Lessons Learned from Building Sustainable Municipal LoRaWan Infrastructure

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***Abstract*—This paper introduces the LoRaWAN Collaboration Framework (LCF), a strategic blueprint for deploying and managing LoRaWAN infrastructures in smart cities with an emphasis on rural and small municipalities. LoRaWAN technology distinguishes itself by its capability to support long-range, low-power IoT applications, making it ideal for extensive and sparsely populated areas. The LCF aims to address common challenges in these settings, such as limited technical expertise, financial constraints, and the need for cross-municipal cooperation. It outlines roles and responsibilities across various stakeholders including municipal authorities, IT service providers, application developers, and end-users. The framework emphasizes the balance of technological, economic, social and ecological sustainability in line with the United Nations' Sustainable Development Goals. In this paper, we describe the experiences from several LoRaWAN projects in small towns and municipalities in Germany and give some insights to these use cases, the derived collaboration framework, and other arguments to consider before implementing LoRaWAN infrastructures.**

Keywords-component; Service delivery; collaboration; sustainability; smart city; infrastructure; LoRaWAN Collaboration Framework (LCF)

I. Introduction

Sustainability [1] and efficient resource utilization is an indispensable reality of today's world. Sustainability is the primary element to execute all development goals that are a part of Sustainable Development Goals 2030 [26] and a sustainable earth for all stages of life [2, 3]. It is assumed to be the ultimate target of not only the United Nation, but of many developed and developing countries [4,5] and for example the World Economic Forum. Lastly, it is expected that sustainability brings long lasting socio-economic benefits to the general masses and the environment [6].

To achieve this, a significant variation in control and monitoring conditions is required, which underlines the importance and high demand for digitalization in the future. The Internet of Things (IoT) is helping to minimize the difference between the digital world and the physical world. Cities may tackle this demand with the help of Internet of Things technologies and develop smarter cities. Long-range wide-area-networks (LoRaWANs) are a big contribution in this development, as their range and costs are well-suited for providing a network infrastructure for smart city applications.

The biggest advantage of LoRaWan lies in the high range and its efficient energy consumption. A single gateway can cover distances up to 5 kilometers in urban settings and up to 15 km in rural areas. The range is dependent on various variables, for example, if there is no impediment between the transmitter and the receiver, the range can also increase, whereas the presence of an hindrance (buildings, trees, heavy rain, snow) can affect the signal quality negatively and reduce the range drastically. That means in order to cover a larger area, multiple gateways or a stronger LoRaWAN gateway antenna are necessary. Although the range depends on the environment and other obstacles, it still has the most advanced and reliable power transfer balance when compared to other communication technologies.

LoRaWAN provides wireless data transmission that is comparable to Wi-Fi and Bluetooth but has its own distinct properties. LoRaWAN is a low-power wide-area network

(LPWAN) technology that facilitates communication of connected devices covering long distances while consuming low energy [7]. This makes LoRaWAN particularly appropriate for rural areas. The LoRa Alliance developed LoRaWAN specification, whose basic modules as open-source software are available [8].

LoRaWAN is an enabler technology [9] that not only helps achieve the Sustainable Development Goals (SDGs) by measuring climate impacts, soil moisture, sealing, modal split, water levels et cetera but it also allows for automating and initiating counter measures, for example to save CO2-binding trees, moorland and so on.

Despite the growing need, only technical experts can perform the required construction work, data integration, processing, and visualization required for an end-to-end LoRaWAN use case, and small towns and municipalities cannot maneuver this alone. This group lacks basic technical knowledge and has insufficient human resources – in particular IT staff. Moreover, there are only limited financial resources available for digitalization. Hence, many projects concerning IoT or "smart city" are conducted using third party funding (public or private) instead of household budgets, or not at all.

Despite the urgent need for climate adaptation at all levels, the willingness of small towns and communities to contribute to climate goals, and the relatively low cost of LoRaWAN, in many cases this is not enough to build technically and organizational sustainable LoRaWAN infrastructures in these regions. This raises the question of a common operating model for LoRaWAN in rural areas, for example across several small towns and municipalities. This would demonstrate efficiency and cost benefit (cost savings, volume benefits, and production efficiencies) to be attained that would make a business economically viable. That can only be achieved if all the required actors have clear areas of responsibility and associate the LoRaWAN infrastructure with a benefit for themselves.

There is a clear need for a framework that:

- defines responsibilities for different stakeholders in LoRaWAN projects,
- balances ecological, economic, technical, and social objectives, and
- enables local authorities and municipalities to sustainably operate LoRaWANs.

Therefore, in this paper we propose the LoRaWAN Collaboration Framework (LCF), which addresses and tries to solve these issues.

The rest of this paper is organized as follows: Section II describes the related work in the areas of sustainability and LoRaWAN service management. Section III describes how we gained our findings and gives some insights into our use cases. Section IV describes the framework including the responsibilities of the various stakeholders and the organizational interfaces and other arguments to consider before implementing LoRaWAN infrastructures from a rural municipalities or rural town's point of view. The conclusions close the article.

II. RELATED WORK

Due to its impact on the economic and social sphere, digitalization is no longer seen as an isolated technical phenomenon. Digitalization as an encompassing process is related to massive changes in the economic production, in communication patterns and in other social aspects of everyday life and therefore has an influence on the society.

LoRaWAN technology helps in attaining Maslow's hierarchmuof needs along with sustainability. It's the hierarchy level that distributes the term "need" into five components, i.e., physiological needs (air, food, water), security needs (health, security, financial performance), social needs (relationships and belonging), respect needs and self-actualization needs. LoRaWAN supports the first two base levels of Maslow's hierarchy of needs (physiological needs and security needs). As they are foundation levels, the other three levels cannot be achieved until these are attained.

Nölting and Dembski found that digitalization, as a process, has no normative direction itself, but, in contrast, is governed by individual and organizational entities in accordance with their own goals [10]. Digitalization technologies such as LoRaWAN provide many opportunities, which can or cannot be used in terms of sustainability in its diverse dimensions. Due to this, some authors underline the necessity to regard the big societal trends, forward digitalization and sustainability, together as a twin transformation. In this setting, digitalization is aimed at normative common goals, and functions as an enabler for sustainability [11, 12, 13].

According to Farsi, Hosseinian Far, Daneshkhah, and Sedighi [14] sustainability is important to maintain the basis for sustainability assessment. In 1987, the United Nations Brundtland Commission defined sustainable as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [15], and hence highlighted the aspect of inter- and intra-generational equity. While sustainability is generally accepted as an important goal in our time, it is important to clarify the meaning and the different dimensions of the term sustainability as used here. In accordance with the current understanding in the scientific community, we consider four different dimensions of sustainability: technological, economic, social and ecological sustainability.

A. *Technological sustainability*

Sustainability of technology means that the IT infrastructure can be used and maintained in the long term and does not require any extensive adjustments in its foreseeable life cycle. No matter who is developing it, a sustainable combination of software technologies that are used together (i.e., "tech stack") should therefore be beneficial in the long term.

This also includes a reference data model for a clear database that is compatible with data from other municipalities. Such a data model would have to define which data is recorded by which sensor in which configuration. Even with seemingly straightforward devices such as soil moisture sensors, various critical factors—such as the depth of installation, soil type, measurement intervals, and calibration—significantly affect the data obtained. Moreover, it delves into the data's transformation processes throughout its lifecycle, including storage practices (data lineage), the mechanisms of data provision, and its semantic description. Finally, the integration of the data into broader metadata portals is essential for maximizing utility and accessibility. By capturing comprehensive, structured metadata, municipalities can ensure data quality, interoperability, scalability, and long-term utility. LoRaWAN is an emerging technology that is helping in technological sustainability across cities, utilities and buildings. It helps in regulating traffic to find a park space in an overcrowded urban area. It increases productivity and efficiency not only for the provider but also for the consumer, for example, to adaptability of power grids in extreme weather conditions. In other words, LoRaWAN has the right blend of market position, technology with the aim of sustainability that gives LoRaWAN an engrossing redeeming feature and appealing aspects.

B. *Economic sustainability*

Ikerd defines economic sustainability as scarcity, efficiency, and sovereignty [16]. Technology is nowadays an important factor of the economy, businesses and companies to achieve economic sustainability alongside monitoring the operations and increasing efficiency, productivity and to meet needs of the society.

To increase the economic sustainability, private and public companies, universities, and colleges should contribute their knowledge and services. It is important to process the division of labor. Economic efficiency and thrift often meet each other, for example, when reduced consumption of resources and energy correspond with lower financial costs. Sustainability in terms of economy also refers to long-term usability of investments. In the case of building a LoRaWAN infrastructure, a municipality must be convinced that the benefit will exceed the costs of implementation (economic viability). This can be achieved, for example, by reducing personnel costs for manual reading of measured values and other routine activities that can be automated using actuators and sensors.

C. *Social sustainability*

This dimension of sustainability considers that social equity and cohesion continue to be indispensable for sustainable development. Social sustainability refers to equal opportunities for "good living" and participation in the society for every individual [12]. With LoRaWAN technology in municipalities, the participation of citizens can be strengthened by promoting citizen science projects to utilize the collected data for their own needs, or to improve the local provision of public services.

A socially sustainable LoRaWAN model prioritizes accessibility, benefits all segments of society, and fosters positive community impacts. For example, low-cost connectivity and easy deployment foster the development of local solutions that address specific community challenges, such as agriculture, healthcare, education, and environmental monitoring. Robust data protection measures must be in place to safeguard user privacy and enhance trust in LoRaWAN services. To tailor LoRaWAN installations to the needs and priorities of the community, collaboration with local authorities and community groups is required.

The three dimensions of social, ecological, and economic sustainability are all part of the sustainable development approach. Consequently, they are all represented in the 17 sustainable development goals of the United Nations [26]. The challenge for practitioners is to find integrated solutions to achieve these goals in a holistic way.

D. *Ecological sustainability*

Ecological sustainability refers to the reduction of consumption and pollution of natural resources and energy. The main goal is to preserve the biosphere [12]. The question here is how technology such as LoRaWAN can be helpful in the protection of natural resources. Examples are the monitoring of environmental data in combination with sensor technology, which can be implemented in the countryside, in parks, and in nature related industries such as agriculture. In the field of agriculture, the monitoring data can be used to reduce herbicides, fertilizers, irrigation and allows precision farming [17]. Other use cases in that field appear when looking at sensors that measure air pollution or traffic dynamics, in order to take measures for improvements. In addition, IoT solutions can be also used for the prediction of extreme weather conditions including heat, flood, storm and wildfire. It is possible to gather data, which has not been measured before or to provide data in a better quality and frequency than before. The data puts the local and regional entities in a better position to take measures of precaution rather than only on repairing damages.

The three dimensions of economic, social, and ecological sustainability are all part of the sustainable development approach established by the United Nations. Some institutions have already shifted from the equality of the three dimensions to a perspective where the SDGs are organized in a hierarchical structure. Following the dependencies of social and economic life on an intact biosphere (see, e.g., [12]), the ecological dimension is prioritized due to building the ground for the social and economic sphere [18]. In line with this, an increasing number of institutions recommend municipal services of general interest on sustainability [12, 19]. The challenge for practitioners is to find integrated solutions for meeting the requirements of these goals in a holistic way.

The scientific discourse on the role of digital technologies in sustainability is ambiguous. On the one hand, digital technologies, including IoT technologies, support progress in sustainability, and on the other hand, they can be part of the problem [11, 17, 19].

Nonetheless, the awareness on the relationship of IoT technology and sustainable development is still limited. An analysis of the World Economic Forum came to the conclusion that, in 2018, 84% of IoT deployments (including the private sector) had the potential to address the Sustainable Development Goals that have already been addressed. Another conclusion they found was that aligning IoT with development goals did not reduce their commercial viability [20].

E. LoRaWAN Service Management

Information Technology Service Management (ITSM) is a process-focused discipline that is concerned with the efficient and structured delivery and support of IT services [21]. While the concept and its popular implementation, the IT Infrastructure Library (ITIL), have long been known and practiced, no work could be found examining the application of service management principles to the LoRaWAN realm.

LoRaWAN sensors and smart city applications have been thoroughly compiled by Bonilla, Campo Verde and Yoo [22]. The contributions edited by Song, Srinivasan, Sookoor, and Jeschke [23] as well demonstrate the breadth of smart city and IoT applications, but also the need for sustainable operating models and service management.

Zanella et al. [24] found that smart city projects can be complex due to heterogeneous technology (wireless transmission standards, sensors, software architecture), the multitude of different use cases, and the integration of data sources and sinks in order to facilitate diverse digital services.

However, most of these findings are based on case studies in larger cities. While extensive research exists on LoRaWAN infrastructure in rural areas, showcasing applications such as agriculture, smart meters, and fire monitoring. No specific studies could be identified that is concerned with LoRaWAN infrastructure for small towns and rural areas with low population density that still want to leverage the technology.

III. Method

We draw our experience from several projects in Germany in which we established LoRaWAN infrastructures, deployed sensors of different types, and created data visualizations. We synthesized our findings from projects in the municipalities Michendorf, Rüdersdorf, and Wiesenburg, and the town Brandenburg an der Havel.

The town of Brandenburg an der Havel is the home of the university where a part of the research team is located. The rural municipalities are nearby, and have contacted us following initial reports of successful deployments. We therefore assume that these are municipalities that are consciously seeking to drive digitalization forward. In some cases, we have already come across acquired funding or ongoing smart city efforts.

Table I illustrates the details of the covered sites. All projects deal with technology transfer in the sense that the university research team applies their knowledge and skills to practical problems of local companies and municipal administrations. Some of the projects are still ongoing, so findings might not be conclusive. Areas of application of the different projects include soil moisture, water temperature, water level, parking spots, presence detection, people counting, and traffic counting.

After clarifying project goals and scope, the project team selected and configured appropriate gateways, sensors, and data visualization platforms. The town or municipality then usually installed the configured sensors themselves. However, a large part of the project duration was spent coordinating with various project participants, organizing site visits, and waiting for service providers, key supporters from within the administration, or decision makers to clarify responsibilities. We had to explain to authorities and network operators that the technology is safe and will not interfere with other radio equipment. Site visits usually took a lot of planning and alignment due to the various ownership structures of buildings, in particular, towers and other tall structures that are already used for other purposes, e. g., sirens and webcams of fire departments, air traffic beacons, and other radio cell systems.

TABLE I. OVERVIEW OF PROJECT SITES

Site	Population	Pop. density (people per sq. km)	Time frame	Deployment	Types of Applications
Brandenburg an der Havel	72,100	320	2022-2024	12 gateways, 25 sensors	weather stations; people counter; water level
Rüdersdorf	15,500	228	2024	2 gateways, ~10 sensors	garbage can levels; water level; indoor temperature, humidity and movements
Michendorf	11,600	202	2023	2 gateways, 38 sensors	traffic counter; parking counter
Wiesenburg	4,900	19	2022-2024	4 gateways, 30 sensors	soil moisture; water level

Funding has been and is a crucial part of every project. Limited short-term funding is usually available, particularly for the procurement of sensors. Due to the way public budgets are planned, there is rarely a permanent funding option for LoRaWAN projects. These are often seen as one-off digitization or technology evaluation projects.

As part of these endeavors, we had frequent talks with all involved stakeholders, such as the municipal administrations, regional utilities, private network suppliers and end-users from other areas such as citizen science and climate initiatives. By accompanying and promoting these processes we learned not only that LoRaWAN projects tend to face similar difficulties in different places, but also that there are many similarities in the needs and capabilities of the stakeholders involved.

Analyzing and conflating these learnings led to the creation of an operational template for LoRaWAN infrastructure and services. This framework names the individual actors as well as their tasks, or responsibilities, in the process of establishing said infrastructure to meet all requirements of the participating stakeholders and especially the end-users.

Before laying out the collaboration framework, we provide a closer look at two of the projects from different perspectives, in order to illustrate our experiences:

A. *Project in Wiesenburg*

In Wiesenburg, we had the chance to accompany the establishment of LoRaWAN-Infrastructure and many of the strategic processes surrounding it. The initial deployment was driven by a citizen science project aimed at establishing a network of soil moisture measurement stations. Soon, the municipal administration and the office of the Smart City project which Wiesenburg shares with its neighboring municipality of Bad Belzig, saw the potential for cooperation. The municipal administration was interested in utilizing LoRaWAN-Sensors for counting visitors to the local castle and for monitoring water levels in fire ponds and wells. As we accompanied the strategic process, we learned about the challenges of elevating a community-driven network to the purpose of fulfilling statutory duties of the municipal administration, such as different requirements in terms of reliability and data storage. On the other hand, joining forces with the administration provided substantial benefits for the other parties, for example when looking for gateway locations and continuous infrastructure support. The project is still ongoing: The sensor network continues to expand, and different solutions for data storage and visualization are under development as of mid-2024.

B. *Project in Michendorf*

The Michendorf Project, launched in 2023, aimed to leverage LoRaWAN technology to enhance mobility and optimize public services. The project involved the deployment of 2 gateways and 38 sensors, specifically focusing on park sensors and traffic counting sensors. This section, more detailed than the last one, provides a comprehensive overview of the project's objectives, implementation strategies, costs and economic sustainability, the outcomes achieved and challenges encountered. It also discusses the sustainability implications of the project, including its economic sustainability and its contributions to long-term ecological and social benefits.

1) Objectives

The primary goal is to enhance mobility by improving local solutions through real-time monitoring and data analysis. This includes deploying traffic-counting sensors to collect data on various roadways, as well as implementing parking sensors to monitor the usage of the "Mitnahmebank", a local initiative aimed at optimizing public services. The “Mitnahmebank” service is intended to make it easier for people without a driver's license or their own car to reach the next district outside of bus times. Nineteen colorful benches have been placed near bus stops in the Michendorf municipal area and are clearly marked as “Mitnahmebank”. Anyone who needs a ride can select the desired district from the directional sign on the bench and then sit down. Passing cars traveling in that direction can stop, pick up the waiting person, and drop them off at a mutually agreed destination. Additionally, intuitive data visualization tools are employed to interpret and present the collected data. These tools ensure that the information is accessible and actionable for various stakeholders, including municipal authorities and citizens, facilitating informed and transparent decision-making and effective communication.

2) Implementation

Michendorf Project was executed in several phases, each focusing on a key aspect of implementation. Initially, detailed planning was conducted to identify optimal locations for gateway and sensor deployment, with coordination from local authorities to ensure necessary permissions and support were in place. The project team selected and configured the appropriate hardware, including gateways and sensors, which the municipality installed under the guidance of the university's technical team. To promote ecological sustainability, the devices were installed using existing structures wherever possible, minimizing environmental damage and preventing ecological disturbances. Once installed, the sensors began collecting data. This data was integrated into a central database for structured analysis. Data visualization tools were employed to transform the collected data into accessible and insightful visual representations. These tools facilitated informed decision-making for municipal authorities and ensured that citizens remained well-informed and engaged with the project's outcomes. The project's successful implementation provided enhanced decision-making capabilities to municipal authorities, improved infrastructure efficiency, and fostered community engagement by providing transparent access to the project's insights. By making data-driven decisions, this approach also promotes social sustainability by ensuring public resources are used efficiently and equitably.

3) Cost

The Implementing an IoT network using LoRaWAN technology involves several key cost components. The initial hardware costs include purchasing gateways and sensors, which are essential for data collection and transmission within the network. For this project, a total of 2 gateways and 38 sensors have been acquired. In addition to hardware, managing already connected IoT devices through platforms like The Things Network (TTN) incurs costs related to subscription or usage fees, particularly as the network grows to include more devices. Hosting a LoRaWAN Network Server (LNS) also adds financial considerations, encompassing server infrastructure expenses, such as hosting fees for cloud or physical servers, along with ongoing operational costs like maintenance, security, and technical support. Michendorf is now actively looking for an affordable hosted LoRaWAN Network Server (LNS).

LoRaWAN devices are designed to be energy-efficient, which can significantly reduce operational costs, especially when deployed in remote or hard-to-reach areas. The technology's long-range capabilities minimize the need for multiple gateways, further lowering infrastructure expenses. LoRaWAN networks are also highly scalable, allowing new devices to be added with minimal additional investment. This scalability ensures that costs remain aligned with network growth, supporting economic sustainability. Using an Internet of Things platform like The Things Network provides a set of open tools and resources for low-cost device management. This platform enables efficient network administration and reduces software expenses. If Michendorf can effectively leverage the low-cost, long-range, and scalable nature of LoRaWAN technology, while also securing affordable hosted LoRaWAN Network Server solutions and optimizing operational efficiencies, the implementation can achieve economic sustainability.

4) Results

In Michendorf project traffic data are collected and analyzed to gain a comprehensive understanding of the traffic in the street network. Traffic counting sensors monitor and record the number of pedestrians, two wheelers, cars, and heavy vehicles traveling on the street. These sensors are installed across various locations, including school zones, main thoroughfares, and bicycle areas. The traffic data can additionally be analyzed in relation to factors like school holidays, weather conditions, social events, and more. For example, Figure 1 illustrates the daily traffic data overview for street "Stückener Dorfstraße". The graph indicates that traffic counts were notably high on November 4th, due to the open house event at the fire station on this street, which attracted a large number of guests.

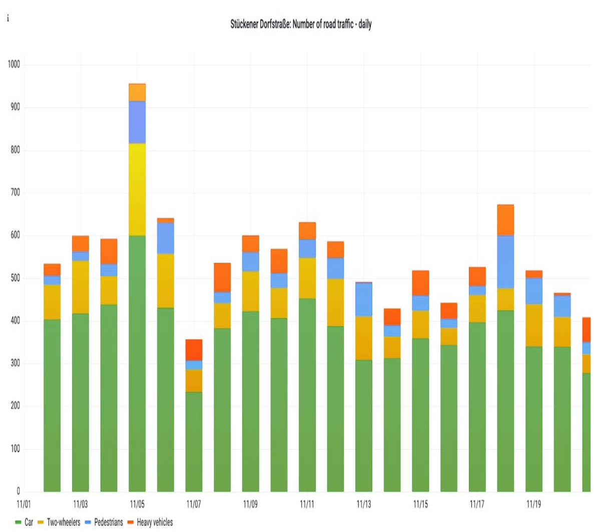

Figure 1. Daily traffic data for street: Stückener Dorfstraße

The use of park sensors helps to assess the efficiency of the "Mitnahmebank", enabling adjustments to enhance public services for the benefit of both citizens and local businesses. Figure 2 illustrates the frequency of use of the "Mitnahmebank".

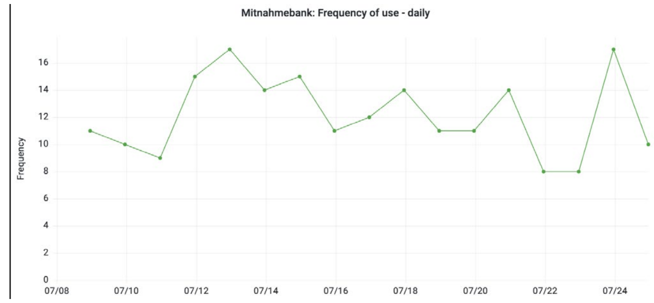

Figure 2. Mitnahmebank: Frequency of use - daily

5) Challenges

Challenges in the project included ensuring clear and continuous communication among all stakeholders, which was crucial for keeping the project on track: This required regular updates and meetings. Proper calibration of sensors was another significant challenge, as it was essential for obtaining accurate data. This necessitated meticulous attention during installation and regular maintenance checks. Additionally, managing large volumes of data and ensuring its accuracy and reliability was a significant challenge, requiring robust data management strategies.

IV. LoRaWAN Collaboration Framework (LCF)

The "LoRaWAN Collaboration Framework" (LCF) serves as a blueprint for effective stakeholder collaboration in the deployment and maintenance of sustainable LoRaWAN infrastructures for communities. It delineates the roles, responsibilities, and necessary capabilities for each participant, ensuring that all involved parties understand what is required of them and what they need from others. This clarity facilitates not only the identification of existing and potential contributors to the LoRaWAN ecosystem but also the establishment of seamless interfaces and partnerships. By highlighting specific needs and capabilities across stakeholders, the LCF aims to streamline operations, foster innovation, and enhance service delivery and citizen engagement within the realm of LoRaWAN-enabled services. Figure 2 illustrates the structure of the LCF and provides details on each role.

	Infrastructure		Application		
	Network operators and utility companies	Hosting and IT service providers	Start-ups, universities, and specialized IT companies	Administrations	End-users
Wants & Needs what stakeholders want and need	• Market expansion • New revenue streams and business models	• Stable contracts and partnerships • Maintainenance-friendly software components • Opportunities to showcase and deploy new technologies • Support by hardware and software vendors	• Evaluating cutting-edge technology • Funding for R&D or transfer projects • Partnerships • Visibility and recognition	• Education on technology options • Fast and efficient delivery of services to citizens • Enhanced citizen engagement and satisfaction • Limited Total Cost of Ownership (TCO) • User feedback on provided services	• Convenient access to municipal services • Intuitive interfaces and good user experience • Integration with other IT systems • Security features to protect user data and privacy • Regular updates and improvements
Capabilities what stakeholders are able to contribute to the LoRaWAN value chain	• Provide sites and connectivity for gateways • Operate the LoRaWAN Network Server (LNS) • On-site servicing of sensors (batteries, cleansing, replacement)	• Provide computing resources (hardware, software, virtual machines, and networks) • Install and configure standard software packages • Configure sensors • Backups & security • Customer support and training for municipal staff and end-users	• Build innovative prototypes • Find or build the right sensors for use cases • Develop custom software • Integrate custom data sources and platforms • Create machine learning models • Support and train end-users	• Problems / use cases • Provide sites for gateways • Deploy sensors • Budget or funding for public IT projects • Collaboration with private entities and other government agencies	• Problems / use cases • Give feedback on services

Figure 3. LoRaWAN Collaboration Framework (LCF) with stakeholders and their responsibilities within LoRaWAN projects.

A. Framework structure: Roles, needs and capabilities

The stakeholders are grouped by "infrastructure" and "application". The infrastructure group is mainly concerned with deployment, operation, and maintenance of the hardware, software, and networking infrastructure. The "application" group, which also includes the end-users, represents the rest of the value chain, including implementation and customization of software and data platforms, deployment of sensors and the provision of the actual use cases or problems to be solved. Each stakeholder group takes on a role in the LoRaWAN ecosystem. The interaction of all roles and the correct distribution of tasks is critical to the success of LoRaWAN projects.

To define each role, the framework is split into "wants and needs" (top row) and the "capabilities" (bottom row) of stakeholders. The wants and needs of one stakeholder group should correspond to the capabilities of another stakeholder group. This creates a balanced system of responsibilities that should make sure projects can be executed successfully. The roles are assigned to columns, which are ordered on a spectrum from technological necessities (left) to an end-user application (right).

By clearly defining the roles and interfaces, the LCF not only ensures that each stakeholder's capabilities are effectively utilized but also fosters a cooperative and dynamic ecosystem. The framework supports the strategic alignment of wants and needs with available capabilities, facilitating a balanced and effective collaboration. The stakeholder roles are briefly described in the following.

1) Network operators and utility companies: Network operators and utility companies are driven by goals of market expansion and the development of new revenue streams. These stakeholders are adept at providing sites and connectivity for gateways, managing LoRaWAN Network Servers (LNS), and conducting essential on-site maintenance such as battery replacement and cleansing of sensors.

2) Hosting and IT service providers: On the technological service front, hosting and IT service providers aim for stable, long-term contracts and opportunities to deploy emerging technologies for their customers. They provide vital capabilities such as the provisioning of computing resources, software installation, sensor configuration, and rigorous data security measures. Moreover, they can provide support and training for municipal staff and end-users, ensuring smooth operation and adoption of technologies.

3) Startups, universities, and specialized IT companies: In the innovation and research sector, startups, universities, and specialized IT companies are focused on evaluating and implementing cutting-edge technologies. These entities are key in building innovative prototypes, selecting or creating appropriate sensors for specific use cases, and developing customized software solutions. They can also handle the integration of custom data platforms and are instrumental in developing advanced machine learning models to support complex data analysis and decision-making processes based on the collected sensor data, e.g., for predictive maintenance applications.

4) Administrations: Administrative bodies concentrate on delivering efficient and enhanced services to citizens while maintaining cost-effectiveness. Their role includes defining clear use cases and overseeing sensor deployment. They might also secure locations for gateway installations. Their collaboration with private sectors and other government agencies is crucial for securing the necessary budget and support for public IT projects, which is essential for sustained technological advancement and community service enhancement.

5) End users): T End-users, crucial to the success of the whole LoRaWAN value chain, require easy access to municipal services via intuitive and potentially mobile-friendly user interfaces, seamless integration with existing IT systems, and robust security features to protect their data and privacy. Their ongoing feedback is instrumental in driving the continuous refinement and user-centered optimization of services.

B. Sharing and swapping responsibilities

Some capabilities in the LoRaWAN value chain can be provided by several stakeholders.

For example, providing sites for gateway installations might be a task a communal administration might want to contribute to in a project. However, ensuring long-term connectivity at the site via wired or wireless connections, having trained maintenance staff on standby in case of breakdowns, and having constant access to necessary equipment (lift trucks, spare parts, etc.) are things which network operators or utility companies have established processes for, resulting in lower cost and higher quality of service.

Another common example is the installation of affordable sensors by citizens configured on municipal or public LNS. The existence of tech-savvy communities and individuals can be considered a substantial benefit for any municipality or town. But it might jeopardize the long-term support of these sensors and by that, data quality. If administrations want to rely on the collected data, there must be some kind of alignment and trust between the two groups.

A last example illustrates another problem of voluntary work. When volunteers create custom data integration layers using Python or JavaScript, this "glue code" might not be documented as required, complicating maintenance and future extensions (e.g., a "temperature" attribute is added to the next sensor model). This also includes simple things like patch management and storage of access credentials.

The same goes for configuring dashboards, providing end-user training, integrating data sources, and creating machine learning models. All these tasks can be handled by different stakeholders with varying degrees of quality, cost, and availability. Initial interest in certain stages of the value chain by any one party does not guarantee that all the required tasks are fulfilled by the role. So, for a stable and sustainable operation, we recommend the responsibilities as componentsd in the LCF, or at most, one "column" away from the original stakeholder group.

In summary, although some capabilities might be taken over by another party than designated in the framework, generally, this hurts sustainability.

C. Business models

A solid business model is needed to sustain a LoRaWAN infrastructure and application ecosystem. The identified "wants and needs" indicate a demand in the market, while the "capabilities" are potential services which satisfy needs in one of the following elements of the value-chain.

1) Supply-side business models: One solution is renting out the network on a per-sensor and per-time basis, thus creating a very low barrier to market entry for customers and allowing for rapid adoption of the service. However, like free Wi-Fi, this might eventually become a commodity and network operators need to find other ways to generate revenue. Netwrok operations and suppliers can capitalize on existing infrastructures, such as data centers and network backbones, to gain a competitive edge. Additionally, revenue generation extends beyond network access fees to include value-added services like sensor commissioning. R&D stakeholders contribute by offering scientific and technical support, optimizing gateway placements, selecting appropriate sensors, and providing custom data integrations, visualizations, and project management, adding significant value to the LoRaWAN ecosystem. Value, of course, is understood differently by different stakeholders. When compared to commercial projects, public projects are rather focused on social and ecological sustainability. This might mean making it possible for citizens to participate in local decision-making like defining speed limits, deciding on the desired quality of air and water, increasing comfort with digital services, or improving public health and safety. In conclusion, the business model of the supply-side of municipal LoRaWAN projects today relies on forward-thinking administrations which actively seek to contribute to achieving the SDGs by using advanced technology like LoRaWAN. In the future, the collection of such data could become a legal requirement. Only then are more local authorities likely to look for joint operating models.

2) Demand-side business models: A shared operations model would be beneficial for small-scale deployments like the ones we described above. For example, a properly set-up LoRaWAN network server (LNS) can easily process data packages from several hundred gateways. Each gateway is technically capable of supporting thousands of LoRaWAN nodes, i.e., sensors and actuators. Sharing the infrastructure costs would therefore be an obvious way to achieve sustainable funding. The problem with this approach in a municipal setting is twofold. First, administrations need to align their demands and timing, and agree on a fair share of the (still) required funding. So, there is a cost for coordinating interested parties. Second, the infrastructure needs to be installed and administered in the partnering regions by the same operator. When these challenges can be overcome, e.g., by applying systematic project and stakeholder management and finding a way to align the diverse interests, there is potential for a low-cost infrastructure that benefits all the stakeholders and thereby provides a holistic societal value.

D. Decision making

The LoRaWAN Collaboration Framework gives an overview on the different stakeholders and roles required to operate a LoRaWAN infrastructure in rural municipalities or rural towns efficiently. In addition, some other questions arise in municipalities, for example, considering potential costs and benefits from a local LoRaWAN infrastructure before deciding to implement such an infrastructure. The following questions and arguments mainly refer to the presented different dimensions of sustainability in section II.

1) Is there a good balance on costs and benefits?: This question addresses economic sustainability: There are numerous different use cases on LoRAWAN technology already practiced, and a lot more may arrive in the future. Use cases can be found for example in the fields of smart cities & smart regions, energy and resource monitoring, disaster control and environmental data collections [17, 25]. To argue for an investment in LoRaWAN infrastructure with public funds in the logic of economic sustainability, one needs to take into account the number of use cases relevant for a region. A larger number of use cases can justify investment costs, in particular at the beginning. Due to that, many stakeholders like municipal utilities (municipal or district level), companies (e.g., waste collection companies, agricultural farms), the civil society (as fire departments, nature conservation groups) and similar stakeholders should be asked for their use cases. The more parties that will share the infrastructure and benefits, the easier a return of the investment can be reached.

2) Can the technology address relevant community problems?: This question relates to ecological and social sustainability: In addition to considerations on the balance of financial costs and benefits, another relevant focus is on benefits for the common good provided by the LoRaWAN infrastructure, which cannot be measured in financial terms. For example, if the technology helps to protect local buildings and citizen's lives due to improved disaster control or improved prediction and monitoring of extreme weather events, the financial costs for implementing it may be high.

3) Is the technology itself harmful for the environment?*:* Although LoRaWAN and sensor infrastructure are characterized by low energy consumption, it should not be overlooked that resources are required to build and operate them. Considerations on where the hardware is manufactured – and under what kind of working conditions – arise. It should also be noted that servers consume a lot of power, which should be taken into account as an invisible factor, although it is hard to meter [25]. These are arguments not to implement the technology if the expected normative value cannot compensate for these negative effects. In order to reduce the energy consumption, there are several viable steps that might be taken: For the case of the measuring sensors it is possible to operate the sensor kit with a solar or photovoltaic panel instead of a battery, and for the case of the servers it is possible to use server farms operation with power from renewable energies.

V. CONCLUSION

The proposed LoRaWAN Collaboration Framework provides a solid foundation for municipalities to successfully set up LoRaWAN projects. By following the framework, municipalities can search for and align with partners, knowing which responsibilities need to be covered by those partners. They now have proper criteria for selecting partners like hardware vendors, utilities, citizen science projects, and innovation leaders from higher education and start-up ecosystems.

A key finding from our projects was that collaboration is vital to successful LoRaWAN deployments in rural areas and small municipalities. Not only allows collaboration access to good practices, but it will also provide an opportunity to pool financial resources and use cases for an efficient acquisition of infrastructure and partners. While we were in the role of technical project management for all the projects, we learned that a more holistic approach is necessary to create a sustainable LoRaWAN deployment.

Further research needs to be done on the economic viability of the described business models. In particular, the shared operation models and its organizational and coordinative prerequisites as well as the proper involvement of citizen initiatives and individual volunteers.

According to the different dimensions of sustainability discussed in this paper, further questions arise for rural municipalities and towns to decide for or against the implementation of LoRaWAN infrastructures. Apart from measurable cost and benefit scenarios, there are also arguments that do not fit the financial cost perspective and some other arguments refer to partially not visible and measurable factors, which should be taken into account in a holistic view on sustainability.

A comprhensive analysis on the overall project outcomes is needed to validate that the ecological, economic, technical, and social objectives are in the desired balance. Because some sustainability dimensions are hard to measure, it must always be carefully weighed up which use cases can realistically make improvements and which are just greenwashed fig leaves. Further research on metering sustainability costs of IoT infrastructures are recommended to lower the remaining uncertainties.

ACKNOWLEDGMENT

This work was supported in part by the German Federal Ministry of Education and Research (grant code 13IHS230A) as part of the "Innovative Hochschule" project.

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