puts forward (Federal Ministry for the Environment, Nature Conservation Building and Nuclear Safety, 2017).

Our probit regression (recall Table 14) searched for explanations why cities decide to self-provision an LPWAN. Both the factor *offer from the city* as well as the *debt per inhabitant*

[82] English translation of the statement: „This fear, that one used to have, to put things like that in the cloud and having third parties or someone else in between…well…this has been abandoned for quite a while, or step by step – one also uses mobile connectivity and telecommunications for voice communication with the mobile devices provided by us." - Original statement in German: „Diese Scheu, die man früher gehabt hat, sowas in die Cloud zu legen und Dritte oder irgendjemanden dazwischen zu haben,...ja... die hat man schon längst, oder ja, mehr und mehr, abgelegt - man nutzt ja auch Mobilfunknetzwerk und Telekommunikation für die Sprachkommunikation jetzt bei den von uns verwendeten Mobilfunktelefonen."

are positively correlated with having a self-provisioned network in the city. Interestingly, we can observe that informing and involving citizens in the smart city process and the will to pursue an open data approach, all elements of the *offer from the city*, go hand in hand with self-provisioned networks. One could hypothesize that these are expressions of an attitude where the city sees itself as the agent for its citizens and hence aims to involve the citizens closely in the development of a smart city – through co-creation but also open data. This very much resonates with the strategy deployed in Barcelona, often considered the leading smart city in Europe (Bakıcı et al., 2013). In democratic societies, a general perception of cities as agents of citizens and hence their transparency and community orientation may be prevalent. The aspect of increasing likelihood of a self-provisioned network in cities with higher debt per capita could be linked to the perceived cost control in the case of a self-provisioned network. Setting up an own infrastructure rather has the character of a one-time investment and not of annually recurring operational costs. This consideration could be especially appealing to cities under financial strain, with high debt per capita.

These results support the view that involving citizens in a smart city is more than a moral imperative; it can be a fruitful connection where citizens shape their living environment by giving new ideas for smart city development (Bakıcı et al., 2013; Hilbig et al., 2020). In Barcelona "living labs are used as tools and processes for the creation of user innovation" (Bakıcı et al., 2013: 142) and might have served as an inspiration for many of the different formats – hackathons, maker spaces, co-creation sessions with citizens – used in the cities of our interviewees. While being considered an anomaly only few decades ago, user innovation has by now become a widely acknowledged phenomenon. It's now broadly understood that users innovate and enhance products and especially in the makers scene such people can be found and inspire innovation also for other market participants (Bakıcı et al., 2013; Gambardella, Raasch, & von Hippel, 2017). The presented survey unveiled that less than half of the cities currently are not interacting with any local IT-related initiative. As tech-savvy citizens organize there and often are early adopters as well as potential user innovators, cities could involve these groups more. They can speed up local adoption of the new technologies, appear as idea generators and user innovators. For example, the first implemented smart city use cases in the city of CA-1 were ideas developed through a hackathon organized by the local maker scene[83].

[83] English translation of the statement: "[T]his [name of the local project for water level monitoring] actually originated from the [name of the local hackathon], so a local hackathon here which is operated in cooperation with

4.5.4 LPWAN as one, but not stand-alone, key component of the smart city ICT backbone

The survey showed that cities currently implement LPWAN (53 of 107, 49.5%) as frequently as cellular technologies (52 of 107, 48.6%). WLANs are slightly more popular (77 of 107, 72.0%). We can see in these numbers what is often claimed: the smart city backbone will not be a single communication technology, but a combination of many different ones to serve the different needs (Ibrahim, 2019; Mekki et al., 2018). Additionally, several respondents mentioned optical fiber as an important future ICT for their city in free text fields of the survey.

LPWAN are seen as one important element in this ICT backbone, as several interviewees emphasized in their outlook on the future. Currently, LoRaWAN is the dominating LPWAN in German cities, but NB-IoT is also rising (recall Figure 15 and Figure 16). Opting for one LPWAN technology and network setup is not opting against another one – we have seen combinations of both closed and open LoRaWANs in the same city and cities with more than one network to cater to different needs. Interviewees explained the parallel existence of open and closed LoRaWANs in the same city through the different needs of utilities, city administrations, and citizens, as previously discussed. Reasons for deploying LoRaWAN alongside other LPWAN may include the availability of specific sensors; for example, one city uses a Sigfox sensor for a gas tank in parallel to a self-provisioned LoRaWAN because, at the time when they installed it, there was no equivalent sensor for LoRaWAN available. These observations illustrate that the complexity of smart cities and the use cases will rely on several technologies in parallel.

4.5.5 Limitations

Insights achieved with this mixed-methods study are also subject to limitations concerning the difference between respondent and unit of analysis, city size defined in our sampling frame, and the geographic focus on Germany. They are not only limitations but, at the same time, suggest areas for further research.

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the city – organized in cooperation – but not originally came from the city but rather from the maker scene." - Original statement in German: „[D]ieses [Name des lokalen Hochwassermonitoringprojekts] kommt tatsächlich von der Idee her ursprünglich vom [Name des lokalen Hackathons], also einem lokalen Hackathon hier, der eben in Kooperation mit der Stadt betrieben wird, - oder veranstaltet wird -, aber eben nicht originär von der Stadt kommt, sondern eher sag ich mal aus der Entwicklerszene."

The seven cities with more than one respondent, which were used to discuss reliability, pointed out one limitation of our study: city representatives were our respondents. At the same time, the unit of analysis was the city. While this provided us with the lucky situation of assessing reliability, it also pointed out one shortcoming: in particular, with questions about opinion and evaluation of opportunities, we received two different responses from two people representing the same city. Either the number of respondents per city could be increased, or multi-respondent sessions could be held to consolidate (potentially additional) responses. Interviewer-led surveys might be an alternative allowing for clarifications and follow-up questions during the interview. Of course, these considerations must be balanced with those approaches' weaknesses.

In our survey, we focused on cities with 20,000 or more inhabitants, the environment in which most (59.5%) of the German population lives (Destatis - Federal Statistical Office, 2021c). The other 40.5% of the German population calls rural areas, villages, and small cities with less than 20,000 inhabitants their home. Results can, however, not be generalized to these smaller communities, as they benefit from smartification efforts in different ways: "in urban areas, a joint use of resources can be achieved thanks to a higher population density, whereas in rural communities, they profit from improved coordination and cooperation" (Hilbig et al., 2020: 9). While asking some of our survey questions to this smaller communities and comparing it to our smart city survey might yield valuable insights and support this argument, others might not be appropriate. For example, for smaller communities, self-provisioning could also be done in cooperation with neighboring villages and cities. Also, districts as an organizational unit might take on the role of the network provider here. The concept of a "smart country" is just emerging, but a similar survey might help to understand how it differs from the established "smart city."

Future work should also compare the German LPWAN setup, where no nationwide LoRaWAN is available, to other countries with such national coverage (e.g., Netherlands, Switzerland). The comparison might help to disentangle whether cities prefer LoRaWAN as a technology or whether it is about the self-provisioning feature.

The topic of technology selection in the smartification of sectors will persist. Maybe today's LPWAN technology selection challenge might become obsolete in the future because further market consolidation and also cooperation among providers of different technologies might remove communication barriers: for example, Deutsche Telekom (NB-IoT) started to cooperate with The Things Industries (LoRaWAN), Sigfox acquirer "UnaBiz has also stated its intention to 'strive towards the convergence of LPWAN'" (Kasujee & Mackenzie, 2022). However, other sectors than cities will aim to become smart and new communication technologies will emerge. Again, actors will face the question of which technology to choose, and they will need to rely on selection criteria. Our work contributes by showing the importance of governance-related criteria for practitioners, a group of criteria that scholars have mostly neglected so far.

4.6 Conclusion

Our exploratory sequential mixed-method design combines the strengths of a qualitative interview study with the power of a survey among 107 German cities to study the role of governance-related criteria as a technology selection criterion. We explored the context, process, and decision criteria as well as the observable outcomes, namely the technology setup, in the context of smart cities and particularly for LPWAN as an important element of the ICT backbone of smart cities.

Smart city is closely linked to a city's larger development strategy. This is supported by evidence from both parts of the study. Improving the city's reputation with its citizen is one of the key benefits expected from engaging in smart city efforts, the survey found. Cities want to be attractive and provide a livable environment to attract citizens, businesses and, in the end, secure their own existence.

In this context, we observe a variety of different technology selection processes in cities, ranging from simply copying neighboring cities to processes initiated either by a practical need or by the will to select a suitable LPWAN to strengthen its own ICT infrastructure as an enabler for smart cities. The variety of processes deployed, as well as difficulties in assessing different technologies with regard to the different technology selection criteria throughout the process, calls for further knowledge generation, diffusion, and exchange among the decision-makers in cities.

The decision criterion, where most survey participants were able to name a clearly superior technology with confidence while also ranking it among the three most important decision criteria, is self-provisioning. We explored that it is closely intertwined with the idea of control, influence, and independence of cities. It goes hand in hand with the involvement of citizens in smart cities as well as with the idea of seeing citizens not only as consumers but also as sources of inspiration and active participants in the smart city. An idea that is at the core of many definitions of smart cities used in democratic countries (Dameri, 2013; Stübinger &

Schneider, 2020). The survey showed that this remains a promise and ideal which many cities still must deliver onto.

The resulting settings are not one single network, but different requirements disentangled through the interviews make it clear that the coexistence of open and closed networks is likely. In the case of LoRaWAN, city administrations often opt for the open network, while utilities lean towards closed setups. Also, the future ICT backbone of smart cities will combine different technologies in some cities and even several LPWAN technologies to cater to all different needs.

The fuzzy concept of the smart city as a whole and its many connotations, the heterogeneity of cities, communities, and settlements in Germany, as well as the many nuances possible in ICT setups, are challenges to the generalizability of this study. Nevertheless, we can conclude that in a democracy, citizens play a crucial role in smart city development: as users and customers, as innovators, as principals for the acting cities, and lastly, as the ones cities aim to impress with their efforts.

5. A decentralized approach to IoT infrastructure? – the case of the blockchain-based LPWAN Helium

5.1 Introduction

IoT is at the core of the information society, yet it still needs to be built up in many places and for many technologies. Building communication networks often comes with a hen-and-egg problem: to build the network, one needs users, and users are willing to pay for a network if it has extensive coverage and many other users. One way to overcome the hen-and-egg problem is for large national telecommunication operators who have the means to make significant upfront investments into the network. In recent years, blockchain technology gained prominence and is also considered an enabler within IoT (Da Bueno Silva, Silva de Morais, Fernandes de Almeida, Luiz Felipe, Da Rosa Righi, & Alberti, 2020: 29). And indeed, it may have the power to revolutionize the provisioning of IoT connectivity by powering a novel approach to building up IoT infrastructure: a decentralized, peer-to-peer IoT network where incentives and transactions are decentrally controlled on a blockchain solution. Helium is such a network and blockchain, and it has been experimenting with this approach since 2019.

Centralization and decentralization in governance mechanisms have been subject to research for decades. IoT networks have traditionally been subject to rather centralized governance, but now the emergence of blockchain technology constitutes an opportunity to develop alternative, decentralized governance structures for these platforms (Chen & Bellavitis, 2020; Constantinides, Henfridsson, & Parker, 2018). Therein lies the revolutionary potential for IoT infrastructure provisioning, with the possibility to make IoT infrastructure a decentralized effort and transform network provisioning into a peer-to-peer transaction. Several networks, for example, Wicrypt and IoTeX, experiment with this approach, with Helium being the most prominent network pioneering this approach. The first case study on the Helium network was conducted by Jagtap et al. (2021) when the network was still immature. Since then, it has expanded in quantity of hotspots by a factor of 100 and developed a global footprint while adjusting its incentive structure. Jagtap et al. (2021) did not use their data to discuss possibilities for Helium's future development. This new case study leverages blockchain data from April 2023 to discuss decentralization, geographical scope, and concentration in the network and its implications for Helium's future development.

With this study, I investigate if „decentralized, cryptocurrency incentives-based network infrastructure [possibly] replacing traditional service providers“ (Musaddiq et al., 2022: 143) can *really* be a novel approach to IoT network provisioning and how. Hence, I study the pioneer of this approach: Helium. First, I clarify the terms and mechanisms of the Helium network and its underlying blockchain. Building on that, I develop a comprehensive understanding of the recent development and status quo of the Helium network. My analyses of the empirical data investigate the decentralization and geographical scope of the physical network, segmentation among the owners of the physical network, and the concentration among those who vote on the change of incentives and mechanisms of Helium. Based on the insights of this exploratory part, I illustrate a possible way forward for Helium and discuss the future of this approach for IoT infrastructures in general.

For this single case study, I first introduce the Helium network and blockchain with its terms and underlying concepts. For the empirical part, I use quantitative data on hotspots and their owners (accounts) web-scraped from the Helium blockchain in April 2023. Graphical and statistical methods are used to explore the data. My research focuses on the supply, i.e., the network-providing side of the Helium network. Three questions on ownership structure in the physical network, segmentation of the owners, and the concentration of voting rights will guide this endeavor.

This study contributes to the research on IoT infrastructure provisioning by discussing a novel approach to deal with the hen-and-egg problem of networks: a "decentralized, cryptocurrency incentives-based network infrastructure" (Musaddiq et al., 2022: 143). Moreover, it provides an in-depth analysis of the most prominent representative of this novel approach, the Helium network, and illustrates possible ways forward. I also highlight areas requiring further research to enhance our understanding of decentralized, blockchain-backed IoT networks and their governance.

This study consists of six sections: This introduction is followed by the second section (5.2), which provides an overview of the Helium network, including its unique approach to IoT infrastructure provisioning (5.2.1) and the concept of decentralized governance and blockchain technology (5.2.2). The section further explains the research setting (5.2.3), including the history and development of the Helium network, its physical architecture, the Helium blockchain, and its governance mechanisms. I close the background section with the current subjects of debate and research questions for this study (5.2.4). Section 5.3 explains the research method, a single case study mainly using quantitative data, data extraction, and an analytical approach to the three guiding questions. Section 5.4 presents the results of the empirical research, including the growth of the Helium network over time, decentralized network ownership and geographic distribution, structure and behavior of hotspot owners, and rewards for hotspot owners. In the fifth section of this study, I discuss the Helium network, its future, and the future research agenda. Finally, the last section of this chapter (5.6) summarizes the study's findings and provides an outlook on future research.

5.2 Background

5.2.1 Helium as a novel approach to IoT infrastructure

Helium is an IoT infrastructure project under a decentralized governance regime. It could provide a chance to move away from centralized governance of networks through large, centralized connectivity providers and hence is worthwhile studying. This study first explores the terminology and functioning of the Helium network infrastructure and its underlying blockchain solution. After that, I analyze quantitative data to draw a comprehensive picture of the development, status quo, and potential ways forward for the Helium network. With this exploratory single case study, I investigate whether the Helium blockchain lives up to the high expectations regarding decentralized governance and being a peer-to-peer network – in short: if it revolutionizes infrastructure deployment for IoT.

I build on the literature on decentralized infrastructure platforms and decentralized governance. After an introduction to the Helium blockchain and its history, I lay out the guiding questions of my study. To answer them, I use the rich Helium blockchain data, which is publicly accessible, and apply quantitative methods to it.

5.2.2 Decentralized governance and infrastructure-focused blockchains

Centralization and decentralization in business organizations have been subject to research for decades. It received strong attention when socialist and capitalist economies competed, of which Hurwicz provides comprehensive literature overviews (Hurwicz, 1972, 1986). Hurwicz laid the foundation for the modern Theory of Mechanism Design. The critical topic of decentralization versus centralization has not exclusively received attention in this context; it has also been discussed in the literature on the internal organization of large firms, modern industrial organization theory, and the regulation of public utilities. (Mookherjee, 2006: 368)

Traditionally, a centralized approach was seen as superior where externalities were strong, and distributional equity needed to be ensured, or in the case of public goods (Mookherjee, 2006: 368). In the case of communication networks, externalities are present, and so is the dsciussion on equity in these networks. For example, in the European Union, all member states are called to pay attention to giving all citizens access to these networks, regardless of where they live (European Union, 2018: §63). Mookherjee (2006) examines the implications of the classic principal-agent view. However, the blockchain traits like transparency and a technical protocol that replaces trust between the market participants are not yet part of his research.

Now, "the emergence of blockchain platforms offers a unique opportunity to examine alternative structures for platform governance and to develop a theory around the value of centralized, semi-decentralized, and decentralized governance" (Chen et al., 2021: 1305) and with this take this discourse into a new direction. Platforms are ecosystems where actors often collaborate around a dominant, stable core – often a technology[84] (Rietveld, Schilling, & Bellavitis, 2019: 1232; Teece, 2018: 1375). In the past years, digital platforms have both been able to disrupt the market with their novel business model and have been subject to governance research (Boudreau, 2010, 2017; McIntyre & Srinivasan, 2017; Rietveld et al., 2019).

Blockchain technology gained prominence less than two decades ago when the Bitcoin inventor Satoshi Nakamoto[85] published his article on the technology in 2008. This publication's title, "Bitcoin: A Peer-to-Peer Electronic Cash System", already points to the decentralized nature of the technology. In the following, scholars observed that the blockchain enables decentrally governed networks in practice (Böhme, Christin, Edelman, & Moore, 2015; Chen et al., 2021). Prominent examples are the Bitcoin and Ethereum blockchains. Antonopoulos

[84] Complementors are individuals and organizations that contribute to the success of a platform through providing complements, i.e., goods, which increase the overall value of the platform for clients, according to Teece (2018: 1375) For example, looking at Youtube as a platform, content creators are complementors, which make the platform more attractive for users. And more users make it more attractive for content creators to upload their content onto Youtube.

[85] The identity of Satoshi Nakamoto is still subject to discussion. It could not be clarified if it is a single person or even a group of developers.

(2017: 217) even calls the decentralized mechanism the "main invention" of the Bitcoin inventor Satoshi Nakamoto.

The blockchain is a compelling case of platform architecture: it offers the possibility to reduce transaction costs and provide network effects without any central trusted party needed. Blockchain technology enables decentralized governance, for example, by communities rather than a single agent (Chen et al., 2021; Chen & Bellavitis, 2020; Jagtap et al., 2021). The degree of centralization of a blockchain application depends on its context of use, as Chen et al. (2021) find: blockchains building infrastructure tend to be decentralized whereas those around applications tend to be more centralized. Helium, the focal network of this study, not only complies with this prediction, but as an infrastructure layer blockchain, it also issues its own coin, the Helium network token (HNT). This is in line with the findings of Constantinides et al. (2018).

Mueller-Bloch et al. (2022) discuss design choices for blockchains and their possible impact. They highlight the importance of a large number of potential validators to prevent attacks from happening and find transaction fees to be a little design choice with regard to decentralization. In the broader picture, "less academic research has examined the implications of blockchain for how we organize contemporary economies, society or organizations." (Beck, Avital, Rossi, & Thatcher, 2017: 381) – and for this study, I may add "or infrastructure provisioning."

This study contributes novel insights into the role of governance by incentives through blockchain technology as a decentralized governance approach. Its novelty lies in the contribution to understanding how decentralized governance enabled through blockchain technology can be used for IoT infrastructure provisioning through studying the Helium case.

5.2.3 Research setting: the Helium blockchain

5.2.3.1 History and development of the Helium network and blockchain

The parent company of the Helium network, Helium Inc., was founded in 2013 by Amir Haleem, Sean Carey, and Shawn Fanning. It took them a few years to develop a cryptocurrency to answer how to get people engaged in collaboratively building the IoT (Joel, 2023). 2019, on July 29th, the first actual entry on the Helium blockchain was recorded (Jagtap et al., 2021: 25).

At first, the Helium network was only available in the United States of America. Only after the summer of 2020, it expanded internationally (Jagtap et al., 2021: 27). In 2020, the Decentral Wireless Alliance (DeWi) was founded to be the non-commercial alliance supporting the growth and expansion of the Helium network. Later it was rebranded to the "Helium Foundation".

2022 also brought a rebranding to Helium Inc., now called Nova Labs, comprising the founders and some lead developers. The rebranding aims to make it easier to distinguish the parent company from the Helium network (Joel, 2023). Moreover, it seeks to account for the broader product offering and include a 5G network and other tokens (called IOT, MOBILE) (Hayward, 2022; Jagtap et al., 2021; Joel, 2023).

In terms of absolute numbers, "Helium boomed in 2021, growing from approximately 14,000 hotspots globally …[in] January to over half a million at the start of 2022" (Ligon, 2022). One could observe a strong presence in the United States and Europe, and Eastern China (see Figure 18). For the geographical mapping of the hotspot locations, the Helium network uses the H3 geospatial indexing system (Uber Technologies, Inc., 2023), which assigns each hotspot location to a hexagonal area on the map. These hexagons are available in different resolutions[86], and when zooming out (like in Figure 18), they are visualized as dots on a map.

[86] Resolutions range from 0 to 12, most commonly resolution 8 is used on Helium maps and in the app where owners can visualize their hotspots' locations. Resolution 0 corresponds to a hexagon with an area of 4,250,546 km^2 and an average edge length of 1,108 km. For resolution 8, the hexagon is approximately 0.73 km^2, and the edge is 0.46 km long. In the highest resolution (12), the hexagon area corresponds roughly to a house with 0.0003 km^2 and an edge length of 9.4 meters.

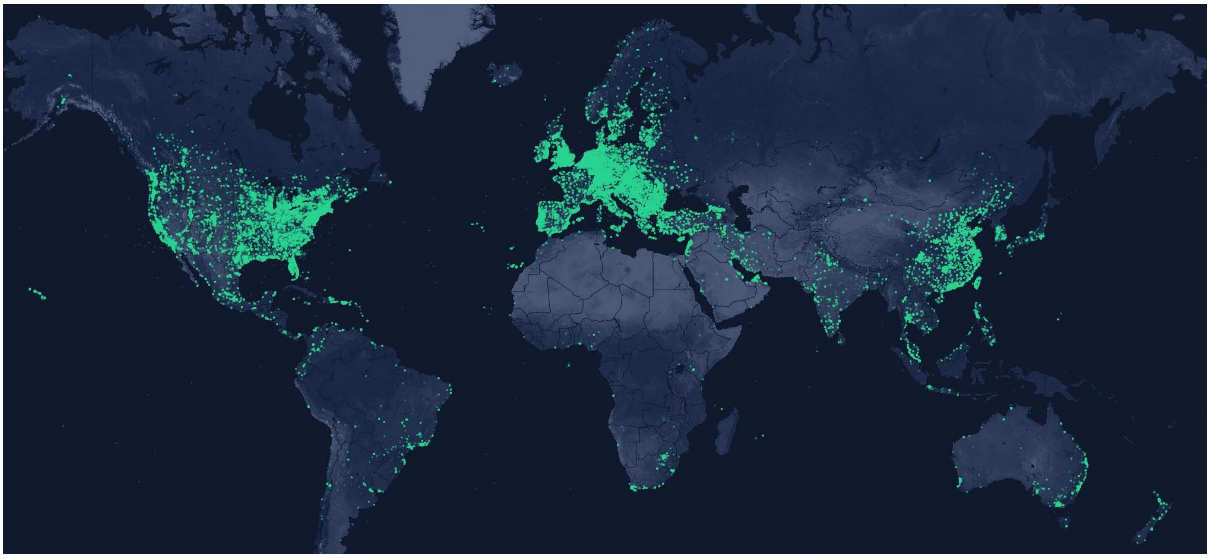

Figure 18 Helium network coverage as of March 13th, 2023, green dots represent a hexagon (of approximately 0.73 km^2) with at least one hotspot (source: screenshot taken from Helium Explorer: https://explorer.helium.com/iot, accessed on 03/13/2023)

While in 2021 roughly 30,000 hotspots were added to the network every month (Jagtap et al., 2021: 25), in 2023, the growth rate decreased to around 2,500 newly added hotspots monthly, a decrease of more than 90% within two years only[87]. This slower supply side, or infrastructure side, growth could be a sign that the Helium network reached saturation in several cities and districts, or it could indicate that incentives for further network expansion are less attractive now. The lower HNT to US$ conversion rate may suggest the latter.

Looking at the other side of the market, demand for IoT transactions, it seems that the previous slow traffic – a point of critique elaborated by Joel (2023) – is now steadily increasing: according to the Helium Foundation, the data packages handled per month grew by factor 10 from September 2022 to January 2023, rising from 121 million to more than 1.5 billion (Hayward, 2023).

5.2.3.2 The Helium network architecture

The Helium network was labeled "The People's Network" by its inventors. It relies on individuals and firms to deploy hotspots (the term in the Helium context to denote base stations/gateways) for the IoT infrastructure. It incentivizes them with a proprietary currency,

[87] Number according to Helium Explorer Website at: https://explorer.helium.com/iot, monitored throughout March 2023.

the HNT. “Helium is building a crowdsourced hotspot infrastructure” (Jagtap et al., 2021: 23), and with this follows a decentralized governance approach to IoT infrastructure, a governance by incentives approach. This makes it a fascinating case to investigate and understand further. In the words of the inventors:

> *“The Helium network is a blockchain with a native protocol token incentivizing a two-sided marketplace between coverage providers and coverage consumers. With the introduction of a blockchain, we inject decentralization into an industry currently controlled by monopolies.” (Haleem et al., 2018: 1)*

Technically speaking, the Helium network uses LoRaWAN network architecture to send data packages between wireless end nodes, mostly sensors, and cloud services hosted on the world wide web. LoRaWAN is a cloud-based protocol that ensures that LoRa data packages are transmitted correctly between the wireless end nodes and the respective cloud service (Jagtap et al., 2021: 23–24). In contrast to other networks using LoRaWANs, the novelty is that anyone can add a hotspot to the network, which constitutes Helium's crowdsourcing and decentralized approach. Figure 19 shows the network structure of the Helium network with the essential components end node, hotspot, and router, which I introduce in the following.

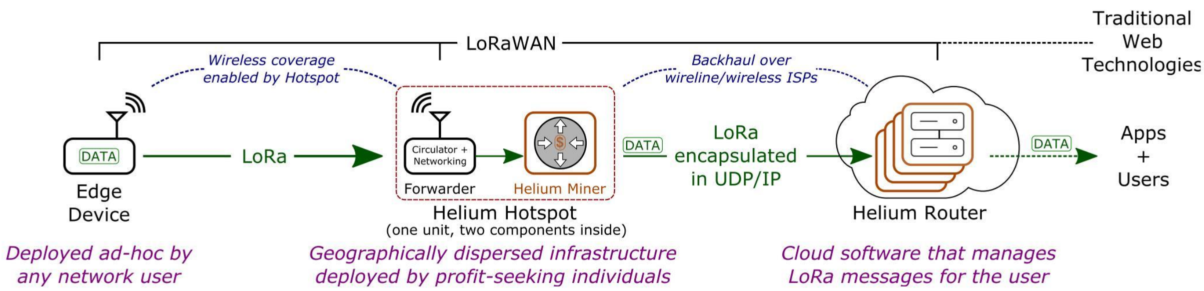

Figure 19 Helium network architecture (Source: Jagtap et al., 2021: 24)

End nodes (sometimes referred to as edge devices, see above) are wireless LoRa-enabled devices or connectivity unit. In most cases, they are part of a sensor. Following the LoRa protocol, they have an assigned Device End User Identified (EUI) and Application EUI. They come with an App Key, used for activating a LoRaWAN web service, eventually via a router. This process is further expanded for Helium: the EUIs are additionally matched to owners, allowing anyone to identify in which wallet they store their rewards. When they send data through the network, they pay transmission fees using currency stored in these associated wallets. (Jagtap et al., 2021: 23–24; Musaddiq et al., 2022: 145)

Hotspots consist of two components: the **packet forwarder** as the conventional LoRa element, and the Helium **miner**, which is the Helium-specific addition on a hardware level. While for normal LoRaWAN, the packet forwarder receives data packages transmitted via LoRaWAN and directs them directly to the owning router, for Helium, it first sends the data packages to its miner in the same hotspot. Miners as Helium-specific elements "transmit encapsulated LoRa packet payloads to and from Helium routers and maintain the Helium blockchain" (Jagtap et al., 2021: 24). Hence, they ensure data transmission and, at the same time, record their transmissions on an immutable blockchain so these transactions can be verified at any time. The hotspots can be installed on private properties, and depending on their antenna, their range is between 5 and 20 km (Musaddiq et al., 2022: 145). **Validators** are a special class of hotspots (not shown separately in the figure). They are elected and can function as cloud-based nodes. They are responsible for handling blockchain-relevant transactions, including "gather transactions, form blocks, and come to a consensus on the state of the blockchain" (Coinbase, 2022). To be eligible as a validator, a hotspot must deposit 10,000 HNT (equivalent to approx. US$ 14,000 end of March 2023). Afterward, it is eligible to become a member of the consensus group. This group of elected hotspots is responsible for recording all transactions, storing them as a block, and attaching the block to the existing blockchain.

Routers (sometimes called Helium web services) are cloud-hosted servers in charge of authenticating end nodes, processing their messages, and negotiating the payment for data with the hotspots. Anyone wishing to join the Helium network can register a Helium-certified router and (edge) devices by purchasing device and application identifiers (Jagtap et al., 2021: 23). This purchase is recorded on the blockchain. I explain the functioning of this blockchain in the next section.

5.2.3.3 The Helium blockchain

The Helium blockchain aims to ensure the functioning of the decentralized network. Blockchains are a mechanism to store data in "a transaction log that is distributed across a network" (Böhme et al., 2015: 213) of participating hotspots rather than storing it with one central, trusted authority. By keeping the shared records decentralized, blockchain technology has the "potential of making trusted third parties redundant" (Mueller-Bloch et al., 2022: 2). The fundamentals of the Helium blockchain were outlined in a whitepaper by Haleem et al.

(2018). Before analyzing the data stored on the blockchain, it is necessary to clarify which data is stored on it and which real-world events it represents.

Proof of Coverage (PoC) is the algorithm used to validate hotspots' physical locations and coverage (Musaddiq et al., 2022: 145). Since Helium is a physical network, its coverage also depends on the locations of the hotspots. Hence, this algorithm should be considered a Helium network core element. The PoC algorithm validates locations stochastically: it makes one hotspot the challenger, which randomly selects another hotspot, then called the challengee or transmitter. The challengee then issues an encrypted data package, and other hotspots geographically located nearby (also called witnesses) can then receive and report this data package and hereby they also confirm the challengee's physical location.

While PoC provides valuable work to the Helium network, it is not a consensus mechanism that decides which data and in which order is to be added to the blockchain. As the increasing network complexity and the variety of tasks to be completed by the hotspots made the network too slow, Helium, Inc. introduced the Proof of Stake and "[g]oing forward, Helium will be powered by both Proof of Coverage (work) and Proof of Stake (consensus)" (Coinbase, 2022).

A **Proof of Stake (PoS)** occurs every epoch (i.e., every 30 blocks) and is how the immutable blockchain is built and expanded. Based on a semi-random process, validators can be elected to the consensus group in each epoch. PoS is a consensus mechanism primarily based on the cryptocurrency fortune of a hotspot, which determines whether it is eligible for the consensus group or not. This process is an alternative to the Proof-of-Work, most prominently used by Bitcoin, which selects consensus group members based on their computing power (Mueller-Bloch et al., 2022). Proof-of-Work is the reason why Bitcoin is often criticized for being too energy-intensive. In Helium, members of the consensus group "receive encrypted transactions for hotspots, pass them around to the other validators in the group. Work together to decrypt them and reach a common agreement on the order of the transactions before forming a block" (Coinbase, 2022). Of course, the validators then get rewarded for their participation with the network's own cryptocurrency.

Helium network tokens (HNT) are Helium's own cryptocurrency, and the network pays any hotspot participating in such a PoC event in HNT. Historically, the value of HNT has ranged from US$0.27 to US$ 50.77[88] (see Figure 20). HNT can be traded for other currencies, a process called "cashing out". Rewards try to incentivize the desired development of the network; for example, more witnesses usually mean higher rewards. That is why completely isolated hotspots are financially not as attractive as others, which extend areas with existing coverage. On the other hand, network expansion is also important; thus, rewards go down in areas too densely equipped with Helium hotspots. These two extremes and finding the optimal equilibrium and aligning incentives to this optimum, are frequently subject to discussions in forums, blogs, and academic literature (Jagtap et al., 2021: 25).

Figure 20 HNT tu US$ exchange rate up to March 9th, 2023 (Source: https://coinmarketcap.com/de/currencies/helium/, last accessed 03/09/2023)

Data credits (DC) are the currency in which data transactions are paid[89]. The very volatile price of HNT could pose a challenge to potential adopters; DC have a fixed value of US$ 0.00001 (Jagtap et al., 2021: 25). HNT can be converted into DC at a variable rate, via a process called "burn HNT", but the conversion vice versa is not possible. Moreover, while HNT can be transferred, DC are a not transferrable currency, and only the party that got them through burning HNT or purchased them from the Sphere Data Credit Portal can use them (Coinbase, 2022).

[88] HNT peaked, like other cryptocurrencies, in November 2021. After that, the crypto winter started, and due to rising interest rates by the central banks, investments went down (Ashmore (2022)). The overall dynamics affected other cryptocurrencies similarly; nevertheless, compared to the leading player Bitcoin, HNT losses were much more severe: Bitcoin lost around 55% of its value between November 2021 and March 2023, and HNT decreased by around 97%.

[89] This is a concept like "Gas" in the Ethereum blockchain.

Helium security token (HST) are the third token in the Helium LPWAN universe. In contrast to HNT and DC, they are not intended to be used as a currency but rather are an investment vehicle, like shares, for which one can receive a dividend (Steidl & Wenz, 2022). Helium Inc. and early investors of the network mostly own them.

The Helium blockchain consists of blocks in which the transactions are recorded. The last block contains the most recent transactions. Blocks correspond to time intervals in which transactions are collected before being added to the blockchain as a batch. The target time for blocks is 60,000 milliseconds (60 seconds). Each block includes the "Previous block hash" as a unique reference to the previous block, and its correctness is proven by the "Threshold signature from the current consensus group". Moreover, each block is assigned a consecutive number ("Block Height"), which can be understood as the time unit of the blockchain. Thirty blocks always constitute one epoch (so roughly 30 minutes). Every epoch, a new consensus group of validators is selected and remains in power for these 30 blocks. After that, a new group of validators is selected.

There are five types of activities that hotspots can engage in to receive rewards (*names of the reward type in italics*): in PoCs, the challenger creating challenges (*PoC Challenger*), as well as the challenged hotspot (*PoC Challengee*) and its witnesses, receive HNT for their participation (*Witnesses*). Moreover, any hotspot transferring data is rewarded HNT (*Network Data Transfer*). Additionally, validators that are part of the consensus group that then builds and attaches the following block to the blockchain receive compensation (*Consensus Group*), and lastly, Helium Inc. and investors can receive rewards thanks to their HST (*Security Tokens*). The share of rewards that went to HST owners – around 33% in 2022 – was subject to criticism: for example, Emerson, Jeans, and Liu (2022) question the Helium claim of being "The People's Network". They criticize the large share of HNT allocated to the network founders, early adopters – including the founders' friends and families – and investors.

5.2.3.4 Helium improvement proposals as key governance element

Adjustments to the Helium blockchain mechanisms were made along the way through a mechanism called Helium improvement proposal (HIP). A HIP is "a community-driven process for making changes to the protocol, network configuration, and other shared concerns" (Dubs, 2023). The HIP-7, also considered a meta-HIP, describes the process of HIPs in detail and builds on the Improvement Proposal processes of Ethereum, Zcash, and Rust (GitHub - @jamiew, 2020).

The process works as follows (*associated HIP status in italics*): Ideas on how to improve the network can be of technical, economic, or process (also referred to as "meta") nature and are the proposal at the core of a HIP. After submitting a *draft*, editors review the submission, and if it meets the logistical requirements, they admit it to the following discussion and approval process. While "in discussion" the HIP is debated on a separate Discord channel or GitHub. The proposal is also presented in the monthly community call on the 4th Wednesday of each month; anyone interested can join the committee of a HIP for discussion and approval. The HIP approval happens through rough consensus: HNT owners can cast a vote via the website "helium.vote". Their on-chain vote is weighted according to the HNT capital in their wallet. They send a small amount of DC (around US$ 0.35) to the Helium blockchain associated with their vote, either "For" or "Against". The HIP is approved or rejected depending on the community's voting. For the approved HIPs, the development phase starts, where several programmers collaborate, and the community can read and contribute to the open-source code. Once successfully tested and committed, the HIP moves to the status *deployed*. (GitHub - @jamiew, 2020)

From a theoretical perspective, the HIP process is a form of token-weighted voting, which Tsoukalas and Falk (2020) discuss in detail. This mechanism is commonly used for blockchains, and the underlying rationale is that actors with a high number of tokens and, thus, decisive votes have a higher incentive to make high-quality decisions for the network, as they will benefit strongly from it. The other side of the coin is that the higher decision-making power of individual actors implies a higher ability to attack the blockchain or at least make decisions that only favor a small group of (large) actors rather than all blockchain participants (Mueller-Bloch et al., 2022: 17). Research on this area of on-chain governance has only recently emerged, as Mueller-Bloch et al. (2022) highlight.

With regards to the Helium implementation of HIPs, there are still many open procedural questions, such as "How do community calls work?" or "How long should a HIP be allowed to remain in a given state?" (Dubs, 2023). These questions are also made publicly available on GitHub; some are regularly discussed either in the online platforms of the community or in the neighborhood calls. The complete list of HIPs and their status are tracked on GitHub. Table 15 shows a selection of particularly powerful HIPs that influence Helium's incentive structure and affect governance mechanisms.

Table 15 Overview of selected HIPs (source: own visualization of GitHub Data: https://github.com/helium/HIP/, last accessed: 03/15/2023)

HIP ID	Title	Category of proposal	Status as of 03/14/2023	Acceptance block and date (if applicable)
17	Hex Density-based Transmit Reward Scaling	Technical	Deployed	Block 635109 12/16/2020
19	Approval Process For Third-Party Manufacturers	Meta	Deployed	11/25/2020
20	HNT Max Supply	Economic	Deployed	Block 946732 08/01/2021
25	Validators	Economic, technical	Deployed	Block 07/07/2021
70	Scaling the Helium Network	Technical	Approved	08/22/2022

HIP-17 and HIP-20 are considered some of the most notable HIPs so far (Emrit, 2022); HIP-19 was essential to boost the supply of hotspots to meet potential wallet owners' many orders and spur coverage of the Helium network. HIP-25 is crucial to understand the current validator role in Helium, and HIP-70 implies a major shift in the Helium business model and is for that reason very important. In the following, I briefly present each of these HIPs.

HIP 17 implements Hex Density-based Reward Scaling, hence modifying the PoC algorithm. It aims to reduce the rewards a hotspot can earn through transmission or witnessing very close hotspots (GitHub - @carniverous, 2023). With this, it encourages the expansion of network coverage: it becomes more attractive to place a hotspot in not yet densely covered areas, while it penalizes placing a hotspot in an oversaturated hex. This HIP affects anyone operating a hotspot, and it especially affects the reward structure for witnesses and challengers and aims to have a knock-on effect on coverage expansion. Despite this progress, first-movers to a new area are still penalized according to the detailed calculation logic in the HIP documentation (see GitHub - @carniverous, 2023).

HIP 19 allowed other manufacturers than Helium Inc. itself to sell Helium miners and, because of this, increased the offer of miners (Joel, 2023). The restricted availability before was seen as a bottleneck for the network's adoption and expansion. Yet, still with several third-party manufacturers participating, people who purchased a hotspot often had to wait months for delivery.

HIP 20 introduces a maximum supply of HNT to the Helium blockchain. To understand the implications of this HIP, it is necessary first to understand how the Helium blockchain aimed to work before the introduction of HIP 20: previously, Helium aimed to reach a **Burn and Mint Equilibrium (BME)** sometime in the future. In this ideal equilibrium, "DC provide a stable, deterministic payment model for network users, while network operators receive incentives in the more speculative form of HNT" (Jagtap et al., 2021: 25). While right now, high HNT rewards ensure fast network infrastructure build-up (i.e., the supply side of the network), in the future high Helium network adoptions and hence much data transfer via the network was expected (i.e., the demand side of the network). For the future, the community expected that burning HNT to have DCs to support data transmission would be equal to HNT needed to reward hotspots. Data transfer would require many HNT to be burnt to have enough DCs to pay for the data transfer. The concept of such a BME is not unique to Helium. Usually, it is used to avoid the velocity problem of utility tokens, i.e., to prevent inflation due to an endless supply of tokens (Atanasovski, 2019). As we have seen, the demand side of the Helium network is not yet that strong, and looking at the HNT to US$ conversion rate, one might also see strong inflation. Hence, a novel approach to handling the inflation issue was needed: net emissions with a restricted supply of HNT.

HIP 20 introduces this maximum HNT supply of 223,000,000 HNT to the Helium blockchain (Coinbase, 2022) and, with this, implements **net emissions**, an innovative economic mechanism discussed by Bitcoin researchers (Chen et al., 2021: 1307) and in other cryptocurrency communities. Its introduction affected all HNT holders, owners of hotspots, and owners of HST. The HIP proposes a fixed schedule of HNT emissions and their allocation to the diverse types of rewards and, consequently, to the mentioned groups. The schedule defines that the number of newly issued HNT per year will halve every two years, starting in 2021 and running until 2070 (Coinbase, 2022; GitHub - @jmfayal, @tjain-mcc, & @rawrmaan, 2023). This allocation over time, according to the schedule, is shown in Figure 21.

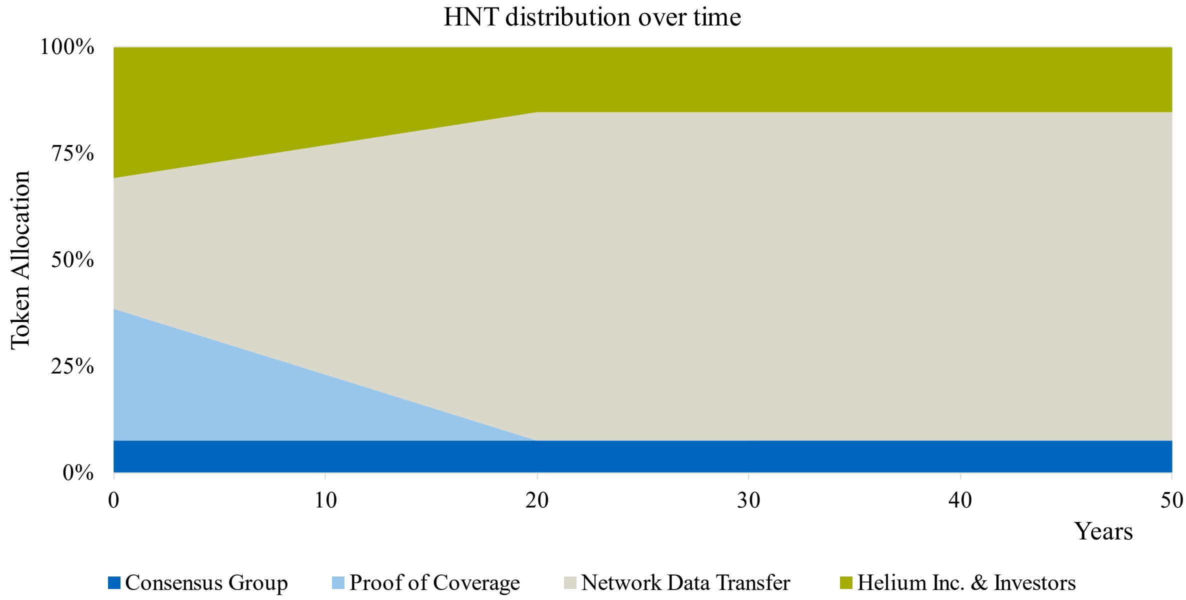

Figure 21 Distribution of HNT over time according to HIP 20 (source: own visualization based on Helium Inc., 2022: www.helium.com/token, last accessed: 03/28/2023)

This means that the amount of yearly issued HNT depends on two sources until 2070: first, a decreasing number of new HNT according to the schedule defined, and second, any HNT which is burnt to DCs implies that another HNT can be issued. The second mechanism will continue to operate beyond 2070 and ensure that data transmitters can receive rewards in perpetuity. Thanks to the net emissions concept, inflation decreases, which was a shortcoming of the previously used BME concept. The contrary is the case: coins with a maximum supply and diminishing coin issuing are commonly associated with deflationary effects, i.e., increasing the value of the blockchain currency (Antonopoulos, 2017: 216–217). However, this could not be observed in the HNT exchange rate until April 2023.

HIP-25 introduced validators in July 2021 and installed a new concept for staking and, in parallel, introduced lightweight hotspots which only forward data but do not contribute to adding blocks to the blockchain. This change affected hotspot owners interested in participating in validation activities and earning HNT. Future validators need to deposit 10,000 HNT to become validators, and 6% of all rewards will – like before – go to the consensus group (GitHub - @evanmcc & Helium Team, 2023). However, the group of nodes eligible to be part of the consensus group becomes much smaller: Rather than choosing the consensus group from all hotspots, now it is selected from the limited group of highly performant hotspots[90], the validators. The targeted stable block time can only be achieved by hotspots with powerful CPUs and with a professional internet connection. Thus, "[i]t is not suitable or recommended to attempt to run from a home internet connection" (GitHub - @evanmcc & Helium Team, 2023). Validators are penalized for not being online or being slow by a "penalties score", making it less likely for them to become part of the consensus group. By March 2023, almost 3,000 validators were online compared to nearly one million hotspots (roughly 0.3%), making it clear that only a tiny fraction of hotspot owners can meet the high requirements for becoming a validator.

HIP-70 was approved in September 2022, and at the time of this research, its implementation is still ongoing. The Helium Foundation considers this HIP one of the most significant changes to its business model as it transfers from the current proprietary blockchain solution to Solana as a more scalable solution. Simultaneously, the PoC and data transfer would be taken off-blockchain and transferred to oracles. (Helium Foundation, 2022) This HIP will make validators and the consensus group, as Helium currently knows it, obsolete, and their reward share will be given back to the total amount available in each block. More importantly, with this HIP, the Helium Foundation and Nova Labs aim to make Helium a network of networks, integrating a wider range of tokens (Hayward, 2022). This study, however, focuses on the Helium LoRaWAN network, powered by HNT, as this LPWAN technology is vital for the further expansion of the IoT. (Ayoub et al., 2019a; Ibrahim, 2019; Marini et al., 2022). This is in line with the approach taken by Jagtap et al. (2021).

5.2.4 Current subjects of debate and guiding questions for this study

The Helium network is a novel approach to tackling the hen-and-egg problem inherent to network goods. Initially, Helium firmly focused on building the network or supply side, i.e., the network infrastructure, and researchers like Jagtap et al. (2021) also focused their research on this side of the network. The second part, adoption by actual users who send data via this network and use the infrastructure, is ongoing. In 2021, Jagtap et al. found 99.2% of all

[90] Key criteria for a hotspot to be considered "highly performant" are, as announced by the Helium Foundation (2023), that a validator provides sufficient CPU power to contribute to building blocks and adding them to the blockchain, that it is on a stable internet connection and can be found by other hotspots.

transactions on the Helium blockchain to be PoC transactions (ibid. 2021: 25), underlining the vital role of the supply side. Musaddiq et al.'s study (2022) on wetland monitoring using the Helium network can be considered the first study investigating the adoption side of Helium. They do so by testing the practicability and maturity of the network for a stationary real-world application. While transmission rates above 98% are convincing, they also highlight areas for improvement of the Helium blockchain. Two major points they put forward are the need for a long-term guarantee for availability and sanctions for fake hotspot locations, which only optimize HNT return but do not contribute positively to coverage (a practice called "spoofing").

Helium also received attention beyond the academic community. Their US$1.2 billion valuation in March 2022, when they closed their US$200 million series D funding, attracted broad attention (Wright, 2022). A Forbes authors team voiced severe concerns in their article "Crypto Darling Helium Promised A 'People's Network.' Instead, Its Executives Got Rich." (see Emerson et al., 2022). Musaddiq et al. (2022) echo their critique of spoofing, which supposedly was also done by Nova Lab employees. Emerson et al. (2022) also claim that the senior leadership around the founders of Helium secured the lion's share of HNT early on and later cashed out. At the same time, any hotspot owner joining later would need several years to get a return on their investment, not yet talking about profits. On the other hand, Helium has recently seen a rise in data transmitted via the network, an indication that the demand-side is gaining traction and growing (Hayward, 2023).

It is unclear which future Helium is heading to and if it can keep its promise of being the "People's Network". This study aims to explore the development and status quo of the Helium network and, with this, develop a fact-based view of potential ways forward for the Helium network. It expands Jagtap et al.'s (2021) work by considering a more extensive (around factor 100) and more recent data set. Also, the Helium network implemented major HIPs since Jagtap et al. (2021) studied the Helium network, which has affected the operations and incentives provided within the network. Moreover, this study focuses on contributing peers, here all hotspot owners, whereas Chen et al.'s (2021) study on decentralized governance mainly focused on platform owners and developers.

For this empirical study of the Helium network, I also consider how the network evolved and changed over time and hereby go beyond a pure assessment of the status quo. Three questions will guide the analyses in this study:

I) Can the Helium network be considered an IoT network of global scope and decentralized ownership?

II) Who are the hotspot owners? Are there different groups identified based on their behavior?

III) How are tokens (HNT) distributed among hotspot owners?

In the next section, I will briefly elaborate on the suitability of quantitative analyses to answer these questions. After that, I will explain my data collection and the analyses I will apply to the empirical data to answer above mentioned questions.

5.3 Method

5.3.1 A single case study using quantitative data

This study is an in-depth exploration of a single case, the Helium network, and its underlying blockchain. This research strategy can yield an in-depth understanding of the dynamics present in the case's environment (Eisenhardt, 1989: 534) and helps to understand the development of the Helium network as a complex phenomenon (Yin, 2009: 5). Case studies are beneficial in contemporary settings where the participants' behavior cannot be manipulated, which is the case for the fully operational Helium blockchain (Yin, 2009: 11).

In their extensive discussion of research approaches and associated methods in social sciences, Morgan and Smircich (1980) consider quantitative approaches suitable when the social world is understood as a concrete structure. This is the case for the Helium network, mainly as interactions between (technical) hotspots or blockchain activities are in focus rather than complex human beings. In an extensive review of previous quantitative research on blockchains, Sanka, Irfan, Huang, and Cheung (2021) find that a plethora of quantitative data has been analyzed for blockchain research in past years, including survey and questionnaire data.

Helium, as a blockchain-based network, follows strict rules, and all these rules are publicly accessible, and those who join the network can know them in advance. Thanks to smart contracts and the open code on GitHub, interested people can learn about Helium's rules and guidelines, analyze them, and understand the system's mechanisms before – or even entirely without – purchasing a hotspot. Thus, the entire blockchain environment can be considered a deterministic or "lawful" system, "an objective phenomenon that lends itself to accurate observation and measurement" (Morgan & Smircich, 1980: 495).

This study addresses the three guiding questions, which are exploratory in nature, but it will surely raise new questions and identify further areas for research. It aims to be one of the "studies that raise questions about a phenomenon [and] can be as valuable as studies that seek to provide answers" (Bettis, Gambardella, Helfat, & Mitchell, 2014: 950). Empirical exploratory research can use various analytical approaches: graphical, algorithmic, and statistical. So does this study, and I elaborate on its approaches in the next section.

5.3.2 Data extraction and analytical approach to the three guiding questions

For this research, I make use of the openly accessible blockchain. All data until the 18th of April 2023 are accessible via the Helium Application Programming Interface (API). The blockchain moved to the Solana blockchain solution (as decided in HIP-70) and thus will no longer be updated. Future research on the Helium blockchain, which wishes to leverage the latest data, will have to access the Solana blockchain data.

I used Python scripts for an automated download of the blockchain data and downloaded the data between April 17th and 18th, 2023 (corresponding to the block heights 1,839,202 to 1,840,583). It resulted in approximately 2.3 GB of data stored in JSON files.

The JSON files were converted to CSV files using Alteryx Designer software in version 2021.3. Further statistical analyses were then conducted using Alteryx or the Stata 16 software.

To replicate some of Jagtap et al.'s (2021) results and allow for insightful comparisons with my data from 2023, I constructed a dataset based on their information that, at the time of their data collection, "there are about 9,000 unique owners total" (Jagtap et al., 2021: 27). This dataset includes the 9,000 earliest hotspot owners of the Helium network[91] and the number of hotspots each owned at the block time 830,064. I validated the data set by reproducing the ownership distribution at that time, as indicated by Jagtap et al. (2021).

Regarding the structure of the empirical analyses, I will briefly investigate the growth of the Helium network before examining the three guiding questions. While Jagtap et al. (2021)

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[91] They were identified based on when their first hotspot was registered in the Helium network. Then, I also identified all other hotspots mapped to their wallet before 830,064 to precisely have the view that Jagtap et al. (2021) supposedly had at that time.

partially explored similar questions as I do in this study, the network grew and matured impressively since they conducted their research. Only two years ago, roughly 30,000 hotspots were registered to the Helium network in April 2023, it is now about to surpass one million hotspots. Understanding this immense growth will set the stage for discussing the three guiding questions and a fact-based view of Helium's future development.

I study **the potential global scope and decentralization in ownership** similarly to what Jagtap et al. (2021) did before. I aim to compare their insights on decentralization in ownership with the status quo data collected in April 2023. This allows me to analyze the network's development in the past two years. For these analyses, I use the fact that each hotspot is associated with a wallet, but one wallet may be associated with several hotspots. To gather insights on the geographical expansion of the Helium network, I will analyze the hotspots' locations nationally to see whether Helium genuinely has a global footprint beyond the apparent intense concentration in the United States of America and Europe (recall Figure 18).

Understanding **who the hotspot owners are and what drives their behavior is crucial to identifying** potential ways forward for the Helium network. To do so, I will explore different owner segmentation approaches, such as segmentation via the number of hotspots owned in line with Jagtap et al. (2021) and the segmentation depending on the adoption timing according to Rogers (1962). A hotspot characteristic that may reveal more information about the owner is whether or not an owner's hotspot(s) are online. Keeping hotspots online requires owners to conduct regular updates and monitor their hotspots' online status in case an error occurs and requires a restart. Hence, the share of online hotspots of an owner will also be the subject of my analyses.

To answer the third guiding question on the **distribution of tokens (HNT) among hotspot owners**, I will calculate the Gini coefficient, a well-established measure for inequality in the distribution of wealth among populations (Mueller-Bloch et al., 2022: 8). To further understand which factors influence an owner's token ownership or wealth, I will use ordinary least squares (OLS) linear regression with the owner's HNT balance as the dependent variable (Bettis et al., 2014: 950).

5.4 Results of the empirical study

5.4.1 Hotspots: the Helium network's growth over time

When the data was collected, the Helium network counted 991,088 hotspots overall. The growth pattern shows a nearly perfect S-shaped curve, as Figure 22 shows. The average block height at which hotspots were registered in the network was 1,184,791 on 07/27/2021[92]. On average, 2.412 hotspots were added per block (σ=3.405), obviously with a large spread ranging from no hotspot added during blocks in the early days to 502 hotspots in block 1,101,013 (on 06/23/2021). 43.58% of all hotspots (431,922) are online during observation, while the majority (56.42%; 559,155) are offline. Comparing this growth curve to the HNT price development (recall Figure 20), only a slight positive correlation can be observed (r^2=0.1650***).

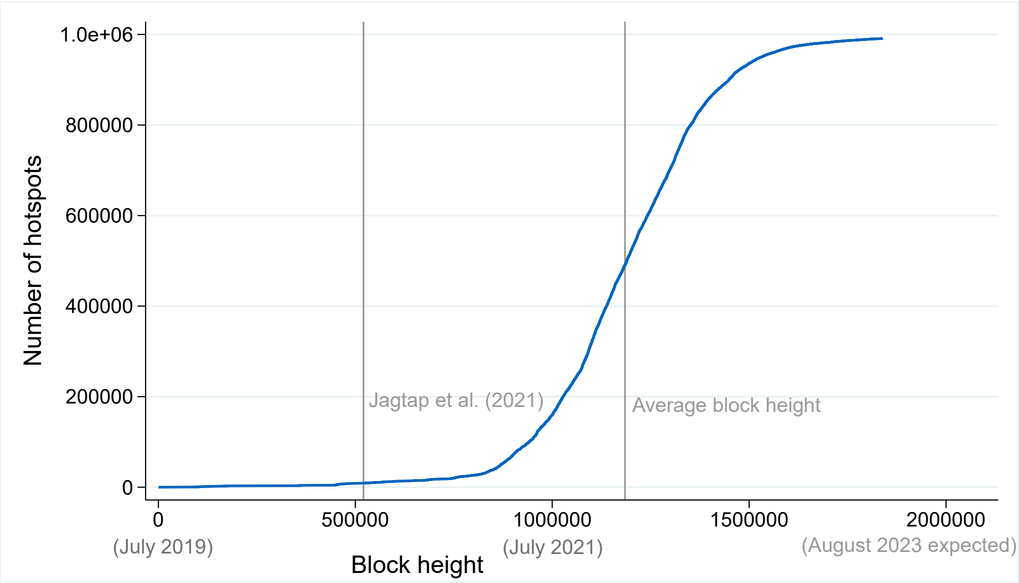

Figure 22 Helium hotspots cumulated over time

Looking at the cumulated number of hotspots installed (Figure 22), one can see that Jagtap et al.'s (2021) study on Helium investigated a yet immature network at the beginning of

[92] First, time is estimated based on known block heights of major Helium network events and the target block time of 60 seconds resulting in 1.440 blocks per day. I verified the estimations through instructing ChatGPT to retrieve a human-readable format of the date by the following instruction: "Could you please convert the following block heights from the Helium network using Helium API to Unix time first and then to a readable format? - [insert block height(s) of interest]".

its expansion. Thus, in the next section, I revisit their analyses on the distributed ownership of hotspots and geographic distribution.

5.4.2 Decentralized network ownership and geographic distribution

To investigate the decentralized network ownership and geographic distribution, I study the number of hotspots per owner and the number of countries where Helium hotspots have already been installed. To measure the decentralization of the Helium network ownership, I investigate how many hotspots have the same owner, i.e., send their earnings to the same account. Using my replicated Jagtap et al. (2021) data, I find that owners, on average own 3.501 hotspots (σ=16.418) in March 2021; in the April 2023 data sample, this number drops to 2.299 hotspots (σ=10.470). While the maximum number of hotspots owned by a single owner was 160 in March 2021 and 1,903 in May 2021 (Jagtap et al., 2021: 27), in April 2023, it is only slightly higher with a maximum of 1,990 hotspots owned by a single owner. Figure 23 compares the ownership distribution between the replicated Jagtap et al. (2021) data and the data from April 2023. During that time, the share of single hotspot owners, i.e., those who own only one hotspot, increased from 64.6% to 66.8%. The percentage of hotspot owners with two or three hotspots followed the same trend. For higher numbers of hotspots owned by a single owner, we can observe a movement in the opposite direction: the share of owners with 15 or more hotspots decreased from 3.0% in the replicated Jagtap et al. (2021) dataset to 1.1% in April 2023. Hence, hotspot ownership has become more decentralized over the past two years.

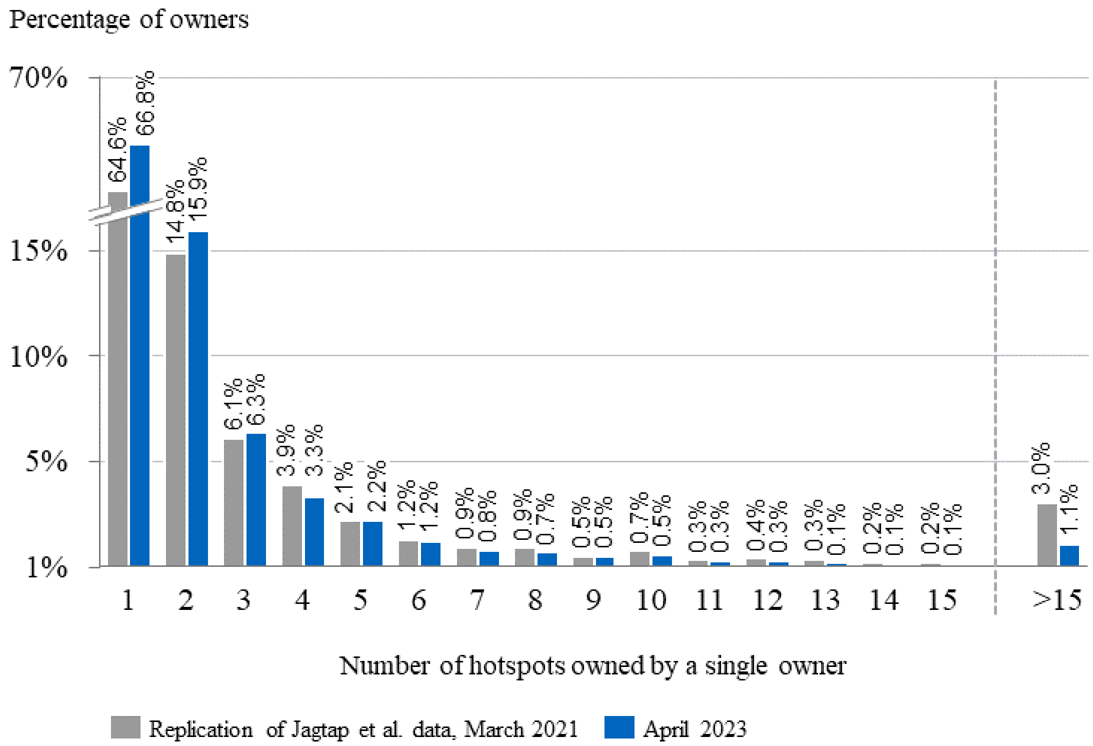

Figure 23 Distribution of the number of Helium hotspots owned by a single owner

I next investigate the geographic distribution of the Helium network; I study both, the absolute expansion and the concentration on single geographies. In terms of expansion, in my replication of Jagtap et al. (2021) data, I find 74 distinct countries. At that time, the vast majority, namely 68.0% of the hotspots (21,925 out of 31,511), were registered in the USA. They were followed by 5.0% (1,562) in China and 4.4% (1,377) in the United Kingdom. No country was indicated for 1,523, i.e., 4.8%, of the hotspots. In April 2023, Helium hotspots were present in 176 countries and have become a global network. While the USA remains the country with the largest number of registered Helium hotspots (37.5%; 372,076), followed by China (9.6%; 95,118), Germany moves in as new number three (5.9%; 58,774). In addition to these results, Figure 24 displays the other countries ranked in the top 10 for both observation times with their respective share among the total. Notably, the percentage of hotspots in countries other than the top 10 rose from 4.6% in March 2021 to 25.5% in April 2023, meaning that the Helium network has a much broader distribution or geographic goverage, becoming less concentrated in its geographic distribution.

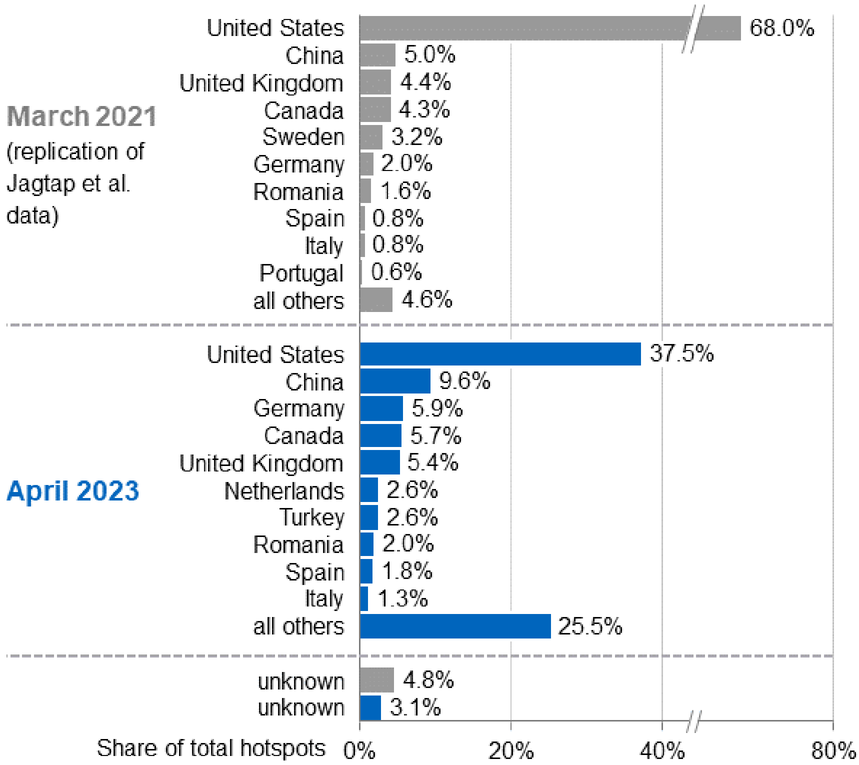

Figure 24 Geographic distribution of the Helium network – top 10 countries

It is essential to differentiate presence in a country from coverage: for example, in the four countries ranking lowest in the analysis of the April 2023 data – Haiti, Liberia, Mali, and Nepal – only one hotspot is registered in each of these countries. This is not enough to ensure coverage, i.e., to enable reliable sending and receiving of data in most places in these countries. Looking at Munich (see Figure 25), an economic center where roughly 3.1% (1,802) of all German hotspots are registered in an area comprising less than a thousandth of Germany, there is not always coverage ensured in the suburban regions apart from highways and other main traffic routes as well as densly populated areas.

Figure 25 Helium network coverage around Munich (screenshot of https://mappers.helium.com/, last accessed 05/10/2023)

5.4.3 Hotspot owners: structure and behavior

Helium, as a decentrally owned peer-to-peer network, heavily relies on (potential) hotspot owners to buy further hotspots, install them, grow the network, and expand its coverage. So far, this study considered owners as one homogeneous group.

However, as seen in the previous section (5.4.2), hotspot owners vastly differ in where they are geographically located and how many hotspots they own. Standard Helium hotspots can be purchased for roughly US$500. While higher prices occur, especially if powerful antennas are purchased to improve signal reception, lower prices are unlikely as Helium hotspots are manufactured by selected partners of Helium Inc. and Nova Labs only (Emerson et al., 2022). Thus, purchasing one hotspot might be viable for a curious tech-affine person or a blockchain enthusiast with the willingness to get into the installation of the device. Buying many Helium hotspots and installing them suggests professional ownership and some underlying business intention. Owners with one to three hotspots most likely install them at their homes, workplaces, and maybe at their friends' or families' places. However, those who own more hotspots must find other locations and eventually even rent additional locations since placing the hotspots too closely together is not beneficial and even sanctioned in the Helium network. Probably these multi-hotspot owners accept these inconveniences only because they have a confident expectation of return or any other non-monetary interest in the Helium network; for example, they may want to use the Helium network for their own IoT devices.

For the analysis of timing, I aggregate the number of new hotspots installed for two different groups: first, the decentrally owned hotspots (i.e., the hobbyists or enthusiasts with three or fewer hotspots per owner, in line with Jagtap et al., 2021) and secondly, professionally or semi-professionally owned hotspots where each owner has 20 or more hotspots. Comparing the number of newly installed hotspots per week, Figure 26 shows that initially, the (semi-) professionally owned hotspots make up most newly installed hotspots per week. Around week 80 (January 2021), the number of newly installed hotspots for the group of (semi-) professional owners saw a steep growth, a development that one can observe among the decentrally owned hotspots only a month later. The latter continues to grow even stronger, becoming the dominant ownership type with high peaks, adding almost 15,000 hotspots to the network per week in their strongest week.

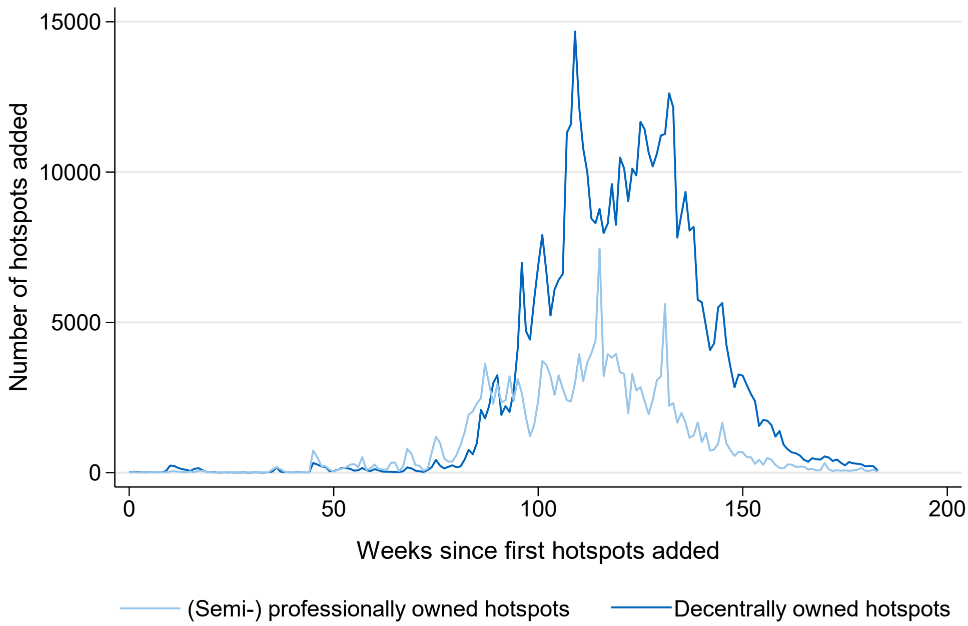

Figure 26 Hotspots added per week for decentrally owned hotspots and (semi-) professionally owned hotspots.

To see if these groups behave differently, aside from timing their hotspot installations, I chose an outcome variable to indicate care for the hotspot and engagement: the share of online hotspots. When I compare the percentage of online hotspots for the decentrally owned and professional or semi-professional owned ones, I find them to be different: owners with one to three hotspots have, on average, 51.63% (σ=0.4773) of their hotspots online. In comparison, (semi-)professional owners with 20 or more hotspots have 27.54% (σ=0.3013) of their hotspots online. Using the Mann-Whitney- Wilcoxon-Test,[93] we clearly should reject the hypothesis of the two groups being equally shaped and having a similar share of hotspots online ($p=0.000$; $z=-25.936$; $n_{decentral}=383{,}503$; $n_{(semi\text{-})professional}=3{,}331$). I complement the statistical analysis with a visual comparison, as Buja et al. (2009) suggested. Figure 27 shows that the two groups are also very different visually.

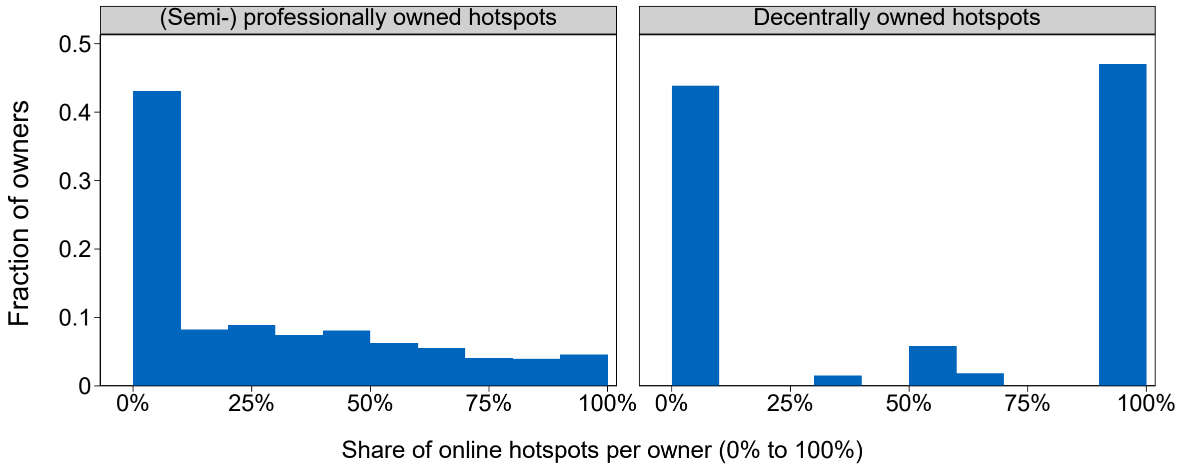

Figure 27 Share of online n hotspots for decentrally owned hotspots and (semi-) professionally owned hotspots, at the time of data retrieval in April 2023 (grouped per 10% interval)

For (semi-) professionally owned hotspots we see that the large majority of owners has only 0% ot 10% of their hotspots online. For decentrally owned hotspots, most owners have either all or no hotspot online, which can be explained by the fact that there are many single hotspot owners included in this group and hence only a dichotomous outcome is mathematically possible. The observation that the (semi-) professionally owned hotspots are less frequently online than the decentrally owned ones seems counterintuitive if "being online" is seen as an expression of maintenance skills and effort. A possible explanation could lie in the timing of hotspot acquisition on professional investment management. Semi-professional owners, on average, joined the network earlier, as Figure 26 shows. They may have recovered their investment earlier, maybe even cashed out, and given the unattractive HNT to US$ exchange rate in the past months, they have only low financial incentives to invest in their hotspots'

[93] Several statisticians identified the test around the same time; hence, it has several names. Other popular names are U test, Wilcoxon rank-sum test or Mann-Whitney U test.

maintenance and keep them online. Decentrally owned hotspots, however, have been purchased later, and given the less favorable HNT to US$ exchange rate, their owners may be far from having recouped their investment. Perhaps they are trying to use any opportunity to earn HNT and thus ensure their hotspots are online. The large share of fully offline owners in the group of semi-professionally owned hotspots possibly points to the fact that several professional owners have entirely withdrawn from Helium, at least for now. In the case of the decentrally owned hotspots, maybe two effects come together in the fully offline subgroup: in addition to some withdrawing from the network, all owners with only one hotspot that temporarily are offline, for example, due to technical issues, are automatically identified as "fully offline".

Hotspots owners also differ with regards to when they have joined the network: recalling the S-curve-shaped growth of the Helium network from section 5.4.1, it is fair to assume that we have seen the whole range from innovators, through early adopters, early and late majority, to the laggards, as Rogers (1962) classified adopters based on the timing when they adopt an innovation[94]. The average number of hotspots per owner decreases from 7.225 (σ=35.004) for the innovators to 1.531 (σ=3.510) for the laggards. Figure 28 shows the quartiles and the median of the hotspots owned for each time-based group. More than 25% of owners consistently decided to own only one hotspot. For the early majority and all following groups, even half of the adopters opted for only one hotspot. While the top quartile among the innovators owns five hotspots or more, this number decreases for later adopter categories. Assuming the maturity of the Helium network according to the S-shaped growth pattern and comparing the adopter groups following Rogers' (1962) classification, I can conclude that throughout Helium's development, a group of a minimum of 25% of the accounts only owns one hotspot. This could mean consistently one forth or even one half (for the early majority to laggards) of the accounts are curious individuals trying out Helium, realizing their own use cases at home with Helium, or installing only one hotspot for other motives.

[94] Rogers (1962) identified five groups of adopters and assigned a percentage p of adopters to them. The groups and their timings are as follows: 2.5% of first adopters are called innovators, the following 13.5% are the early adopters. They are followed by the early majority, constituting the next 34%, followed by an additional 34% named the late majority, and, finally, the remaining 16% are the laggards (ibid., p.160-163). For this study, I mapped Rogers' (1962) distribution to the first registration time of each hotspot, resulting in the following groups: innovators registered their hotspots in the Helium network before block 851,915 (12/03/2020), early adopters then until 1,012,455 (09/15/2021), the early majority until block 1,202,925 (01/26/2022), the late majority then joined until 1,380,118 (05/19/2022), and the laggards followed after that.

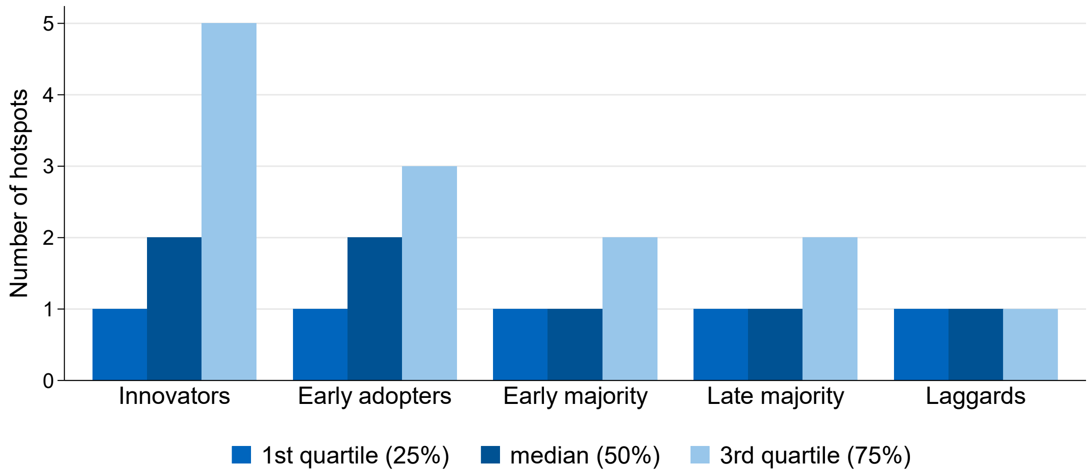

Figure 28 Quartiles of hotspots owned per account along the adopter categories defined by Rogers (1962), at the time of data retrieval in April 2023

Looking at Figure 18 and Figure 25, assuming saturation in the Helium network seems inappropriate, and an alternative explanation for the S-shape of the Helium network's growth should be considered. Considering the declining growth rate since late 2021, the declining exchange rate of Helium (recall Figure 20) could be an explanation. The declining exchange rate made investing in a Helium hotspot financially less attractive. While in the early days of the Helium network, the initial investment into a hotspot could be recuperated within a few months (Emerson et al., 2022), in the meantime, the declining HNT rewards, as well as the falling exchange rate made the amortization period longer and made it riskier to recuperate the investment at all. To understand different types of network participants and their motivations, it is worthwhile to comprehend who continued to invest when cashing out HNT on the cryptocurrency market became not attractive anymore.

In operational terms, I construct a subset of my data with hotspots first registered after mid-November 2022 (block 1,619,546). This date is six months after the HNT exchange rate fell below US$10 /HNT to account for the extended delivery time that has complicated the Helium hotspot supply chain for years (Joel, 2023). The subset contains the 16,961 hotspots newly registered in the Helium network between mid-November 2022 and the data retrieval time (April 2022). Of these hotspots, 49.27% (8,356) were associated with first-time hotspot owners. The other 50.73% (8,605) were from owners who had already owned hotspots before, 21.854 (σ=52.178) hotspots on average. These hotspots were installed in geographies where the Helium network is active, and no difference between the groups was observable. While at the beginning of the observation period, end of 2022, slightly more hotspots were installed, towards the end of the observation period in spring 2023, the installation rate declined. This supports the impression of the overall slow-down in hotspot installation, as discussed in 5.4.1.

5.4.4 Rewards for hotspot owners

The rewards in Helium's native token HNT are recorded per account and stored as the variable "balance". Note that this denotes only the rewards owned at the time when this variable is retrieved. When hotspots receive rewards, they are added to their associated accounts' balance. If sensors are associated with accounts, the balance can be reduced by burning HNT to DCs. Moreover, if account owners decide to cash out, the balance decreases by the amount of HNT being cashed out. Thus, the balance must be considered a snapshot wealth measure and does not represent the total wealth generated for one account.

In April 2023, on average, each owner had 63.22 HNT (σ=14,152.01) in their wallet[95]. The distribution is, however, very concentrated: the Gini coefficient is 0.9834. Thus, there is a very concentrated distribution of rewards in the wallets among accounts (Mueller-Bloch et al., 2022: 7). Due to the token-weighted voting system on HIPs, the distribution of rewards is critical to the Helium network. These results must be interpreted cautiously, as potential cash-outs are not visible in my dataset. Thus, owners in the sample with relatively low rewards may have made money from selling their rewards on the crypto market. My data thus clearly allows us to conclude that rewards were highly unequally distributed at the time of observation and that if any voting were to happen right now, voting rights would be very concentrated on a few wealthy accounts. We cannot draw any conclusions from the data set used for the analyses here for earlier voting procedures or the cumulative allocation of rewards. As wealthy accounts can generate more money by cashing out, one can assume they are more likely to cash out. If this were the case, it would mean that in earlier voting, voting power was even more concentrated than it is today. Considering the unattractive HNT to US$ exchange rate, which has been around since mid-2022, it may have become unattractive to cash out for many market participants. It may thus be fair to assume that only a few cashed out, and many are waiting for a better exchange rate, implying relatively stable voting power.

[95] Data on accounts was collected between blocks 1,839,301 and 1,839,432, the Helium network's average conversion rate for HNT and US$ of this time span was used.

If many owners of small amounts of rewards cashed out between the last voting and the time of data collection, then for the previous HIP voting, power would have been less concentrated than today.

This study aims to shed further light on the factors that lead to higher – or, respectively, lower – number of rewards in the wallet of owners. Ideally, I would use the cumulative HNT earned by the owner. Still, as this information is unavailable in my dataset, I used the rewards in the owner's wallet at the time of observation. For the interpretation of the following regression, one thus has to be aware of this difference and that there is likely an omitted variable bias present, as HNT cash-outs affect the dependent variable (*rewards balance of an owner*). Still, there is no independent variable in my data set that could represent balance-reducing cash-outs.

Regardless of the timing, it seems plausible that a higher number of hotspots owned and a higher share of those online positively influence the rewards an owner receives and hence also has in their wallet. Having more hotspots and ensuring they are online means they have higher chances to participate in HNT-rewarded transactions, increasing their associated account balance. Further, those who joined the Helium network earlier had a more extended period to participate in these HNT-rewarded activities and could accumulate higher rewards over time, especially since there were more HNT emitted per time unit in the earlier days of the network (GitHub - @jmfayal et al., 2023). Burning HNT to DC reduces the HNT balance. The DC balance is then reduced through DC consumption by sending data through the Helium network. Like the HNT balance, the DC balance only reflects a snapshot when the data is retrieved. As DCs cannot be converted back to HNT and are not conventionally traded, it is justified to assume that account owners who do not want to use the Helium network for data transmission will not burn any HNT. Those who aim to transmit data carefully think about how many HNT to convert to DCs. Through this process, owners who burn HNT to DCs and use the DCs to pay transactions to reduce their rewards balance. Hence, I would expect the DC balance to negatively affect an owner's HNT balance. As Helium started in the United States of America and the network in the country is still among the densest ones, one could assume that hotspots there can earn higher rewards from all types of transactions. The following equation summarizes these thoughts:

Rewards balance =

$$b_0 + b_1 \times \textit{Hotspots owned} + b_2 \times \textit{Share of online hotspots} + b_3 \times \textit{DC balance} + b_4 \times \textit{Earliest time the owner added a hotspot} + b_5 \times \textit{Avg. time a hotspot was added} + b_6 \times \textit{Last time the owner added a hotspot} + b_7 \times \textit{Dummy US}$$

The dataset contains single-hotspot owners as well as multi-hotspot owners. I run two separate regressions, as the equation changes significantly for hotspot owners who only have one hotspot. In the case of single-hotspot owners, the variable *share of online hotspots* becomes dichotomous (one hotspot can either be online or not), and all three time-related values (*earliest time the owner added a hotspot, avg. time a hotspot was added, last time the owner added a hotspot*) will always be the same. To account for these differences, I decided to run separate regressions for the two hotspot owner groups.

The equation used for the single-hotspot owner regression is:

Rewards balance$_{\textit{single hotspot owner}}$ *=*

$$b_0 + b_1 \times \textit{DC balance} + b_2 \times \textit{Time the hotspot was added} + b_3 \times \textit{Dummy Online} + b_4 \times \textit{Dummy US}$$

Regression for single hotspot owners. The leverage-versus-squared-residual plot suggested the existence of single outliers, which would have distorted the outcome of a simple OLS regression. As Verardi and Croux (2009: 442) explain in detail, robust regression is a powerful approach to address isolated outliers. The robust regression identified and omitted one outlier in the dataset containing all single hotspot owners (n=284,572). Running an OLS regression on the reduced data set resulted in an improved R-squared (r^2=0.015 instead of r^2=0.004 with the outlier included). The results of this OLS regression, including the standardized coefficients, are shown in Table 16.

Table 16 OLS regression results with standardized coefficients for owners with one single hotspot (n=284,571)

Rewards balance of an owner	**Coef.**	**St.Err.**	**p>|z|**	**Std. Coef.**
DC balance of the owner (in 1,000,000)	-0.498	0.533	0.353	-0.002
Time the hotspot was added (in 100,000 blocks)	-1.407	0.023	0.000	-0.118
Dummy Online	1.346	0.087	0.000	0.029
Dummy US	0.521	0.088	0.000	0.011
Constant	18.005	0.287	0.009	.

Mean dependent var	1.620	SD dependent var	23.143
R-squared	0.015	Number of obs	284,571
F-test	1,047.799	Prob > F	0.000

In this regression for single hotspot owners, I observe that the *time the hotspot was added* has the most substantial impact on the dependent variable *rewards balance* (standardized coefficient -0.118). Assuming target block times are kept (i.e., 60 sec per block), installing a hotspot half a year later (equal to ~260,000 blocks) roughly leads to 3.66 HNT less in the owner's wallet. The results also show that both being online at the time of observation and located in the US have a highly significant, positive effect on the rewards balance of a single hotspot owner, even though they are not as strong as the impact of timing. Being online at the time of observation corresponds to a 1.35 HNT higher *rewards balance* while being in the US results corresponds to finding 0.52 HNT more in the owner's wallet. Note that the R-squared of this model is relatively low at 0.015, meaning the model introduced with the single-hotspot-owner equation only explains 1.5% of the variation in the rewards balance of a single-hotspot owner. A possible explanation for this could be omitted variables, like the previously discussed effect of cash-outs which are not available in my data set. And while the R-squared of 0.015 surely would be very small for prediction models, in the case of this empirical data set, where we are looking for explanations, it yields interesting insights.

Regression for multiple hotspot owners. Following the same approach as for the single hotspot owners, the results of the robust OLS, including standardized coefficients, Table 17 shows the results for multiple hotspot owners. Removing the four outliers improved the R-squared from r^2=0.109 (n=74,612) to r^2=0.147 (n=74,608) for the results shown in the table.

Table 17 OLS regression results with standardized coefficients for (semi-) professional owners (n=74,608)

Rewards balance of an owner	**Coef.**	**St.Err.**	**p>|z|**	**Std. Coef.**
Hotspots owned	54.051	.496	0.000	0.333
Share of online hotspots	113.187	30.926	0.000	0.010
DC balance of the owner (in 1,000,000)	-1.504	2.433	0.536	-0.002
The earliest time the owner added a hotspot (in 100,000 blocks)	-65.328	14.695	0.000	0.012
The average time when a hotspot was added (in 100,000 blocks)	-120.297	26.805	0.000	-0.131
The last time the owner added a hotspot (in 100,000 blocks)	138.508	14.033	0.000	-0.113
Dummy US	-5.37	23.569	0.82	0.008
Constant	109.237	76.241	0.152	.

Mean dependent var	179.296	SD dependent var	3176.681
R-squared	0.147	Number of obs	74,608
F-test	1,843.125	Prob > F	0.000

In the OLS regression for (semi-) professional hotspot owners with three or more hotspots, I find the number of *hotspots owned* to have the most decisive impact on the *rewards balance of an owner* (standardized coefficient of 0.333). Having one hotspot more increases an owner's rewards balance by 54.01 HNT. Again, here we also observe that timing matters: considering the average time when hotspot owners had installed their hotspots, a difference of half a year (~260,000 blocks) translates into a difference of 312.77 HNT. This means any multi-hotspot owner could have had more than 300 HNT in their wallet if they had just started around half a year earlier. For the timing of the first hotspot installed by an owner (*The earliest time the owner added a hotspot*), I can observe a similar effect but varied in its size: installing the first hotspot half a year earlier here corresponds to a 169.85 HNT higher rewards balance in the wallet at the time of observation. Surprisingly, the sign is inverted for the third timing-related explanatory variable, the *last time the owner added a hotspot*. Hence, the effect goes in a different direction: installing the last hotspot half a year later yields an additional 360.12 HNT. An explanations for this seemingly counterintuitive result could be that more recently installed hotspots could come with more advanced antennas, improving their network contribution and earnings. Installing hotspots recently could also indicate that the owner strongly believes in the Helium network and its future growth. Given the current HNT exchange rate, it is likely that this owner wouldn't cash out their HNT but rather bet on an exchange rate that improves in the future. Thus, this could also be the expression of a particular investment strategy. These speculations about possible explanations again point to the direct of possibly omitted variables bias in this regression, particularly regarding cashing out activities. The results show low standardized coefficients and non-significant coefficients for both being in the US (*Dummy US*) and the *DC balance of the owner*; we cannot find a clear and impactful relationship between these two variables with the *rewards balance of an owner*. This model can explain 14.7% of the variation in the *rewards balance of an owner*.

5.5 Discussion

5.5.1 The Helium blockchain: the "People's Network" with a bright future ahead?

In the previous sections, I explored the history and status quo of the Helium network, which I now bring together into one comprehensive view: I start with the development, then evaluate the promise of a "People's Network" and finally discuss perspectives on the future development of the network.

Over the past two years, Helium has become a more decentrally owned network with a presence in most countries. The share of decentrally owned hotspots (three or fewer hotspots per owner) has slightly increased since Jagtap et al.'s (2021) study, while the share of large (semi-) professional owners declined. Mainly since 2022, the small owners have heavily contributed to the network's growth. Causality cannot be asserted here, but it can be observed that this engagement peaked shortly after the HNT exchange rate peaked at the markets.

Helium has evolved from a US-centric IoT network in 2021 into an IoT network with global footage in 2023. Despite its presence worldwide, coverage is yet to be available everywhere. Even in countries where Helium has a strong presence, coverage is mainly ensured in industrial centers and densely populated areas, often also along main traffic routes, but less so in remote areas. People may perceive hotspot installations in their homes or workplace as easier. Those with a more professional approach to providing coverage optimize for returns and thus rent places in less crowded areas where they can still earn higher rewards or bet on future data traffic in certain areas. One example might be popular traffic routes where they expect high data traffic from logistics applications in the future. Before the Helium network can thus be considered a truly global IoT network competing, for example, against the NB-IoT piggybacking on LTE/5G, there is still some coverage to be provided.

More than 25% of the new owners own exactly one hotspot, so in this regard, one may be inclined to call Helium "The People's Network". The purchasing, installing, and registering of the physical device are easy enough to reliably attract new people to the network and get them involved. Based on the data underlying this study, I cannot distinguish specific sub-groups within these single hotspot contributors. Still, considering their development over time (recall Figure 26), it seems possible that these were initially more IoT enthusiasts and tech hobbyists. Later, when the HNT exchange rate peaked, cryptocurrency speculators got involved. Despite the strong presence of small hotspot owners, Helium's claim to be a "People's Network" has been questioned by recent media coverage (see Emerson et al., 2022). And it is at least partly questionable, indeed, as this study shows: while I found decentralized ownership of hotspots, even a slight tendency to further decentralization, the distribution of rewards tells a different story: both visual comparisons and the very high Gini coefficient showed that rewards are highly concentrated on few hotspot owners in the network. This concentration is critical because

Helium uses a “governance by incentive” architecture. And this architecture can be adjusted via HIPs which are approved or rejected based on a token-weighted voting scheme. Hence, the opinion of hotspot owners with high amounts of HNT has a higher weight when voting on HIPs with the power to change the incentives provided in the system. This could lead to system changes favoring only the tiny group of reward-rich owners. Here is a point where further research is needed to improve our understanding of these powerful accounts within the Helium network and how this plays out in the votes on HIPs. Thus, I would like to support Tsoukalas and Falk’s (2020) call for further research in this area, where theoretical considerations can be complemented with empirical data as this study does. Additionally, I would like to highlight again that the cash-outs of owners are not visible in the dataset used. Hence, there is a vagueness regarding the hotspot owners that may have had a high amount of HNT and sold them on the crypto market[96]. Understanding why they sold their HNT and, at this moment, also gave up some or most of their voting rights could reveal more about the owners’ motivations, their view on the future of the Helium network, and why they gave up their influence.

The interpretation of the empirical data from the past regarding the future of Helium results in three different scenarios: a plateau is reached, and further network growth, if at all, will be slow. The second possibility is that network growth is paused right now, waiting for conditions to improve and continue the strong growth. A third possibility is that Helium fails. I outline the empirical evidence I found for each possibility in the following.

The nearly perfect S-curve supports the first possibility. Less than half of all hotspots are online could be interpreted as a sign that being online currently is not worth the effort to fix software- or hardware-related issues or even connect the hotspot to power. The almost non-existent correlation of the HNT price with the number of new hotspot installations indicates

[96] Hotspot owners mining HNT and cashing out in the early days of the network claim to have made high returns and even recuperated their investment in less than a month. For example, the Youtube channel VoskCoin claims to have made US$1,300 within 30 days in April/May 2021 with one miner purchased for US$300 (https://www.youtube.com/watch?v=cofKps88NAA&ab_channel=VoskCoin; published on 06/14/2021; accessed on 06/06/2023). At that time, one HNT was valued at roughly US$22. With the declining HNT to US$ exchange rate since then and lower rewards for each miner, the possible earnings have shrunk. Mid-2022, software developer Asheq Reza already pointed out that US$1 to US$3 per day seemed a realistic range, hence resulting in US$30 to US$90 per month (https://www.quora.com/How-much-can-you-make-mining-Helium-HNT; accessed on 06/06/2023). Similar numbers are mentioned in other chats, discussions, and articles on Helium (e.g., https://medium.datadriveninvestor.com/is-it-too-late-to-earn-passive-income-with-helium-mining-a31c8da35371; published on 02/20/2022; accessed on 06/06/2023). In 2023, the HNT exchange rate reached its low so far. Returns of US$5 per month are realistic now. Considering that also re-sale prices of miners have dropped, one could expect around 700 days to recover the initial investment (Beachy, 2023).

that the dropping HNT exchange rate cannot be the only reason for the slower growth. Furthermore, the two groups I identified driving the network's growth in spring 2023 (recall section 5.4.3) are either new joiners or owners already owning many hotspots. As it is currently not financially promising to join the network, I suppose there must be other reasons to do so, for example, an own use case where coverage is needed[97]. In the case of the first group, they could either have received their hotspots very late, as supply chain issues persist, or purchased them at a lower price on the secondhand market so that amortization still seems realistic. Of course, they could also be interested in the technology or simply ill-informed. For the second group, a possible explanation is that these owners expect higher returns in the future, leading us to the second possibility to be considered as a way forward.

Helium seems to be at a decision point: the network's growth pauses, and future scenarios from growth to failure are possible. Reasons for this pause could be diverse, such as the unattractive HNT exchange rate or a "wait and see" attitude because of the uncertainty in the market around the novelties introduced (e.g., Solana blockchain infrastructure in spring 2023, first announced for autumn 2022; the introduction of IOT and MOBILE coins; withdrawal of prominent partners as public testimonials such as Salesforce and scooter company Lime) (Emerson et al., 2022; Hayward, 2022). If any of these reasons were to hold, one could expect the Helium network to grow strongly again once the environmental conditions changes. There is potential to grow further: far more hotspots are needed to provide reliable coverage despite Helium already having reached a broad geographic scope.

The third possibility could occur if the above-outlined uncertainties and doubts cannot be resolved and persist in the market. The current Helium system, including the distribution of rewards, is built upon the assumption of further growth. Without such further growth, the network's existence is at risk. And while the network side has seen strong growth so far, the demand side, i.e., the devices using the network for data transmission, is still weak (Joel, 2023). If Helium cannot solve these challenges, it will likely, at some point, collapse due to lacking

[97] A person looking for LoRaWAN coverage at home could set up a private LoRaWAN or join the TTN, which has no data transmission fee. However, installing a TTN hotspot might require more technical knowledge, whereas Helium hotspots claim to be easy to install, and users can control them via the Helium website and app. Also, users experimenting with an application they aim to convert into a product and business may prefer to test it in its future operational environment. TTN does not have any Service Level Agreements in place. Thus, for commercial solutions, some providers may prefer Helium or the business network of The Things Industries (the company supporting TTN as a side-project).

demand. If that failure of Helium was to happen, in-depth studies of the Helium network could still help researchers and practitioners to understand which features and decisions caused it to fail and see if there would be other feasible setups for the future.

Given the three possible scenarios, the situation of Helium at the time of data collection in April 2023 should be considered a decisive phase for the case itself, but also for the broader research on decentrally provisioned IoT networks.

5.5.2 Helium as IoT infrastructure – a research agenda for the future

Helium is a novel approach to IoT infrastructure. As such, its success or failure is of much higher importance than just for Helium network participants (Jagtap et al., 2021: 22). Thus, alongside the strengths and achievements of this study, I suggest a research agenda for this field.

This study focuses on the infrastructure side of an IoT network. The description of the Helium blockchain solution showed the importance of understanding token-weighted voting and the incentives put forward in this system governed by incentive. Token-weighted voting, at its core, aims to efficiently aggregate information from a wide variety of users with diverse backgrounds (Tsoukalas & Falk, 2020: 3843). The high concentration of rewards revealed in 5.4.4 must thus be considered alerting as it puts this mechanism at risk in the Helium network. Further empirical research should specifically target HIP voting processes and, if possible, include longitudinal data to address the cash-out effects some accounts may have faced. Future studies should evaluate if this concentration in rewards translates into extreme inequality in the voting weights and whether these are still proportional to the voters' contribution of information to the Helium network and blockchain. The call to include cash-outs into the data set is further strengthened by the potential omitted variable bias observed in the two OLS regressions conducted.

The decentralization found in hotspot ownership supports Chen et al.'s (2021: 1305) claim that "platforms of the infrastructure layer […] tend to become more decentralized". Following the authors' claims, one must raise the question of whether Helium became overly decentralized – understanding Helium as a two-sided platform, a network with externalities, and the demand side regarding data sent through the network is critical as it contributes to more available rewards. This demand side should urgently be addressed in future research, and the use of DCs for data transmission is a crucial indicator.

Suppose Helium also succeeds on the demand side of IoT network and connectivity. In that case, it can successfully disprove fundamental critique as (Joel, 2023) said: “Helium has not yet found a sustainable business model.” For the time being, Helium’s business model is still on trial.

5.6 Conclusion

This study used the context of the Helium network to conduct in-depth research on a blockchain-based and decentrally owned (at least according to its branding) IoT network, an approach to overcome the hen-and-egg problem of IoT networks. I focused on the supply or infrastructure side of the Helium network. First, I described the Helium network and blockchain mechanisms before conducting exploratory analyses with the network data extracted from the Helium blockchain in April 2023. This study extracted three key findings from the empirical data on the Helium network.

First, looking at the development of the Helium network, I could show that the hotspots are decentrally owned, that the network has nearly followed an S-shaped growth between 2019 and 2023, and that now in times of small growth, mostly single owners, and owners with 20 or more hotspots drive this development.

This slowed-down growth of the Helium network leads to the second key finding: right now, the network seems to be at a decision point, and many uncertainties – such as the exchange rate, the move of Helium from the proprietary blockchain infrastructure to Solana, and the question mark regarding the adoption on the demand, connectivity-consuming side – allow for a range of future options: further growth, remaining at the current level, or complete failure. I assessed these paths forward based on the insights gathered from the empirical data. There are arguments in favor of each of them. In any case, monitoring the Helium network’s future development can enable practitioners and researchers to learn more about the possibility and mechanisms of decentrally owned IoT infrastructure.

In contrast to the decentrally owned hotspots, the high concentration among reward owners was identified as an area for further investigation. Helium implements a token-based voting scheme, meaning that wealthy accounts have a more influence on shaping Helium’s reward mechanisms. As Helium is governed by incentives, shaping the reward mechanisms means shaping the network. Further research is thus needed here, at first to identify cash-outs in the data and verify the observation of high concentration from this study, and later, to investigate how this concentration translates into governance and expansion of the Helium network.

This exploratory research has identified several directions for future research. A crucial one, the rewards concentration in combination with the token-based voting scheme, has already been mentioned. Further, I presented important HIPs as the manifestation of this token-based voting scheme. They may be used for future analyses of the effects and outcomes of the token-based voting scheme. Abstracting from Helium's case, the question was whether IoT networks could be set up in a revolutionary way: decentralized ownership. I have contributed with an analysis showing that the infrastructure can indeed be decentrally owned. However, I have also demonstrated that Helium is now at a decision point where success and failure are still possible. To see if this novel decentralized approach to building IoT networks can succeed in the long term and why and how future research will need to accompany further and learn from this case.

This study elaborates on a novel approach to building IoT infrastructure; it is relevant for all practitioners concerned with the hen-and-egg problem of connectivity provisioning and adoption. The Helium network does pioneer work here; observing and learning from its development is imperative. Participants of the Helium network may also expand their understanding of the network through these analyses, which go beyond what current tools, such as the navigator, provide them with. For the Helium network itself, this study has made clear that uncertainties must be reduced, and the adoption side also needs to receive attention now to ensure the survival and future growth of the network.

I want to emphasize again that this study used data from April 2023, which contains only limited historical information, such as date of installation of the hotspot. It does not contain a full historical record of transactions, including potential cash-outs of high numbers of tokens. This research had to rely on the rewards balance in owners' wallets at the time of observation for the analyses without having a complete record of the cumulative HNT earnings and all cash-outs. To further understand cumulative earnings of rewards and who cashed out when a different data set would need to be constructed.

Future research may examine the reward-based voting scheme and reward concentration among Helium accounts to accompany its future development directions and enhance our understanding of them. It should complement this supply-side-focused work with another adoption-side-focused analysis of empirical data.

This study has illustrated several potential future scenarios for the Helium network and based this outlook on an in-depth analysis of empirical data. So far, it is the first study using data from what appears to be a relatively mature Helium network. Its findings are insightful to the Helium ecosystem and relevant to the broader question of how IoT infrastructures will be set up in the future. Here, it delivers insights and further research directions for a decentralized ownership approach that could revolutionize how we think about provisioning IoT connectivity.

6. Summary and outlook

6.1 Findings and contribution

This dissertation explored the adoption of LPWAN technologies, a key technology of the ICT backbone enabling the IoT. LPWAN constitute a context to explore the importance of the governance-related features for IoT technology adoption and to investigate decentralized approaches to IoT network provisioning, which could be a novel approach to the hen-and-egg problem inherent to networks. Below, I briefly summarize the key findings and contributions from my meta-study on previous LPWAN research and the three empirical studies conducted in Chapters 3, 4, and 5.

In Chapter 2, I provided an extensive summary of previous research on LPWAN and conducted a meta-study of LPWAN technologies and their comparisons. Therein, I identified the need for more research on the importance of governance-related features in technology adoption decisions, primarily focusing on technology-related features.

In Chapter 3, I followed an empirical exploratory approach to identify LPWAN technology decision criteria relevant to practitioners, be it end users or other stakeholders. The findings rest on the thematic analysis of 29 semi-structured interviews of a total length of almost 25 hours. In this study, I first presented a compilation of the relevant adoption criteria per stakeholder group and then synthesized these findings into the TOE framework adapted for the LPWAN segment. Additionally, I developed a guiding framework mapping IoT use cases to LPWAN technologies based on insights from the interviews. This empirical study unveiled that a broad set of adoption criteria is important in LPWAN adoption, and it identified self-provisioning of connectivity as a vital one. Evidence from the interviews suggest that self-provisioning of networks could be interpreted as a democratization of coverage. This might be relevant not only for LPWAN, but for IoT adoption as a whole.

In Chapter 4, the smart city study explored the context, process, decision criteria, and observable outcomes of smart city implementation, combining qualitative interviews and a survey of 107 German cities in an exploratory mixed-methods design. This second empirical study examined the role of governance-related decision criteria in selecting LPWAN technologies for smart city implementation. The study found that improving a city's reputation among its citizens is a crucial benefit of smart city initiatives, and the possibility of self-provisioning of connectivity is one of the most critical technology selection criteria. As LoRaWAN is the only LPWAN technology allowing for that, it is also the most frequently implemented LPWAN technology among cities. The study also observed technology selection processes, with the coexistence of open and closed networks likely to emerge in the future. Citizens play a crucial role in smart city development as users, innovators, principals, and the target audience for cities' efforts.

In Chapter 5, I studied the blockchain-based, decentralized network Helium as a novel and significantly different approach to building IoT networks and overcoming the hen-and-egg problem. As part of this study, I first introduced the terms and mechanisms of the Helium network and blockchain. Next, I analyzed empirical data from April 2023, where Helium had reached a decision point in its development, a plateau with prolonged growth and an unclear way forward. The novel data and the development of a perspective on the future development of the Helium network fundamentally distinguishes my work from earlier Helium studies, like the one of Jagtap et al. (2021). I find that contrary to Helium 's decentralized ownershipand globally distributed network, votes in the token-based voting scheme are highly concentrated. I could identify different network contributor types, which differ in the number of hotspots owned, level of active engagement, and the time they joined the network. Based on these empirical findings, I evaluated the Helium network's promise and future perspectives. Moreover, the study points towards areas for further investigation, such as the high reward concentration among certain owners. The study highlights the importance of monitoring the future development of the Helium network. One cannot yet draw a final conclusion on the viability of this revolutionary approach to building IoT infrastructure, which is why further attention to the Helium case and research on its broader applicability remains imperative for future research.

Across all three studies, I could identify governance-related features as highly relevant criteria for adopting LPWAN technologies. The empirical data in Chapters 3 and 4 shows the many facets of these governance-related features. They include intellectual property rights ownership, supply chain concentration, alliances and standardizing organizations, and the self-provisioning feature, as the mixed-method study on smart cities powerfully illustrated. The ongoing coexistence of LoRaWAN, NB-IoT, and Sigfox in the LPWAN segment, with their respective distrinct manifestations of these features, could provide a fertile context for future research on the IoT network supply side. Looking at the demand side, the IoT applications, it became clear that understanding IoT network technology adoption is crucial to many stakeholders and ultimately determines market success. In Chapter 5, it became apparent that the network provisioning highly depends on the technology's acceptance by the demand side. Lacking data traffic is a primary challenge for the Helium network. Also, the smart city study (Chapter 4) revealed that many cities do not yet have promising use cases generating data traffic on the network but are rather in an experimental stage. They are not yet realizing the manifold benefits of smart cities as, for example, illustrated by Mohanty et al. (2016). Thus, understanding and shaping IoT adoption will remain an essential aspect of IoT research.

6.2 Practical implications

The research on LPWAN networks in this dissertation also has implications for practitioners in the growing IoT industry. The implications of this dissertation for different stakeholders along the value chain are outlined below.

For network operators as representatives of the network provisioning side, it is crucial to understand that within the LPWAN segment, competition dynamics are different from classic telecommunications competition in licensed bands. In addition to NB-IoT in the licensed bands, they also compete with Sigfox and LoRaWAN in the unlicensed bands, so that totally different business models compete against each other (Marini et al., 2022). Network operators need to take a conscious decision if they want to compete within their known environment consisting of 3GPP standardized technologies in the licensed spectrum (e.g., Telekom and Vodafone in Germany follow this path) or whether they wish to broaden their traditional offer with LoRaWAN networks (e.g., KPN in the Netherlands and Swisscom in Switzerland took this direction). Furthermore, they should closely monitor the future development of Sigfox and evaluate a possible addition of that technology to their portfolio, since Sigfox's new owner UnaBiz has vaguely announced to "strive towards the convergence of LPWAN" (Kasujee & Mackenzie, 2022: 1) – a fundamental shift to previous Sigfox technology strategy.

Other partners along the value chain who also contribute to the supply side – such as equipment manufacturers, integrators, and software providers – also face a complex yet more traditional strategic situation: depending on the strength of their lock-in for a specific LPWAN technology, they may want to select this technology very carefully. For example, a sensor manufacturer who optimized her sensor for LoRaWAN features, will have high investments and needs time to re-configure that sensor for use in NB-IoT networks. Thus, those with high lock-in should very carefully select the LPWAN technology they are committing to. A careful definition of their target users and applications in combination with the framework suggested in Chapter 2 may provide guidance here. Understanding their users' needs is a prerequisite to addressing them successfully. This dissertation has clearly shown that governance-related requirements constitute one important facet of users' needs which should therefore be taken into consideration.

For IoT-implementing individuals and institutions, understanding their own needs is also the basis of a successful implementation. In addition to technical requirements, this dissertation has shown the importance of being clear about governance-related requirements. Throughout this dissertation several of these criteria were discussed: standardizing organization, IPR ownership, alliances, and partnerships – to name a few. Exchange with other adopters in their specific adoption segment, as Chapter 4 has illustrated for smart cities, can facilitate adoption decisions. Especially for smart cities, there is a massive potential for more exchange on technology adoption, possible infrastructure setups, and use cases that are being implemented. The high interest the study has provoked among practitioners underlines this observation (see media coverage of the study in Appendix F).

6.3 Limitations and future research

As I outlined in each of the studies, there are limitations to the research conducted in this dissertation. I commented limitations of the individual empirical studies in the respective chapters. This section focuses on three key limitations affecting all empirical studies and presents associated key areas for future research.

First, the methodological approach taken in the Chapters 3 and 4 allowed us to explore LPWAN technology adoption from different viewpoints and develop a comprehensive framework. Complementing it with a survey as part of the mixed-methods approach in Chapter 4 allowed us to further support the discoveries quantitatively. Nevertheless, both studies rely on self-reported experiences or city representatives' self-reported numbers. Thus, I suggest employing further quantitative research in this direction: increase the number of observations, with that enhance the statistical possibilities, and enable causal statistical analyses on the relationship between governance-related criteria and technology adoption.

Second, all three studies are confined in their data collection to 2021 and 2023, which is only a snapshot of the fast-paced IoT market. Similarly, Chapters 3 and 4 rest on EU-centric data and Chapter 5 analyzes a global blockchain, which emerged from the United States of America. Thus, the research presented in this dissertation must be considered to rest on western-hemisphere data. A simple transfer of the insights to any significantly different cultural context may not be able to describe reality, as Hofstede explains in his seminal book “Culture’s Consequences” (1980). Hence, I propose conducting studies similar to those in this dissertation in another context: for example, in the strictly regulated LPWAN segment in China with NB-IoT as a governmentally funded and favored outcome (Huang, 2018). Also, expanding the data collection span for the Helium network could yield valuable insights into the success or failure of a decentralized approach to building IoT infrastructure.

Lastly, this dissertation was explicitly dedicated to the three currently dominating LPWAN technologies. This implies that business models and governance-related features of many other less prominent technologies in this ICT segment were not assessed. It became apparent that business models of technologies using the licensed or unlicensed spectrum differ and that this distinction also affects competition and strategic choices by market participants, as discussed in Section 6.2. The sale of Sigfox to UnaBiz and the announcement of adjusting its business model and further pushing global connectivity without roaming is another exciting development in the field (Blackman, 2023; Kasujee & Mackenzie, 2022). For the future growth of IoT, it is vital to understand these competitive dynamics and resulting strategic options for all stakeholders. This dissertation is one contribution to it, but there are many questions beyond governance-related features to be addressed and many other ICT segments and technologies to be covered.

Appendix A: Glossary

Bandwidth is expressed in the unit Hertz (Hz) and describes the number of radio ***frequencies*** (usually a range) occupied by the signal. A higher bandwidth means that a broader range of frequencies is occupied by the signal. Higher bandwidth goes hand in hand with shorter transmission time, on the other hand a lower bandwidth is associated with a more robust signal (https://www.thethingsnetwork.org/docs/lorawan/glossary/, last accessed 05/05/2023).

Base station is a message-receiving and sending unit in a network which forwards the data packages via an internet backlink between the ***end device*** and the network server. Its functionality is comparable to a router used at home for the connection to the world wide web. Base stations physically constitute the network, they ensure that ***coverage*** can be provided to end devices.
The term base station is mostly used in the NB-IoT context, Sigfox and LoRaWAN most commonly use ***gateway*** (Almuhaya et al., 2022: 175).

BPSK is the ***modulation*** technique used by Sigfox (Hossain & Markendahl, 2021: 889–890).

CCS is the ***modulation*** technique used by LoRaWAN.

Coverage refers to the geographic area from which signals sent by ***end devices*** can be detected by ***gateways/ base stations*** of the respective communication technology. High coverage within a country by a communication technology thus means, that in most parts of the country connectivity to the network can be established.

Downlink message is a message sent by the network server to an ***end device***. The opposite is called an ***uplink message*** (https://www.thethingsnetwork.org/docs/lorawan/glossary/, last accessed 05/05/2023).

Duty cycle refers to the defined on-airtime for an end device in a specific spectrum. In the unlicensed LPWAN spectrum, regulators define this duty cycle in Europe as 1%, i.e., 36 seconds/ 1 hour (Marini et al., 2022).

End device denotes a sensor or – less commonly – an actuator which is connected to a wireless LPWAN. It is the end point that collects data and transfers it to the system via ***uplink messages*** or it receives ***downlink messages*** by a ***hotspot/base station*** (Almuhaya et al., 2022: 175).

Frequency describes how often a radio wave oscillates (measured in the unit Hertz), ranging from 30 Hz to 300 GHz for radio frequencies. The use of single frequencies or groups of neighboring frequencies (called frequency bands) is strongly regulated by national authorities to avoid interferences between different users and applications. For licensed bands the access is restricted and licensees pay fees for their use. Unlicensed bands can be used by anyone respecting basic rules (e.g., air time vs. down time is often defined) without being charged for using the spectrum. A potential downside, however, may be that the spectrum is overpopulated and not all messages get through (https://www.thethingsnetwork.org/docs/lorawan/glossary/, last accessed 05/05/2023).

Gateway is a term mostly used in LoRaWAN and Sigfox contexts to denote ***base stations***.

Handover is the process when one base station hands over the responsibility for a device to another base station. This takes place in networks, where end devices are assigned to a single ***base station***/ ***gateway*** (like NB-IoT), but not where end devices send their signal to all base stations nearby (like LoRaWAN and Sigfox) (Mekki et al., 2019).

Interference Interference can occur in unlicensed bands of the spectrum and lead to damages in the data packages or even complete loss of the data package and decreasing coverage (Mekki et al., 2018).

Latency is the delay between the occurrence of an event and the time, when an observer notes it. In telecommunications this denotes the time interval between creation of sensor data (e.g., temperature measured) in the ***end device*** and the time it reaches the backend servers. In LPWAN latency is high and can be several minutes or even hours. 5G, on the contrary, has a very small latency and this feature allows to use it for real-time applications such as autonomous driving (Juneja, Juneja, Bali, & Mahajan, 2021: 6).

LoRa is a ***modulation*** technique to encode information transmitted through radio ***frequencies*** and it is based on the ***CCS*** technology (https://www.thethings network. org/ docs/lorawan/glossary/, last accessed 05/05/2023).

LTE Long term evolution

Modulation is the change of signal parameters such as bandwidth to make adjustments in the transmission characteristics. In the context of LPWAN different modulation techniques are used: ***CCS***, ***BPSK***, and ***QPSK***. They take place in the physical layer (PHY) (https://www.itwissen.info/lex-images/Uebersicht-ueber-die-verschiedenen-Modulationsverfahren_en.png, last accessed 05/03/2023).

MAC layer	is the second lowest level of the OSI (Open System Interconnection) reference model and as such it is concerned with network protocols and access management (Day & Zimmermann, 1983).
Network server	is the core component of a LPWAN backend, where the data collected via the base stations/gateways is sent to. From there it is further distributed to the respective application server for further processing (Almuhaya et al., 2022: 175).
QPSK	is the ***modulation*** technique used by NB-Io T in the downlink (Almuhaya et al., 2022).
Topology	Describes the network structure of a communication network. LPWAN have a star topology, meaning ***end devices*** cannot communicate directly with one another, but always go via a ***gateway/base station***. ***Gateways/base stations*** can process multiple signals from different end devices at the same time. There are other communication networks which allow direct communication between end devices, this is then called a mesh topology (Juneja et al., 2021: 6).
TTN	is an open and community based LoRaWAN for the IoT. Anyone can connect his or her LoRaWAN end device to the network, and also anyone can expand the network's coverage by privately purchasing a gateway, connecting it to the internet and registering it in the TTN. As of April 2023, 21,200 gateways were part of the network in 153 countries. It is also the organizing unit of the world's largest LoRaWAN conference "The Things conference". The TTN backend is hosted on servers by the Dutch company ***TTI***. (https://www.thethingsnetwork.org/, last accessed 05/16/2023)
TTI	is a company strongly involved in LoRaWAN community: some of their employees were the founder of the ***TTN*** and they still strongly support the community based LoRaWAN by hosting its servers and sharing open-source code. Their offering includes offers with service level agreements, LoRaWAN consulting services and customized support for firms across the globe. The company is located in the Netherlands in Amsterdam. (https://www.thethingsindustries.com/, last accessed 05/16/2023)
Uplink message	contains information sent from an ***end device*** to the network server, its counterpart is the ***downlink message*** (https://www.thethingsnetwork.org/docs/lorawan/glossary/, last accessed 05/05/2023).

Appendix B: LPWAN characteristics literature overview

The analysis includes data from 13 publications in scholarly outlets published between 2017 and 2023 as well as two reports published by industry players in 201s8 and 2019. Authors within each group are listed alphabetically with numbers 1 to 13 referring to the academic publications. Appendix Table B – 1 provides an overview of the literature included in the analysis.

Appendix Table B – 1 Literature included in the analysis of LPWAN characteristics

	Authors	Year	Academic journal/conference	Technologies
[1]	Almuhanya et al.	2022	Electronics	Ingenu, LoRaWAN, NB-IoT, Sigfox, Telensa
[2]	Ayoub et al.	2019	IEEE Communications Survey & Tutorials	LoRaWAN, NB-IoT, DASH7
[3]	Durand et al.	2019	IET Communication	LoRaWAN, NB-IoT, Sigfox, GPRS
[4]	Hossain, Markendahl	2021	Wireless Personal Communication	LoRaWAN, LTE-M, NB-IoT, Sigfox
[5]	Iqbal et al.	2020	IEEE Region 10 Symposium (TENSYMP)	LoRaWAN, NB-IoT, Sigfox
[6]	Klaina et al.	2022	Measurement	LoRaWAN, NB-IoT, Sigfox
[7]	Lalle et al.	2019	Global Information Infrastructure and Networking Symposium (GIIS) 2019	LoRaWAN, NB-IoT, Sigfox
[8]	Mekki et al.	2018	PerIoT'18 Second International Workshop on Mobile and Pervasive Internet of Things, Athens	LoRaWAN, NB-IoT, Sigfox
[9]	Mekki et al.	2019	ICT Express	LoRaWAN, NB-IoT, Sigfox
[10]	Mumtaz et al.	2017	IEEE Industrial Electronics Magazine	EC-GSM, Ingenu, LoRaWAN, NB-IoT, Sigfox
[11]	Raj et al.	2023	International Journal of Intelligent Systems and Applications in Engineering	LoRaWAN, NB-IoT, Sigfox
[12]	Raza et al.	2017	IEEE Communications Survey & Tutorials	Ingenu, LoRaWAN, Sigfox, Telensa
[13]	Sinha et al.	2017	ICT Express	LoRaWAN, NB-IoT
[14]	Northstream	2018	Report (grey literature)	LoRaWAN, NB-IoT, LTE-M
[15]	vodafone business	2019	Report (grey literature)	NB-IoT; LTE-M

In the following Appendix Table B – 2, I summarize the characteristics of each technology in detail as provided by the different authors. If different values were mentioned for a characteristic, I include minimum and maximum values and the respective sources, while sources indicating values in between are not explicitly mentioned.

Appendix Table B – 2 LPWAN comparison of LoRaWAN, NB-IoT, and Sigfox based on literature

	Characteristic	LoRaWAN	NB-IoT	Sigfox
Coverage	Coverage-urban (max.)	**2** [2, 3] **to 5 km** [1, 2, 3, 5, 6, 7, 8, 9, 11, 12, 13]	**1** [1, 6, 7, 8, 9, 11] **to 15 km** [5]	**3** [1, 5, 7] **to 10 km** [1, 5, 6, 7, 8, 9, 11, 12]
	Coverage-rural (max.)	**15** [2, 13] **to 20 km** [1, 3, 5, 6, 7, 8, 9, 11, 12]	**10** [6, 7, 8, 9, 11] **to 40 km** [1, 13]	**15** [12] **to 40 km** [1, 5, 6, 7, 8, 9, 11]
Signal	Spectrum	**Unlicensed** [2, 3, 8, 9, 10, 11, 13, 14, 15]	**Licensed** [3, 6, 7, 9, 10, 11]	**Unlicensed** [3, 8, 9, 10, 11, 14, 15]
	Frequency	**868 MHz in Europe, 915 MHz in North America, 433 MHz in Asia** [3, 4, 7, 8, 9, 11]	**In LTE bands** [6, 8, 13, 15]	**868 MHz in Europe, 915 MHz in North America, 433 MHz in Asia** [4, 7, 8, 9]
	Latency	**1 ms** [12] **to 10 s** [2], **low latency** [7]	**1.6 s** [14] **to 10 s** [14], **low latency** [9, 14]	**High latency** [7]
	Modulation	**CSS** [1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13]	**QPSK** [1, 2, 3, 5, 6, 8, 9, 11, 13]	**BPSK** [1, 3, 4, 6, 8, 9, 11, 12] **UNB** [1, 3, 6, 7, 12]
Data transmission	Bi-directional	**Yes/Half-duplex** [4, 5, 8, 9]	**Yes** [14] **/ Half-duplex** [4, 5, 8, 9, 14]	**Limited** [14] / **Half-duplex** [4, 5, 8, 9]
	Upload capacity	**50 bps** [2, 4, 11] **to 300 bps** [2, 8, 11]	**125 bps** [2, 4], **500 bps** [3, 11, 15] **to 200,000 bps** [3, 14, 15]	**< 1 bps** [11, 15] **8 bps** [1, 4, 8]
	Download capacity	**50 bps** [4, 11, 14] **to 300 bps** [8, 11]	**125 bps** [4], **300 bps** [3, 11, 15] **to 180,000 bps** [3, 15]	**< 1 bps** [11, 15] **12 bps** [1, 4, 8]
Energy	Battery life in years	**10 or more** [6, 7, 11, 13, 14, 15]	**10 or more** [5, 6, 7, 9, 11, 12, 13, 14, 15]	**10 or more** [6, 7, 11, 14, 15]
Network	Localization	**Yes (TDOA)** [1, 8, 9]	**No** [1, 8, 9]	**No** [14] **Yes (RSSI)** [1, 8, 9]
	Handover	**End-devices do not join a single base station** [8]	**End-devices join a single base station** [8]	**End-devices do not join a single base station** [8]
Financial	Cost per gateway or base station	**$100** [2, 9, 13] **to $1,000** [2, 4, 9, 13]	**$3,000** [4] **to $15,000** [2, 9, 13]	**$4,000** [4, 9]

	Cost per device	**$3** [9] **to $6** [9, 11]	**<$6** [15] **or >20€** [9] **or $12** [11]	**< $3** [9, 11]
Governance	Standardization organization	**LoRa Alliance** [1, 2, 5, 8, 9]	**3GPP** [1, 2, 5, 8, 9, 10, 13]	**Sigfox is collaborating with ETSI** [1, 8, 9]
	Private network allowed	**Yes** [1, 8]	**No** [1, 8]	**No** [1, 8]

Appendix C: Contribution to Chapter 4

Contribution to the working paper
"Technology governance as a selection criterion – the case of smart cities"
(Chapter 4 of the dissertation)

This chapter reflects joint work with my supervisor Joachim Henkel (Technical University of Munich). As the study's first author, I initiated the research project, and led the data collection and analysis for both qualitative and quantitative data. The complete paper was drafted by me, with suggestions from my co-author regarding further analyses and theoretical framework. The working paper was revised iteratively in a collaborative process.

Appendix D: German survey questionnaire and English translation

Seite 1 (Startseite)

[Informationstext]
Herzlich Willkommen zur Smart City Umfrage

Danke für Ihre Teilnahme. Sie ermöglichen es uns, ein faktenbasiertes, umfassendes Bild von Smart Cities in Deutschland zu erstellen. Im Zentrum der Umfrage stehen Kommunikationstechnologien, die
Zielsetzung Ihres Smart City-Engagements und konkrete Anwendungsfälle in Ihrer Stadt.

Zum Datenschutz gelten die folgenden Hinweise:

- Die gesammelten Daten werden vertraulich behandelt und nur anonym, in aggregierter Form, ausgewertet. Aus den veröffentlichten Ergebnissen sind keine Rückschlüsse auf einzelne Städte möglich.
- Die Postleitzahl Ihrer Stadt erheben wir lediglich, um für die Analyse demografische und wirtschaftliche Daten (bspw. Einwohnerzahl, Arbeitslosenquote) ergänzen zu können.
- Die Veröffentlichung der Umfrageergebnisse erfolgt unter Berücksichtigung der Datenschutz-Grundverordnung (DSGVO, Link: https://dsgvo-gesetz.de/).
- Die Teilnahme dauert 10 bis 15 Minuten.

Als Dank für Ihre Teilnahme senden wir Ihnen nach Abschluss der Umfrageanalyse gerne eine auf Ihre Stadt zugeschnittene Auswertung zu. Diese nimmt eine Einordnung Ihrer Stadt im Vergleich zu den anderen teilnehmenden Städten vor. Sie können diese gerne für Ihre Zwecke verwenden. Zum Erhalt dieser Auswertung geben Sie bitte am Ende der Umfrage Ihre Emailadresse an.

Für Rückfragen steht Ihnen Lucia Baur gerne per Email zur Verfügung: lucia.baur@tum.de.

Herzlichen Dank für Ihre Teilnahme!

Prof. Dr. Joachim Henkel - Technische Universität München - Lehrstuhl für Technologie- und Innovationsmanagement
Lucia Baur - Technische Universität München - Doktorandin am Lehrstuhl für Technologie- und Innovationsmanagement

Technische Hinweise:

- Unterbrechung: Sie können die Umfrage unterbrechen und mittels Ihres Teilnahmecodes später wieder zurückkehren.
- Kommentare: Ihre ergänzenden Kommentare können Sie uns sehr gern am Ende der Umfrage mitteilen.

[Auswahl einzelner Option, zwingend notwendig; wenn zweite Option gewählt → Seite 15 und Beenden der Umfrage]

Möchten Sie die Umfrage jetzt starten?

- Ja, ich möchte die Umfrage jetzt starten und stimme den obigen Hinweisen zum Datenschutz zu.
- Ich stimme den Hinweisen zum Datenschutz nicht zu und möchte nicht teilnehmen.

Seite 2: Rahmendaten zu Smart City in Ihrer Stadt

[Informationstext]

Smart City verstehen wir im Rahmen dieser Umfrage wie folgt:
Smart City verstehen wir im Rahmen dieser Umfrage als Digitalisierungskonzept für Städte. Es umfasst insbesondere die Verfügbarmachung drahtloser Kommunikationsnetzwerke für verschiedene Anwendungsfälle und Nutzergruppen.

In welchem Jahr haben Sie erstmals Smart City als ein Thema in Ihrer Stadt wahrgenommen?
Wenn Sie sich an kein genaues Datum erinnern können, schätzen Sie bitte.
[Einfache Auswahl in einem Dropdown] Noch gar nicht/ 2000/ 2001/ 2002/ 2003/ 2004/ 2005/ 2006/ 2007/ 2008/ 2009/ 2010/ 2011/ 2012/ 2013/ 2014/ 2015/ 2016/ 2017/ 2018/ 2019/ 2020/ 2021/ weiß nicht

Auf welche Stadt beziehen Sie Ihre Angaben in dieser Umfrage?
Nennen Sie eine beliebige Postleitzeit im Stadtgebiet.
Postleitzahl: [Freitext; Einschränkung: nur fünfstellige Nummern werden akzeptiert]

[Auswahl, Mehrfachauswahl möglich]

Erhält oder erhielt Ihre Stadt Fördermittel für Smart City und wenn ja, welche?
Mehrfachauswahl möglich.

- keine Förderung
- Förderung aus EU-Mitteln
- BMI (jetzt BMWSB) Programm „Modellprojekte Smart Cities“
- anderweitige (außer BMI bzw. jetzt BMWSB) Förderung aus Bundesmitteln
- Förderung aus Landesmitteln
- Förderung aus privaten Mitteln, z.B. durch Unternehmen oder Stiftungen (ggf. auch in Form von Sachspenden)
- Förderung aus anderen Mitteln, nämlich: (Freitext)
- Weiß nicht

Seite 3: Verständnis von Smart City in Ihrer Stadt

[Informationstext]

Im Folgenden möchten wir gerne genauer verstehen, wie Smart City in Ihrer Stadt derzeit gelebt wird.

[Auswahl, Mehrfachauswahl möglich]

Wen sehen Sie in Ihrer Stadt als die treibende Kraft für Smart City?
Mehrfachauswahl möglich.

- Städtische Verwaltung, z.B. Chief Digital Officer (CDO), Digitalisierungsbeauftragte*r, IT-Verantwortliche*r
- Städtische Versorgungsunternehmen, z.B. Stadtwerke, Stadtnetze
- Bürgerinitiativen, Vereine und andere bürgerschaftliche Engagements
- Demokratisch gewählte Bürgervertretungen, z.B. Stadtrat
- Lokale Unternehmen
- Lokale Niederlassungen/Standorte internationaler
- Lokal ansässige Bildungseinrichtungen, z.B. Berufsschule, Hochschule
- Andere: [Freitext]
- Niemanden

[Auswahl, Mehrfachauswahl möglich]
Mit welchen lokalen IT-affinen Initiativen sind Sie im Austausch?
Mehrfachauswahl möglich.

- Lokale Sektion des Chaos Computer Clubs
- Lokale TTN (The Things Network) Community
- Lokale Code for Germany Gruppe
- Andere: [Freitext]
- Bisher mit keiner derartigen Gruppierung

[Auswahl, als Skala angezeigt – je Aussage nur eine Antwort erlaubt]
Wie schätzen Sie Ihre Stadt bezüglich Smart City Stand heute ein?
Meine Stadt ist bei Smart City im Vergleich zu anderen deutschen Städten…
[Antworten] überhaupt nicht fortschrittlich/ wenig fortschrittlich/ durchschnittlich/ eher fortschrittlich/ sehr fortschrittlich/ weiß nicht
Smart City erfährt in meiner Stadt ein angemessenes Maß an Aufmerksamkeit.
[Antworten] überhaupt nicht fortschrittlich/ wenig fortschrittlich/ durchschnittlich/ eher fortschrittlich/ sehr fortschrittlich/ weiß nicht

Seite 4: Technologien für die Smart City und Technologieauswahl

[Informationstext]
Im Folgenden befragen wir Sie zur Nutzung verschiedener Konnektivitätstechnologien für Smart City in Ihrer Stadt.

[Auswahl]
In unserer Stadt setzen wir Mobilfunktechnologien, z.B. LTE und 5G, für Smart City ein.
Ja./ Nein./ Weiß nicht.

[Auswahl]
In unserer Stadt setzen wir Wide-Local-Area Netzwerke (WLAN), z.B. WiFi, für Smart City ein.
Ja./ Nein./ Weiß nicht.

[Auswahl; Filterfrage für die Detailseiten zu LPWAN Technologien, d.h. S. 5 & 6 werden nur gezeigt, wenn hier „Ja“ ausgewählt wurde]

In unserer Stadt setzen wir Low Power Wide Area (LPWA) Konnektivitätstechnologien, z.B. LoRaWAN, Sigfox, Narrowband-Internet-of-Things (NB-IoT) oder LTE-M, für Smart City ein.

Ja./ Nein./ Weiß nicht.

[Freitextfeld, optional]

Welche weiteren Konnektivitätstechnologien (z.B. wireless Ambus und Glasfasernetz) setzen Sie derzeit in Ihrer Stadt für Smart City ein?

Sofern zutreffend, nennen Sie gern weitere Netzwerke. [Freitext]

[Likert-Skala für jedes Statement]

Inwiefern treffen die folgenden Aussagen auf Ihre Stadt zu?
In unserer Stadt...

- erfolgt die Technologieauswahl bedarfsgesteuert, d.h. für jeden Anwendungsfall suchen wir die dafür passende Technologie aus.
- haben wir einen standardisierten Auswahlprozess für Smart City Netzwerktechnologien, z.B. mittels einer Technologielandkarte.
- haben wir bei der Stadt und ihren Tochtergesellschaften die Kompetenz, Netzwerke selbst aufzubauen und zu betreiben.
- erhalten wir regelmäßig von anderen Städten Anfragen, unsere Erfahrungen mit ihnen zu teilen.
- steht in den Smart City Projekten derzeit die Erprobung der Machbarkeit im Vordergrund.

[Likert-Skala Elemente] Trifft überhaupt nicht zu/ trifft eher nicht zu/ teils-teils/ triff eher zu/ trifft vollständig zu/ kann ich nicht beurteilen

Seite 5: Low Power Wide Area (LPWA)-Netzwerke für die Smart City

[Auswahl]

Welche Reihenfolge beschreibt am treffendsten die zeitliche Abfolge der Technologie-entscheidung in Ihrer Stadt?

- Wir hatten einen konkreten Anwendungsfall in unserer Stadt und haben dann die dafür passende Technologie gesucht. Diese LPWA-Konnektivitätstechnologie haben wir dann auch für andere Anwendungen eingesetzt.
- Wir haben unsere LPWA-Konnektivitätstechnologie als zukunftsrelevant identifiziert und eingeführt. Danach haben wir dann passende Anwendungsfälle gesucht.
- Andere, nämlich: [Freitext]

[Dieselbe Skala für den Implementierungsprozess wird für jede Technologie abgefragt; diese Frage fungiert als Filterfrage für die Detailseiten zu jeder Technologie, d.h. nur wenn „geplant“ oder weiter fortgeschritten hier ausgewählt wird, dann werden die jeweiligen Detailseiten angezeigt (S.6-10)]

In welchem Umfang planen Sie die genannten LPWA-Konnektivitätstechnologien für Smart City in Ihrer Stadteinzusetzen bzw. in welchem Umfang setzen Sie sie bereits ein?

Bitte vervollständigen Sie den Satz.

In unserer Stadt ist der Einsatz von...

- LoRaWAN
- Sigfox
- NB-IoT
- Weitere(optional): [Freitext]
- Weitere(optional): [Freitext]

[Implementierungsprozess-Skala Elemente] Kein Thema/ in Diskussion/ geplant/ in Umsetzung/ seit max. 6 Monaten umgesetzt/ seit über 6 Monaten umgesetzt/ eingestellt worden/ weiß nicht

[Auswahl]
Wie viele LPWA-Netzwerke sind in Ihrer Stadt nach Ihrem Kenntnisstand heute parallel vorhanden?
Wenn Sie z.B. ein geschlossenes LoRaWAN für die Stadtwerke betreiben, ein an das The-Things-Networkangeschlossenes Netzwerk sowie noch eine Sigfoxabdeckung haben, dann wären dies drei Netzwerke.

- 1
- 2
- 3
- Andere, nämlich: [Freitext]
- Weiß nicht

Seite 6: Low Power Wide Area (LPWA) Netzwerke für die Smart City

[Einschätzung jeder Aussage mit einem Gewicht]
Wie wichtig waren Ihnen die genannten Kriterien bei der Auswahl der LPWA-Konnektivitätstechnologie?

- Unabhängigkeit von Dritten, d.h. eigener Aufbau des Netzwerks möglich
- Umsetzung durch lokale IT-Unternehmen oder Netzwerkanbieter
- Hohe Netzwerkverfügbarkeit und entsprechende Services, z.B. 24/7 Hotline für Fehlermeldungen
- Niedriger Energieverbrauch der batteriebetriebenen Endgeräte
- Hohe IT-Sicherheit, z.B. Serverstandorte, Verschlüsselung der Daten
- Zugänglichkeit für Bürger*innen
- Zugänglichkeit für lokale Unternehmen
- Hohe Verfügbarkeit von Endgeräten/Sensoren und Gateways/Base Stations auf dem Markt
- Geringes Anfangsinvestment, z.B. Infrastruktur
- Geringe laufende Kosten
- Andere: [Freitext]
- Andere: [Freitext]

[Gewichte] (unwichtig) 1/ 2/ 3/ 4/ (sehr wichtig) 5/ weiß nicht

[Angabe einer Technologieoption für jede Aussage]
Welche LPWA-Konnektivitätstechnologie erfüllt Ihrer Einschätzung nach das jeweilige Auswahlkriterium am besten?

Bitte wählen Sie jeweils aus.

- Unabhängigkeit von Dritten, d.h. eigener Aufbau des Netzwerks möglich
- Umsetzung durch lokale IT-Unternehmen oder Netzwerkanbieter
- Hohe Netzwerkverfügbarkeit und entsprechende Services, z.B. 24/7 Hotline für Fehlermeldungen
- Niedriger Energieverbrauch der batteriebetriebenen Endgeräte
- Hohe IT-Sicherheit, z.B. Serverstandorte, Verschlüsselung der Daten
- Zugänglichkeit für Bürger*innen
- Zugänglichkeit für lokale Unternehmen
- Hohe Verfügbarkeit von Endgeräten/Sensoren und Gateways/Base Stations auf dem Markt
- Geringes Anfangsinvestment, z.B. Infrastruktur
- Geringe laufende Kosten
- Andere: [Freitext]
- Andere: [Freitext]

[Technologieoptionen] LoRaWAN/ LTE-M/ N-IoT/ Sigfox/ andere/ weiß nicht

[Angabe des Zustimmungsgrades zu jeder Aussage]
Inwieweit stimmen Sie folgenden Aussagen zum Einsatz von LPWA-Konnektivitätstechnologien in Ihrer Stadt zu?

- Der Einsatz von LPWA-Konnektivitätstechnologien ist kompliziert.
- Sicherheits- und/oder Datenschutzaspekte verkomplizierenden Einsatz von LPWA-Konnektivitätstechnologien.
- Interoperabilitätsprobleme verkomplizieren den Einsatz von LPWA-Konnektivitätstechnologien.
- LPWA-Konnektivitätstechnologien sind gut kompatibel mitunseren existierenden IT-Infrastrukturen.
- Es gibt gute Möglichkeiten, LPWA-Konnektivitätstechnologien vor deren Einsatz zu testen.
- In der Vergangenheit haben wir LPWA-Konnektivitätstechnologien getestet (z.B. in Pilotprojekten).

[Zustimmungsgrade] Stimme überhaupt nicht zu/ stimme eher nicht zu/ teils-teils/ stimme eher zu/ stimme voll und ganz zu/ weiß nicht

Seite 7: LoRaWAN

[Auswahl, Mehrfachauswahl möglich]
Wie ist das technische Setup des(der) LoRa-Netzwerks(e) in Ihrer Stadt umgesetzt oder geplant?
Wählen Sie die ähnlichste(n) Option(en) für Ihr(e) Netz(e).

- Ein externer Netzwerkanbieter stellt Konnektivität zur Verfügung. Er verantwortet auch Installation und Betrieb der Gateways.
- Die Stadt/ein Tochterunternehmen der Stadt betreibt ein eigenes, geschlossenes LoRa-Netzwerk für eigene Zwecke.
- Die Stadt/ein Tochterunternehmen der Stadt tritt mit einem eigenen LoRa-Netzwerk als Netzwerkanbieter auf und bietet externen Kunden (privat/kommerziell) auf Vertragsbasis LoRa-Konnektivität an.

- Die Stadt/ein Tochterunternehmen der Stadt betreibt ein eigenes öffentliches Netzwerk, das von Bürger:innen und Unternehmen genutzt werden kann.
- Die Stadt/ein Tochterunternehmen der Stadt stellt Standorte und Gateways bereit, die Teil des öffentlichen TheThings Networks (TTN) sind und somit für alle zugänglich sind.
- Andere: [Freitext]

Wie viele Sensoren aus städtischer Hand (inkl. städtische Tochterunternehmen) senden derzeit Daten über das LoRa-Netzwerk in Ihrer Stadt?
Bitte schätzen Sie, wenn die genaue Zahl unbekannt ist.
Anzahl Sensoren: [Freitext]

Wie hoch waren Ihre anfänglichen Investitionskosten in das LoRa-Netzwerk ungefähr und wie hoch sind Ihre jährlichen Betriebskosten?
Bitte schätzen Sie, wenn die genaue Zahl unbekannt ist.
Möchten Sie die Frage nicht beantworten, können Sie sie überspringen.
Investitionskosten: [Freitext] €
Jährliche Betriebskosten: [Freitext] €

Seite 8: LoRaWAN

Wie viele LoRa-Gateways betreiben Sie derzeit ungefähr in Ihrem Stadtgebiet?
Bitte schätzen Sie, wenn die genaue Zahl unbekannt ist.
Anzahl LoRa-Gateways: [Freitext]

[Auswahl; Mehrfachauswahl möglich]
Welche Kundengruppen möchte Sie als Stadt oder Tochterunternehmen der Stadt langfristig mit Ihrem LoRaWAN-Service ansprechen? Und soll die Nutzung des LoRaWAN kostenfrei oder kostenpflichtig sein?
Wir möchten unseren Service...

- für eigene Zwecke nutzen.
- allen innerhalb des Stadtkonzerns [Bitte auswählen] bereitstellen. [Auswahloptionen] kostenlos/ kostenpflichtig / weiß nicht
- Privatpersonen [Bitte auswählen] bereitstellen. [Auswahloptionen] kostenlos/ kostenpflichtig / weiß nicht
- Unternehmen [Bitte auswählen] bereitstellen. [Auswahloptionen] kostenlos/ kostenpflichtig / weiß nicht
- Sonstiges: [Freitext]
- Weiß nicht.

[Auswahl; Mehrfachauswahl möglich]
Welche LoRa-Services wollen Sie in Zukunft anbieten?

- Bereitstellung der LoRa-Konnektivität („Netzwerkbetreiber“)
- Unterstützung bei der Endgeräteauswahl und -beschaffung
- Unterstützung bei der Anbindung an Server bzw. private IT-Infrastruktur bei Bürger*innen
- Unterstützung bei Datenverarbeitung, u.a. Visualisierung

- Weitere: [Freitext]
- Weiß nicht.

Seite 9: Narrowband-IoT (NB-IoT)

[Auswahl]
Wie ist das technische Setup des NB-IoT-Netzwerks in Ihrer Stadt umgesetzt oder geplant?
Bitte wählen Sie die ähnlichste Option.

- Ein externer Netzwerkanbieter stellt Konnektivität über seine bestehenden Mobilfunkstandorte zur Verfügung und die Stadt ist ein Geschäftskunde.
- Ein externer Netzwerkanbieter stellt Konnektivität über von der Stadt bereitgestellte Standorte
- zur Verfügung, dafür erhält die Stadt Sonderkonditionen.
- Ein externer Netzwerkanbieter hat Konnektivität auf Anfrage durch die Stadt vor Ort aufgebaut und bietet diese nun allen Kund*innen an.
- Andere: (Freitext)

Wie viele Sensoren aus städtischer Hand (inkl. städtische Tochterunternehmen) senden derzeit Daten über das NB-IoT-Netzwerk in Ihrer Stadt?
Bitte schätzen Sie, wenn die genaue Zahl unbekannt ist.
Anzahl Sensoren: [Freitext]

Wie hoch waren Ihre anfänglichen Investitionen/Setup-Kosten für das NB-IoT-Netzwerk ungefähr und wie hoch sind Ihre jährlichen Betriebskosten?
Bitte schätzen Sie, wenn die genaue Zahl unbekannt ist.
Möchten Sie die Frage nicht beantworten, können Sie sie überspringen.
Investitionen/Setup-Kosten: [Freitext] €
Jährliche Betriebskosten: [Freitext] €

Seite 10: Sigfox

[Auswahl]
Wie ist das technische Setup des Sigfox-Netzwerks in Ihrer Stadt umgesetzt oder geplant?
Bitte wählen Sie die ähnlichste Option.

- Sigfox Germany stellt Konnektivität über seine bestehenden Funkstandorte zur Verfügung und die Stadt ist ein Geschäftskunde.
- Sigfox Germany stellt Konnektivität über von der Stadt bereitgestellte Standorte zur Verfügung, dafür erhält die Stadt Sonderkonditionen.
- Auf Anfrage der Stadt hat Sigfox Germany lokale Konnektivität aufgebaut und die Stadt ist ein Geschäftskunde.
- Andere: [Freitext]

Wie viele Sensoren aus städtischer Hand (inkl. städtische Tochterunternehmen) senden derzeit Daten über das Sigfox-Netzwerk in Ihrer Stadt?
Bitte schätzen Sie, wenn die genaue Zahl unbekannt ist.
Anzahl Sensoren: [Freitext]

Wie hoch waren Ihre anfänglichen Investitionen/Setup-Kosten für das Sigfox-Netzwerk ungefähr und wie hoch sind Ihre jährlichen Betriebskosten?
Bitte schätzen Sie, wenn die genaue Zahl unbekannt ist.
Investitionen/Setup-Kosten: [Freitext] €
Jährliche Betriebskosten: [Freitext] €

Seite 11: Motivation für die Umsetzung von Smart City

[Informationstext]
Im Folgenden möchten wir von Ihnen erfahren, was Sie (als Stadt/repräsentative Person) sich von Smart City erhoffen und was Sie motiviert hat, sich mit dem Thema zu beschäftigen.

[Zustimmungsskala zu jeder Aussage]
Inwieweit stimmen Sie den folgenden Aussagen zu den Vorteilen von Smart City zu?
Smart City...

- führt zu einer Verbesserung der wirtschaftlichen Lage unserer Stadt.
- führt zu Kosteneinsparungen in unserer Stadt.
- generiert zusätzliche Einnahmen für unsere Stadt (z.B. durch die Gewerbesteuer).
- verbessert die Außenwirkung unserer Stadt.
- ermöglicht es, städtische Aufgaben besser auszuführen.
- macht die Stadt lebenswerter; bzw. erzeugt einen Mehrwert für die Bürger*innen.
- trägt zur Schonung der Umwelt bei.
- macht die Stadt attraktiver für Unternehmen.

[Zustimmungsskala Elemente] Stimme überhaupt nicht zu/ stimme eher nicht zu/ teils-teils/ stimme eher zu/ stimme voll und ganz zu/ weiß nicht

[Zustimmungsskala zu jeder Aussage]
Inwieweit stimmen Sie den folgenden Aussagen zur Rolle der Bürger*innen bei Smart City zu?

- Smart City kommt Bürger*innen vor allem direkt zugute (z.B. durch effizientere Abläufe in der Verwaltung).
- Smart City kommt Bürger*innen vor allem indirekt zugute (z.B. durch die Schaffung zusätzlicher Arbeitsplätze).
- In der Vergangenheit haben wir Bürger*innen über Smart City informiert.
- In der Vergangenheit haben wir Bürger*innen in die Entwicklung unserer Smart City eingebunden.
- Unsere Stadt möchte Sensordaten erheben, die für die Öffentlichkeit zugänglich sind (Open Data Ansatz).
- Smart City-Infrastrukturen müssen wie z.B. innerstädtische Grünflächen als öffentliches Gut verstanden werden.
- Smart City-Infrastrukturen müssen für alle Bürger*innen zugänglich sein weil sie mit Steuergeldern aufgebaut sind.

[Zustimmungsskala Elemente] Stimme überhaupt nicht zu/ stimme eher nicht zu/ teils-teils/ stimme eher zu/ stimme voll und ganz zu/ weiß nicht

Seite 12: Smart City-Anwendungsbereiche

[Informationstext]
Im Folgenden geht es um Anwendungsbereiche von Smart City-Technologien in Ihrer Stadt und Ihre Einschätzung deslangfristigen Potenzials dieser.

[Auswahl des Anwendungsbereichs und dann die Auswahl der Technologie für jeden; Mehrfachauswahl auf beiden Ebenen möglich]
In welchen Anwendungsbereichen setzen Sie welche Smart City-Konnektivitätstechnologien ein?
Mehrfachauswahl möglich.

- <u>Intelligente Energieversorgung und -nutzung</u> (z.B. Intelligente Steuerung von Straßenbeleuchtung)
- <u>Abfallwirtschaft</u> (z.B. Einsatz von Gewichtssensoren in Abfallbehältern)
- <u>Verkehr</u> (z.B. Analyse und Überwachung der Parksituation)
- <u>Umweltüberwachung</u> (z.B. Überwachung der Luftqualität)
- <u>Gebäudemanagement</u> (z.B. Intelligente Temperatursteuerung)
- <u>Andere</u>: [Freitext]
- <u>Andere</u>: [Freitext]

[Auswahl der Technologie - Optionen] Mobilfunktechnologie, z.B. LTE und 5G/ Wide Local Area Netzwerke (WLAN), z.B. Wifi/ LoRaWAN/ Sigfox/ Narrowband-IoT (NB-IoT)/Andere: [Freitext]/ Weiß nicht

[Einordnung jedes Anwendungsbereichs gemäß der gegebenen Skala]
Wie schätzen Sie generell (also nicht nur in Ihrer Stadt) das Potenzial von Smart City-Konnektivitätstechnologien in den folgenden Anwendungsbereichen langfristig ein?

- Intelligente Energieversorgung und -nutzung (z.B. Intelligente Steuerung von Straßenbeleuchtung)
- Abfallwirtschaft (z.B. Einsatz von Gewichtssensoren in Abfallbehältern)
- Verkehr (z.B. Analyse und Überwachung der Parksituation)
- Umweltüberwachung (z.B. Überwachung der Luftqualität)
- Gebäudemanagement (z.B. Intelligente Temperatursteuerung)
- Andere: [Freitext]
- Andere: [Freitext]

[Skala] Gering/ eher gering/ mittel/ eher hoch/ hoch/ weiß nicht

Seite 13: Informationen zur antwortenden Person

[Auswahl]
Zu welcher Personengruppe gehören Sie?

- Mitarbeiter*in der Stadtverwaltung
- Mitarbeiter*in der Stadtwerke/eines anderen städtischen Unternehmens

- Andere, nämlich: [Freitext]

[Auswahl, Mehrfachauswahl möglich]
Wie und wo haben Sie das notwendige Wissen und ggf. auch formale Qualifikationen für die Bearbeitung von Smart City-Themen erworben?
Mehrfachnennungen möglich

- Frühere Berufserfahrung, nämlich als: [Freitext]
- Interne Weiterbildungen/Binnenqualifikation
- Frei zugängliche (Online-)Medien
- Konferenzen und Tagungen
- Austausch mit Unternehmen
- Austausch mit anderen Städten auf eigene Initiative
- Austausch über den Deutschen Städtetag
- Austausch über andere Organisationen und Initiativen, nämlich: [Freitext]
- Andere, nämlich: [Freitext]

[Auswahl, als Skala angezeigt]
Uns interessiert Ihre persönlich wahrgenommene fachliche Kompetenz für die Arbeit im Kontext der Smart City.
Es gibt keine richtigen oder falschen Antworten – es zählt Ihr persönliches Empfinden. Wie sehr stimmen Sie diesen Aussagen zu?

- Bezüglich des benötigten Wissens bin ich auf dem Laufenden. [Bitte auswählen]
- Die für meine Arbeit bedeutsamen Konzepte und Technologien verstehe ich. [Bitte auswählen]

[Skalenelemente] (stimmt völlig) 1/ (stimmt weitestgehend) 2/ (stimmt teilweise) 3/ (stimmt gerade noch) 4/ (stimmt eher nicht) 5/ (stimmt überhaupt nicht) 6 / kann ich nicht beurteilen

Seite 14: Freiwillige Angabe von Kontaktdaten

[Auswahl, Mehrfachauswahl möglich, freiwillige Angaben; Emailabfrage auf S. 15 nur angezeigt, wenn hier mindestens eine der Optionen ausgewählt wurde]
Sind Sie mit der Verwendung Ihrer Emailadresse für eine Kontaktaufnahme und Zusendung der personalisierten Auswertung einverstanden?

- Ich bin damit einverstanden, dass das Umfrageteam bei Rückfragen über meine Emailadresse Kontakt zu mir aufnimmt.
- Ich bin damit einverstanden, dass mir die Umfrageergebnisse nach Auswertung an meine Emailadresse zugestellt werden.

Seite 15: Kontaktdaten

Bitte geben Sie hier Ihre Emailadresse an: [Freitext]

Ihre Ergänzungen oder Kommentare zur Umfrage
Sollten Sie keine Ergänzungen oder Kommentare haben, klicken Sie gerne direkt auf „Weiter“.
[Freitext]

Letzte Seite

Vielen Dank für Ihre Teilnahme!
Ihre Antworten wurden gespeichert.

English translation of the survey questionnaire

Page 1 (start page)

[Information text]

Welcome to the smart city survey

Thank you for your participation. You are assisting and enabling us to create a fact-based, comprehensive impression of smart cities in Germany. The focus of this survey is on communication technologies, the objectives of Smart City Engagements and concrete application scenarios in the respective cities.

In regard to data security, the following applies:

- The collected data would be processed with confidentiality and remain anonymous and assessed in aggregated form. It would not be possible to infer from the published results back to individual cities.
- We collect the city zip codes solely for the purpose of complementing analyses regarding demographic and economic data (for example, number of inhabitants, unemployment rate).
- The publication of the survey results is conducted according to the basic regulation of data privacy (DSGVO, Link: https://dsgvo-gesetz.de/).
- Participation in this survey takes 10 to 15 minutes.

In return for your participation, we would gladly send you a customized evaluation of the survey results of your city. The evaluation would place your city in comparison to other participating cities. You can use the results for your own purposes. To receive the corresponding results, please leave your email at the end of the survey.

For further question, please to not hesitate to contact Lucia Bauer through email:
lucia.baur@tum.de.

Thank you very much for your participation!

Prof. Dr. Joachim Henkel - The Technical University of Munich - Chair of Technology and Innovation Management
Lucia Baur - The Technical University of Munich - Chair of Technology and Innovation Management

Technical instructions:

- Interruptions: you can leave the survey midway if necessary and return to your progress with your participant code afterwards
- Comments: If you have any feedback you would like to share with us, you are welcome to do so at the end of the survey

[The selection of one option is necessary; if there is a second option selected, this survey jumps to page 15 and end the survey]

Would you like to start the survey now?

- Yes, I would like to start the survey now and I agree to the above-mentioned data privacy clauses.
- I do not agree with the above-mentioned data privacy clauses and would not like to participate.

Page 2: Underlying/general data on Smart City in your city

[Information text]
Smart City is understood in the context of this survey as follows:
Smart City is understood in the context of this survey as a digitalization concept for cities. It concerns especially the availability of wireless communication network for various application scenarios and user groups.

[Simple selection in drop-down menu]
In which year did the topic of Smart City become visible/part of the formal agenda in your city?
If you cannot recall an exact date, please provide an estimate.
[Dropdown] Not at all/ 2000/ 2001/ 2002/ 2003/ 2004/ 2005/ 2006/ 2007/ 2008/ 2009/ 2010/ 2011/ 2012/ 2013/ 2014/ 2015/ 2016/ 2017/ 2018/ 2019/ 2020/ 2021/ don't know

[free text; restriction: only 5-digit numbers are accepted]
Which city is being considered in answering this survey?
Please provide one valid zip code from your city area.
Zip code: [free text]

[Selection, multiple-selection possible]
Has your city (and/or continue to) received support for Smart City, and if yes, which ones?
Multiple choice possible.

- No support
- Support from EU funds
- BMI (now BMWSB) program "model project smart cities"
- other form of federal support (other than BMI/BMWSB)
- support from federal state funds
- support from private funds, e.g., from companies or foundations (possibly also in the form of in-kind donations
- support from other means, namely: [free text]
- don't know

Page 3: Understanding of Smart City in your city

[Information text]
In the following section, we would like to understand more in detail how your Smart City is currently lived in your city.

[Selection, multi-selection possible]

Who do you see as the driving force for Smart City?
Multiple choice possible.

- city administration, e.g., Chief Digital Officer (CDO), digital official representative, authority responsible for IT
- city utility companies, e.g., municipal utilities, municipal network
- citizens' initiative, associations, and other civic engagements
- democratically elected citizen representatives, e.g., city council
- local companies
- local branches/locations of international companies
- locally based educational institutions, e.g., vocational school, university
- others: [free text]
- no one

[Selection, multi-selection possible]
With which local IT-related initiatives are you in contact with?
Multiple choice possible.

- local section of the Chaos Computer Club
- local TTN (The Things Network) Community
- local Code for Germany group
- others: [free text]
- so far, no such group exists

[Selection shown as scale – only one selection permitted]
How do you rate your city in terms of smart city status today?
My city compared to other German cities is considered a Smart City....
Not at all progressive/ little progressive/ average/ rather progressive/ very progressive/ don't know
Smart City is receiving an appropriate amount of attention in my city.
Not at all progressive/ little progressive/ average/ rather progressive/ very progressive/ don't know

Page 4: Technologies for the smart city and choice of technology

[Information text]
In the following section, we will survey you on the use of various connectivity technologies for Smart City in your city.

[Selection]
In our city, we deploy mobile technologies, e.g., LTE and 5G, for Smart City.
Yes/No/Don't know.

[Selection]
In our city, we deploy Wide-Local-Area Networks (WLAN), e.g. WiFi, for Smart City.
Yes/No/Don't know.

[Selection; filter question for detailed pages on LPWAN, i.e. pages 5 and 6 are only shown if "Yes" has been selected here]

In our city, we deploy Low Power Wide Area (LPWA) connectivity technologies, e.g. LoRaWAN, Sigfox, Narrowband Internet-of-Things (NB-IoT) or LTE-M, for Smart City.
Yes/No/Don't know.

[free text, optional]
What other connectivity technologies (e.g., wireless Ambus and fiber-optic network) are you currently deploying in your city for Smart City?
If applicable, feel free to name other networks. [free text]

[Likert-scale for each statement]
To what extent do the following statements apply to your city??
In our city...

- the technology selection is demand-driven, i.e., we select the appropriate technology for each application.
- we have a standardized selection process for smart city network technologies, e.g., using a technology map.
- we have the competence at the city and its subsidiaries to build and operate networks ourselves
- we regularly receive requests from other cities to share our experiences with them.
- the focus of smart city projects is currently in a testing phase for feasibility.

[Likert-scale elements] Does not apply at all/ rather not applies/ partially applies/ rather applies/ applies completely/ I cannot judge

Page 5: Low Power Wide Area (LPWA) Networks for the Smart City

[Selection]
Which sequence most accurately describes the timing of the technology decisions in your city?

- We had a specific use case in our city and then looked for the right technology for it. We then used this LPWA connectivity technology for other applications as well.
- We identified and introduced our LPWA connectivity technology as relevant for the future. We then looked for suitable use cases.
- Other, namely: [free text]

[For each technology the same scale for rating the implementation process is used, this question serves as a filter question for the detail pages for each technology, i.e., only if „planned“ or more advanced implementation stages are selected, the respective detailed pages are shown (p.6 to 10)]
To what extent do you plan to deploy, or are already deploying the above LPWA connectivity technologies for Smart City in your city?
Please complete the sentence.
In our city the use of...

- LoRaWAN
- Sigfox
- NB-IoT
- Other (optional): [free text]
- Other (optional): [free text]

[implementation process scale elements] Not a topic/ under discussion/ planned/ in implementation/ implemented for max. 6 months/ implemented for more than 6 months/ discontinued/ don't know

[Selection]
To the best of your knowledge, how many LPWA networks exist in parallel in your city today?
For example, if you "run a closed LoRaWAN for the municipal utility, have a network connected to The-Things-Network, and still have Sigfox coverage", that would be three networks.

- 1
- 2
- 3
- Other, namely: [free text]
- Don't know

Page 6: Low Power Wide Area (LPWA) networks froth the smart city

[Assessment of each statement with a weight]
How important were the above criteria to you when selecting LPWA connectivity technology?

- Independence from third parties, i.e., own construction of the network possible
- Implementation through local IT companies or network providers
- High network availability and corresponding services, e.g., 24/7 hotline for error messages
- Low energy consumption of the battery-powered terminals
- High IT security, e.g., server locations, encryption of data
- Accessibility for citizens
- Accessibility for local businesses
- High availability of terminal devices/sensors and gateways/base stations on the market
- Low initial investment, e.g., infrastructure
- Low running expenses
- Other: [free text]
- Other: [free text]

[Weights] (unimportant) 1/ 2/ 3/ 4/ (very important) 5/ don't know

[Indication of one technology for each option]
Which LPWA connectivity technology do you think fits each selection criterion the best?
Please select in each case.

- Independence from third parties, i.e., own construction of the network possible
- Implementation through local IT companies or network providers
- High network availability and corresponding services, e.g., 24/7 hotline for error messages
- Low energy consumption of the battery-powered terminals
- High IT security, e.g., server locations, encryption of data
- Accessibility for citizens

- Accessibility for local businesses
- High availability of terminal devices/sensors and gateways/base stations on the market
- Low initial investment, e.g., infrastructure
- Low running expenses
- Other: [free text]
- Other: [free text]

[Technology options] LoRaWAN/ LTE-M/ N-IoT/ Sigfox/ others/ don't know

[Indication of level of agreement for each option]
To what extent do you agree with the following statements about the use of LPWA connectivity technologies in your city

- The deployment of LPWA connectivity technologies is complicated.
- Security and/or privacy issues complicate the use of LPWA connectivity technologies.
- Interoperability issues complicate the deployment of LPWA connectivity technologies.
- LPWA connectivity technologies are well compatible with our existing IT infrastructures.
- There are good opportunities to test LPWA connectivity technologies before deploying them.
- In the past, we have tested LPWA connectivity technologies (e.g., in pilot projects).

[Options] Do not agree at all/ tend to disagree/ partially agree/ tend to agree/ fully agree/ don't know

Page 7: LoRaWAN

[Selection, multi-selection possible]
How is the technical setup of the LoRa network(s) implemented or planned in your city?
Select the most appropriate option(s) for your network(s).

- An external network provider provides connectivity. It is also responsible for installing and operating the gateways.
- The city/a subsidiary of the city operates its own closed LoRa network for its own purposes.
- The city/ a subsidiary of the city acts as a network provider with its own LoRa network and offers LoRa connectivity to external customers (private/commercial) on a contract basis.
- The city/ a subsidiary of the city operates its own public network, which can be used by citizens and companies.
- The city/ a subsidiary of the city provides sites and gateways that are part of the public The Things Network (TTN) and so accessible to all.
- Others: [free texts]

How many city-owned sensors (incl. city-owned subsidiaries) are currently sending data over the LoRa network in your city?
Please estimate if the exact number is unknown.
Number of sensors: [free text]

What were your estimations of your initial investment costs in the LoRa network and what are your annual operating costs?

Please estimate if the exact number is unknown.
If you wish not to answer this question, you can skip it.
Investment costs: [free text] €
Annual operating costs: [free text] €

Page 8: LoRaWAN

Approximately how many LoRa gateways do you currently operate in the metropolitan area of your city?
Please estimate if the exact number is unknown.
Number of LoRaWAN gateways: [free text]

[Selection, multi-selection possible]
As a city or a subsidiary of the city, which customer groups do you want to address with your LoRaWAN service in the long term? And should the use of LoRaWAN be free of charge or subject to a fee?
We would like to offer our service...

- for our own purposes.
- provide to all within the city conglomerate [options] free of charge/ for a fee / don't know.
- provide to individuals [options] free of charge/ for a fee / don't know.
- provide to companies [options] free of charge/ for a fee / don't know.
- Other: [free text]
- Don't know.

[Selection, multi-selection possible]
What LoRa services do you plan to offer in the future?

- Provisioning of LoRa connectivity ("network operator")
- Support in the selection of procurement of end devices
- Support for connecting to servers or private IT infrastructure from citizens
- Support for data processing, including visualization
- Others: [free text]
- Don't know.

Page 9: Narrowband-IoT (NB-IoT)

[Selection]
How is the technical setup of the NB-IoT network implemented or planned in your city?
Please choose the most similar option.

- An outside network provider provides connectivity through its existing wireless communication locations and the city is considered a corporate customer
- An external network provider will provide connectivity via locations provided by the city, and the city receives special conditions in return.
- An external network provider has built connectivity on site at the request of the city, and now offers it to all customers

- Others: [free text]

How many city-owned sensors (including city-owned subsidiaries) are currently sending data over the NB-IoT network in your city?
Please estimate if the exact number is unknown.
Number of sensors: [free text]

What were your estimations of your initial investment costs in the NB-IoT network and what are your annual operating costs?
Please estimate if the exact number is unknown.
If you wish not to answer this question, you can skip it.
Investment costs: [free text] €
Annual operating costs: [free text] €

Page 10: Sigfox

[Selection]
How is the technical setup of the Sigfox network implemented or planned in your city?
Please choose the most similar option.

- Sigfox Germany provides connectivity through its existing radio communication locations and the city is a corporate customer.
- Sigfox Germany provides connectivity via sites provided by the city, and the city receives special conditions in return.
- At the city's request, Sigfox Germany built local connectivity and the city is a corporate customer.
- Others: [free text]

How many city-owned sensors (including city-owned subsidiaries) are currently sending data over the Sigfox network in your city?
Please estimate if the exact number is unknown.
Number of sensors: [free text]

What were your estimations of your initial investment costs in the Sigfox network and what are your annual operating costs?
Please estimate if the exact number is unknown.
If you wish not to answer this question, you can skip it.
Investment costs: [free text] €
Annual operating costs: [free text] €

Page 11: Motivation for the implementation of smart city

[Information text]
In the following section, we would like to hear your opinion on what you (as a city/representative) hope to achieve from Smart City, and what motivated you to get involved with the topic.

[Scale of agreement with each statement]

To what extent do you agree with the following statements about the benefits of Smart City?
Smart City...

- leads to an improvement of the economic situation of our city.
- leads to cost saving in our city.
- generates additional revenue for our city (e.g., through business tax).
- improves the external image of our city.
- enables municipal tasks to be carried out more effectively.
- makes the city more livable, i.e., generates added value for the citizens.
- contributes to the protection of the environment.
- Makes the city more attractive for companies.

[Scale of agreement options] Do not agree at all/ tend to disagree/ partially agree/ tend to agree/ fully agree/ don't know

[Scale of agreement with each statement]
To what extent do you agree with the following statements about the role of citizens in Smart City?

- Smart City benefits citizens directly (e.g., through more efficient administrative processes).
- Smart City benefits citizens mainly indirectly (e.g., through creating additional jobs).
- In the past, we have informed citizens about Smart City.
- In the past, we have involved citizens in the development of our Smart City.
- Our city would like to collect sensor data that is available to the public (Open Data approach).
- Smart City infrastructures, like intra-urban green spaces, must be understood as a public good.
- Smart city infrastructures must be accessible to all citizens because they are built with taxpayers' money.

[Scale of agreement options] Do not agree at all/ tend to disagree/ partially agree/ tend to agree/ fully agree/ don't know

Page 12: Smart City – areas of application

[Information text]
The following is about the area for application for smart city technologies in your city and your assessment of their long-term potential.

[First the selection of the area of application and then the selection of the technology for each case; multiple selection is possible on all levels]
In which application areas do you use which smart city connectivity technologies?
Multiple choice possible.

- Intelligent energy supply and use (e.g., smart control of street lighting)
- Waste management (e.g., use of weight sensors in bins)
- Traffic (e.g., analysis and monitoring of the parking situation)
- Environmental monitoring (e.g., monitoring of air quality)
- Facility management (e.g., smart temperature control)

- Others: [free text]
- Others: [free text]

[First ,technology options] cellular technologies, e.g., LTE und 5G/ Wide Local Area Networks (WLAN), e.g., Wifi/ LoRaWAN/ Sigfox/ Narrowband-IoT (NB-IoT)/ Others: [free text]/ don’t know

[Assessment of each area of application based on the given scale]
In general (not just in your city), how do you assess the potential of Smart City-connectivity technologies in the following application areas in the long term?

- Intelligent energy supply and use (e.g., smart control of street lighting)
- Waste management (e.g., use of weight sensors in bins)
- Traffic (e.g., analysis and monitoring of the parking situation)
- Environmental monitoring (e.g., monitoring of air quality)
- Facility management (e.g., smart temperature control)
- Others: [free text]
- Others: [free text]

[Scale] Low/ rather low/ medium/ rather high/ high/ don't know

Page 13: Respondent’s data

[Selection]
Which group do you belong to?

- Employee of the city administration
- Employee of the municipal utilities company/another municipal company
- Other, namely: [free text]

[Selection, multiple selection possible]
How and where did you acquire the necessary knowledge and, if applicable, formal qualifications to work on Smart City issues?
Multiple selection possible

- Previous work experience, namely as: [free text]
- Internal training/ internal qualification
- Freely accessible (online) media
- Conferences and meetings
- Exchange with companies
- Self-initiated exchange with other cities
- Exchange through the German Association of Cities
- Exchange through other organizations and initiatives, namely: [free text]
- Others, namely: [free text]

[Selection, shown as scale]
We are interested in how you personally perceive your professional competence for working in the context of the Smart City.
There are no right or wrong answers – it is your personal feeling that counts. How much do you agree with these statements?

- Regarding the required knowledge, I am up to date. [Please select]

- I understand the concepts and technologies that are of importance to my work. [Please select]

[Scale elements] (completely true) 1/ (largely true) 2/ (partially true) 3/ (just about true) 4/ (rather not true) 5/ (not at all true) 6 / I cannot judge

Page 14: Voluntary provision of contact details

[Selection, multiple selection possible, voluntary indication; Email collection on p. 15 is only shown if here minimum one oft he two options was selected]
Do you agree to the use of your email address to contact you and send you the personalized evaluation?

- ☐ I agree that the survey team will contact me via my email address in case of further queries.
- ☐ I agree that the survey results after evaluation will be sent to my email address.

Page 15: Contact details

Please insert you remail address here: [free text]

Your additions or comments to the study
If you have no further additions or comments, feel free to click “Next” directly. [free text]

Last page

Thank you for your participation!
Your answers have been saved.

Appendix E: Political analyses

Appendix Table E – 1 Tabulation of year a city initiated its smart city efforts and the political party of the mayor in that year

	Mayor's party in "Year"							
Year	CDU	CSU	FDP	Grüne	SPD	Other	Without party	Total
2009	0	0	0	0	1	0	1	2
2010	0	0	0	0	3	0	1	4
2011	1	0	0	0	0	0	0	1
2012	1	0	0	0	0	0	0	1
2013	0	0	0	0	0	0	1	1
2014	0	0	0	0	3	0	0	3
2015	1	0	0	0	2	0	2	5
2016	3	2	1	1	5	0	0	12
2017	6	2	1	1	4	0	0	14
2018	7	1	0	0	5	0	3	16
2019	7	0	2	0	9	0	0	18
2020	9	0	0	0	3	1	3	16
2021	2	1	0	0	3	0	0	6
Total	37	6	4	2	38	1	11	99

Appendix Table E – 2 Tabulation of year a city initiated its smart city efforts and the gender of the mayor in that year

	Mayor's gender in „Year“		
Year	f	m	Total
2009	1	1	2
2010	0	4	4
2011	0	1	1
2012	1	0	1
2013	0	1	1
2014	0	3	3
2015	0	5	5
2016	0	12	12
2017	1	13	14
2018	1	15	16
2019	0	18	18
2020	1	16	17
2021	1	5	6
Total	6	94	100

Appendix Table E – 3 Overview of Follower-Leader and mayors gender

	Mayor's gender		
FollowLead	f	m	Total
Don’t know	0	2	2
1	0	6	6
2	2	24	26
2.5	0	1	1
3	1	34	35
3.5	0	2	2
4	2	22	24
5	1	3	4
Total	6	94	100

Pearson Chi2 = 4.24 Prob = 0.7519

Appendix Table E – 4 Two-sample Wilcoxon rank-sum (Mann-Whitney) test for year when smart city efforts were started

MayorIsSPD	Obs	Rank	sum	Expected
0	61		3188.500	3050
1	38		1761.500	1900
Combined	99		4950	4950
Unadjusted variance	19316.67			
Adjustment for ties	-375.10			
Adjusted variance	18941.56			
H0: StartY~m(MayorI~D==0) = StartY~m(MayorI~D==1)				
z = 1.006				
Prob >	z	=		0.3143

Exact prob = 0.3168

Appendix Table E – 5 Two-sample Wilcoxon rank-sum (Mann-Whitney) test for operational cost of LoRaWAN (relative to population)

MayorIsUnion	Obs	Rank	sum	Expected
0	11	98		110
1	8	92		80
Combined	19	190		190
Unadjusted variance	146.67			
Adjustment for ties	-0.13			
Adjusted variance	146.54			
H0: Lo~l_Rel(MayorI~n==0) = Lo~l_Rel(MayorI~n==1)				
z = -0.991				
Prob >	z	=		0.3215

Exact prob = 0.3417

Appendix Table E – 6 Two-sample Wilcoxon rank-sum (Mann-Whitney) test for operational cost of LoRaWAN (relative to population)

MayorIsSPD	Obs	Rank	sum	Expected
0	10	129	100	
1	9	61	90	
Combined	19	190	190	
Unadjusted variance 150.00				
Adjustment for ties -0.13				
Adjusted variance 149.87				
H0: Lo~l_Rel(MayorI~D==0) = Lo~l_Rel(MayorI~D==1)				
z = 2.369				
Prob >	z	=	0.0178	

Exact prob = 0.0167

Appendix Table E – 7 Pairwise correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) Self-Provisioning	1.000							
(2) Number of parallel networks	-0.027	1.000						
(3) CDU or CSU in city parlianment	0.068	-0.170	1.000					
(4) SPD in city parliament	-0.107	0.200	-0.106	1.000				
(5) FDP in city parliament	0.027	0.113	-0.118	-0.291 ***	1.000			
(6) Green party in city parliament	0.044	0.042	-0.348 ***	-0.366 ***	0.213 **	1.000		
(7) Linke in ciy parliament	-0.024	0.110	-0.469 ***	-0.343 ***	0.228 **	0.081	1.000	
(8) AfD in city parliament	-0.012	-0.194	-0.492 ***	-0.447 ***	0.247*	-0.106	0.492 ***	1.000

Appendix F: Smart city publications

The Smart City study was well-received in public. Below follows a compilation of publications related to it. When available, circulation information is added.

- **Baur, Lucia (2023)**: Smart City – eine Frage der Technologie, in: Kommune 21, 3/2023, p.14-15. *Invited article in the magazine targeting primarily public servants in cities, circulation of 12,000.*

- **Kommunaler Beschaffungsdienst (2023)**: Smart City – Netze nicht aus der Hand geben, in: Kommunaler Beschaffungsdienst, 1/2023, p.6-8. *Magazine targeting primarily public servants in cities, circulation of 15,000, and freely accessible online magazine at https://app.smarticle.com/html5/JVU4eDsDex/LOwuHJ5UIrjcI/6?article index=true, last accessed 07/09/2023.*

- **Federal ministry for living, city development and construction (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen) (01/12/2023)**: Technologieauswahl: Kommunen wollen unabhängig von Dritten sein; in: Smart City Praxiswissen | Ausgabe 01/23. *Article about the smart city study in the newsletter of the national smart city effort.*

- **Kommune 21 (10/21/2022):** Smart-City-Studie veröffentlicht; available at: https://www.kommune21.de/meldung_39804_gn, last accessed 07/09/2023. *Press release on the website of the magazine.*

- **Zeitung für kommunale Wirtschaft (10/16/2022):** Studie – so setzen deutsche Städte Smart-City-Konzepte um; available at: https://www.zfk.de/digitalisierung/smart-city-energy/studie-so-setzen-deutsche-staedte-smart-city-konzepte-um, last accessed 07/09/2023. *Press release on the website of the newspaper.*

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