Beyond Connectivity: A Sustainable Approach to Municipal LoRaWAN Infrastructure and Services

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***Abstract*—Long-Range Wide-Area-Networks (LoRaWANs) are distinguished by their capability to support Internet of Things (IoT) applications, making it ideal for vast and sparsely populated areas. While technical features like security, scalability, and bandwidth have been examined in detail, forms of collaboration between stakeholders have yet to be explored. Hence, we introduce the LoRaWAN Collaboration Framework (LCF), a blueprint for deploying and managing LoRaWAN infrastructures with an emphasis on rural and small municipalities. 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, Information Technology (IT) service providers, application developers, and end-users. The framework emphasizes the balance of technological, economic, ecological, and social sustainability. We describe the experiences from several LoRaWAN projects in small towns and municipalities in Germany and the derived collaboration framework to provide a basis for similar projects.**

Keywords-LoRaWAN; Service delivery; collaboration; sustainability; smart city; infrastructure.

I. INTRODUCTION

Sustainability and efficient resource utilization is an indispensable reality of today's world. To meet these sustainability goals, a transformative shift towards advanced digital technologies is essential, emphasizing the role of digitalization in enhancing environmental, social, and economic outcomes. Cities may tackle this demand with the help of IoT technologies. 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 in rural areas.

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 [1]. This makes LoRaWAN particularly suitable for rural areas and regions with large areas and limited electrical energy, such as developing countries. The LoRa Alliance developed LoRaWAN specifications, whose basic modules are available as open-source software [2].

LoRaWAN is an enabler technology [3] that can not only help achieve the Sustainable Development Goals (SDGs) by measuring climate impacts, modal split, soil moisture, sealing, 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.

Although demand is growing, the construction, data integration, processing and visualization required for an end-to-end LoRaWAN use case can only be done by technical experts, and small cities and local governments cannot do it 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 municipalities 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 operate LoRaWANs in the long term.

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. Section IV describes the framework including the responsibilities of the various stakeholders and the organizational interfaces. 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. Nölting and Dembski found that digitalization, as a process, has no normative direction, but, in contrast, is governed by individual and organizational entities in accordance with their own goals [4]. Digitalization technologies, such as LoRaWAN provide many opportunities, which can or cannot be used in terms of sustainability in its diverse dimensions.

According to Farsi et al. [5], sustainability is important to maintain the basis for sustainability assessment. 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 the three dimensions of sustainability [6]: economic, environmental or ecological, and social sustainability. We also consider technological sustainability an important factor of sustainability and will discuss it as well.

A. *Technological sustainability*

Sustainability of technology in the past has been mostly focused on green IT, while more recent research, for example by Dao et al. [7], demonstrates a more holistic approach. For LoRaWAN projects, it means that the IT infrastructure can be used and maintained in the long term and does not require 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. A requirement for this is the availability of code and documentation under permissive licensing, as it is common for open-source software.

Technological sustainability 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. Adding metadata can increase data quality and allow the data to be used outside the original measurement context, e.g., to create dashboards to monitor and improve the SDGs at a local level.

B. *Economic sustainability*

Ikerd defines economic sustainability as scarcity, efficiency, and sovereignty [8]. 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 its 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. *Ecological sustainability*

Ecological sustainability refers to the reduction of consumption and pollution of natural resources and energy as they are exhaustible fundamentals of social and economic life, according to Beer et al. [9]. To preserve the (ecological) basis of living for future generations on earth is the core definition of sustainable development as defined by the United Nations [10]. LoRaWAN technology can be used for the protection of natural resources, for example in the field of environment data measurement. For example, solar panels can power remote gateways, reducing the system’s carbon footprint. Infrastructure can be installed in locations that minimize environmental disruption, using existing structures where possible to avoid additional land use and ecological disturbance.

D. *Social sustainability*

The last dimension of sustainability considers that social equity and cohesion are further indispensable for a sustainable development. Social sustainability refers to equal opportunities for “good living” and participation in the society for every individual [11]. About 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 local 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 [12]. The challenge for practitioners is to find integrated solutions to achieve these goals in a holistic way.

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 [13]. 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 et al., Campoverde and Yoo [14]. The contributions edited by Song et al. [15] 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. [16] found that smart city projects can be complex due to heterogenous technology (wireless transmission standards, sensors, software architecture), many different use cases, and the integration of data sources and sinks to make possible diverse digital services.

However, most of these findings are based on case studies in larger cities. No research 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 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 durations 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***
Brandenburg an der Havel	72,100	320	2022-2024	12 gateways, 25 sensors
Rüdersdorf	15,500	228	2024	2 gateways, ~10 sensors
Michendorf	11,600	202	2023	2 gateways, 38 sensors
Wiesenburg	4,900	19	2022-2024	4 gateways, 30 sensors

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.

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.

A. *Framework structure: Roles, needs and capabilities*

Fig. 1 illustrates the structure of the LCF and provides details on each role. 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 deals with the implementation and customization of software and data platforms, deployment of sensors, and the direct application of technology to solve practical community problems. Stakeholders take on at least one 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. This alignment ensures that the capabilities of one group meet the needs of another, facilitating a symbiotic relationship that enhances the efficiency and success of LoRaWAN projects.

By strategically aligning roles along a spectrum from technological infrastructure (left) to end-user applications (right), the LCF ensures effective utilization of each stakeholder’s capabilities, fostering cooperative dynamics across the ecosystem. This structured approach helps stakeholders like network operators serve multiple municipalities, which can share best practices and collaborate on common sustainability goals. The 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.

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

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, such as municipal digital officers in town halls, Smart City managers, and economic development teams, play a crucial role in ensuring the efficient and cost-effective delivery of enhanced community services. They handle strategic planning and governance, including defining use cases for technologies like LoRaWAN, overseeing the deployment of sensors, and determining locations for gateway installations. These officials are key in facilitating collaborations with the private sector and other government agencies to secure funding and support for public IT projects. By aligning such technological deployments with broader municipal goals, these bodies work to improve city operations and enhance services provided to citizens.

5) End users

End-users, crucial to the success of the whole LoRaWAN value chain, include individual citizens, local businesses, and public institutions. These users 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. For citizens, this might mean improved traffic management and waste collection services. Local businesses could utilize data from LoRaWAN sensors for optimizing operational efficiency and reducing costs. Public institutions might use the technology to enhance facility management and public safety. 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 defined 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.

Network operators 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 forwardthinking 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 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 administrated 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.

V. Conclusion

Our research aimed to determine whether there is an effective operating model for municipalities to implement LoRaWAN projects successfully. The proposed LoRaWAN Collaboration Framework provides a robust foundation by delineating roles and responsibilities, enabling municipalities to engage with suitable partners like hardware vendors, utilities, and innovators from academia and startups.

A crucial insight from our study is the essential role of collaboration in the successful deployment of LoRaWAN in rural and smaller municipalities. Collaboration not only facilitates access to best practices but also helps pool financial resources, optimizing the acquisition of necessary infrastructure and partners. Our experience in technical project management across these initiatives has underscored the need for a more holistic approach to ensure sustainable LoRaWAN deployment.

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

A comprehensive 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.

Acknowledgements

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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