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Mind the gap: The AURORAL ecosystem for the digital transformation of smart communities and rural areas

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ABSTRACT

Rural areas play a crucial role in addressing challenges related to climate change, food provision, biomass, and energy. At the same time, digital solutions have proven essential in improving safety, quality of life, and resilience in daily life. However, the lower population density and the lack of digital infrastructure in such rural areas make it difficult to develop technology-driven private businesses and public services. This can negatively impact socio-economic indicators and hinder the development of new services to cover peoples' needs. For this reason, in this document, we seek to provide a stronger focus on rural regions in digitalization efforts and create new opportunities for rural communities. For that, we analyze the barriers and needs of the rural environment and present AURORAL, a digital service platform designed to meet the needs and contexts of rural areas. This ecosystem, comprising sustainable and multi-interoperable apps and services, can help communities succeed in innovation and smart transformation, providing the necessary infrastructure to facilitate long-lasting social, environmental, and economic benefits by prioritizing openness, interoperability, and decentralization. On the principle that the full potential of these technologies can only be realized when they are integrated into societal and economic activity and organization, AURORAL aims to promote economic growth and digitalization in the rural domain and contribute to bridging the digital divide between rural and urban areas.

1. Introduction

Innovation and technological breakthroughs are changing how society is today, presenting new opportunities for business growth and delivering enhanced digital services. Traditionally, the focus on digitization and the creation of smart ecosystems has centered around urban areas. As a consequence, Smart Cities have emerged as environments that leverage data and technology to improve the quality of life for their residents, enabling a multitude of services and advancements. This includes implementing sensor networks to optimize traffic flow,

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adopting renewable energy sources for sustainable building operations, and ensuring high-speed internet access for all Sánchez-Corcuera et al. [1]. Nevertheless, while Smart Cities have gained considerable attention and witnessed rapid progress in various sectors such as transportation, e-government, education, healthcare, and Industry 4.0, this momentum has not been equally translated to rural areas Cunha et al. [2]. That is, the digitalization of rural communities has not kept pace with the urban ones, resulting in a growing disparity.

According to the European Union's (EU) definition, rural areas are characterized by regions outside urban clusters with a majority of the population residing in sparsely populated cells, typically with a density of fewer than 300 inhabitants per square kilometer Commission and Eurostat [3]. These areas face unique challenges compared to urban environments, such as lower population and business density, which make it difficult to foster private enterprises and public services that cater to their specific needs. As a result, the socio-economic development of rural areas is hindered, limiting their potential to create smart ecosystems that enhance residents' well-being Cowie et al. [4]. This growing disparity between rural and urban areas results in a digital divide, with limited access to contemporary Information and Communications Technology (ICT) solutions. Factors such as broadband access, digital literacy, and other technical aspects contribute to this divide Young [3]. Consequently, rural communities are often marginalized and left behind in the face of the profound structural changes associated with smart development initiatives Hosseini et al. [5]. At the same time, rural areas, known for their abundant natural resources, play a critical role in addressing global challenges such as climate change, food provision, biomass utilization, and energy-related issues. Thus, by leveraging their natural resources and adopting sustainable practices, rural communities can make significant contributions to tackling these challenges, being essential for the long-term health and resilience of the global environment and economy Anastasiou et al. [6]. Nonetheless, despite the importance of rural development, the EU has not yet achieved the desired level of progress in this regard Rey-Alvite and Fernandez-Crehuet [7].

To bridge this digital divide and address the unique needs of rural communities, the H2020 AURORAL project[2] has been initiated. Focusing on Europe, where, according to data from the European Rural Observatory,[3] predominantly rural areas account for 83% of the total territory and are home to 30% of the population, AURORAL aims to overcome the barriers and disparities between rural and urban areas. More particularly, it represents a collaborative effort involving multidisciplinary approaches to promote connected rural areas and enhance digital infrastructures and services within these communities. The goal is to create Smart Communities that recognize the vital role of individuals and organizations in driving economic prosperity while embracing innovative strategies to achieve sustainable growth.[4] That is, extending the concept of Smart Villages by adopting a more territorial and human-centric approach while leveraging technology and ICT to improve infrastructure and services Commission et al. [8].

Accordingly, in this paper, we present our vision of highly linked Smart Communities that harness the power of cutting-edge technology to meet the diverse needs of rural areas across five key domains: farming, mobility, energy, tourism, and health. Farming, being inherently aligned with the green and digital transformation of rural areas European Commission [9], is not the sole domain that contributes to fostering Smart Communities. Mobility is crucial for accessing vital services and logistics resources, particularly in spread-out rural communities, while also promoting sustainable transportation Viggiano [10]. Energy plays a critical role in establishing resilient and environmentally friendly practices, contributing to factors like climate change mitigation OECD [11]. Rural tourism offers new opportunities for local residents and acts as a catalyst for local economic growth and social change World Tourism Organization [12]. Additionally, healthcare is a vital domain in rural areas, presenting unique challenges in terms of access and service delivery, which must be addressed to prevent a digital divide that leaves certain groups or communities behind Cortelyou-Ward et al. [13].

Hence, we propose a comprehensive vision for the digitalization of the rural environment. This includes analyzing the barriers and needs specific to these areas and assessing the expected impact on the development of rural areas and the evaluation methods to be employed. This vision is supported by the introduction of the AURORAL architecture, which aims to establish a digital environment in these domains. This new digital enviroment encompasses intelligent objects and interoperable services that collaborate seamlessly, fostering dynamic rural ecosystems comprising innovation chains, applications, and services where users and institutions play a pivotal role. In this sense, we define the technical principles needed to create a digital ecosystem that stimulates the socio-economic and sustainable prosperity of diverse local rural communities and domains, adapting to their specific needs. These principles prioritize security and data governance, aiming to bridge the interoperability gap among various smart objects and ensure the safeguarding of user data and privacy within an open, sovereign, and independent digital environment. Overall, the contributions of this paper are twofold:

- The analysis of the challenges and enablers for rural areas' digital growth, including the value proposition of AURORAL and an assessment framework for evaluating the expected benefits and impacts of the proposed solution.
- The description a novel ecosystem for rural areas that supports a device and standard-independent open platform for digital infrastructures. This ecosystem ensures interoperability and adheres to principles of security, privacy, and data sovereignty in rural domains.

The paper is structured as follows. Section 2 reviews the barriers and challenges to rural sector digitalization and the importance of considering its particular context. Section 3 highlights the need for specific impact assessment frameworks, introducing the evaluation context of AURORAL and the foundation for the subsequent sections. Then. Section 4 presents the AURORAL architecture and Section 5 showcases the integrated services and their potential through use cases. Finally section 6 addresses the implications and gaps in digital transformation and how the presented approach aims to overcome them, while Section 7 provides conclusions and outlines future work.

2. Addressing digitalization challenges for smart communities

Rural areas have the potential to play a key role in the transition to a more sustainable and resilient future. However, despite offering numerous opportunities, they must also overcome structural and technological weaknesses to unleash this untapped potential. To address these issues, initiatives like the EU's Rural Action Plan aim to promote rural development. This plan focuses on promoting territorial cohesion, creating new opportunities, and improving infrastructure and services in rural regions, supporting sustainable agriculture and diversified economic activities [14]. A crucial aspect of this plan is, indeed, the utilization of digital tools and technologies to foster innovation and enhance service delivery in rural communities. Thereby enhancing their competitiveness and resilience across various sectors. Ultimately, these efforts empower rural Smart Communities with the necessary information, markets and tools to adapt themselves to evolving environmental and economic conditions.

For this reason, to fully leverage the benefits of digitization in rural areas, it is essential to understand the primary challenges associated

[2] https://www.auroral.eu/.
[3] https://observatory.rural-vision.europa.eu/.
[4] http://www.eu-smart.community/#/alentejo-protocol.

with this process and to implement targeted policies, measures, and approaches that specifically address their unique circumstances Feurich et al. [15]. Those include demographic challenges (i.e., depopulation and limited employment options), lack of connectivity, or inadequate access to essential infrastructure and services (e.g., healthcare, transportation, and education) AUGÈRE-GRANIER and McELDOWNEY [16]. Thus, addressing these challenges for driving digital advancements in sectors like energy Streimikiene et al. [17], mobility Mounce et al. [18], tourism Pan et al. [19], healthcare Buzza et al. [20], and agriculture Caffaro and Cavallo [21]; Sivertsson and Tell [22]. The barriers associated with each of those sectors in these previous works illustrate the unique needs for the digitization of rural areas, which encompass both technological and social factors. On the one hand, technological barriers arise from inadequate infrastructure and its limited cost-effectiveness, which increases the existence of a digital divide that hinders the creation of digital services in rural environments. On the other hand, social and demographic limitations contribute to these barriers by impacting the acceptance, adoption and integration of digital technologies in rural communities. Overcoming them requires comprehensive solutions that promote digital inclusion and foster a mindset shift towards embracing digital transformation in rural areas.

2.1. Technical aspects hindering digitalization in rural areas

A crucial aspect of digital inclusion in rural areas is infrastructure adaptation. However, it comes with numerous technical challenges, including technological limitations, logistical obstacles, and difficulties in establishing reliable connectivity in remote and sparsely populated regions. These challenges, as highlighted by Gerli et al. [23], impede the broader adoption of digital services in rural areas. That is, insufficient connectivity and underdeveloped infrastructure act as barriers to rural communities' economic and social development, making them a prerequisite for achieving a successful digital transformation de Clercq et al. [24]. For instance, the European rural observatory reports that only 44% of rural households have access to fast broadband internet, in contrast to the 87% availability in urban areas European Commission [9]. Indeed, this glaring connectivity disparity is one reason for the limited accessibility to digital services in rural regions Proietti et al. [25]. Addressing these accessibility challenges, particularly by enhancing networking infrastructure, becomes crucial in overcoming these disparities, as they have significant social and economic implications for rural communities Correa and Pavez [26].

Nonetheless, compared to urban areas, creating such infrastructures and targeting small-density zones decreases the cost-benefit ratio of providing new digital services and connectivity. By highlighting the value and attractiveness of offering services in rural regions, infrastructure development and connectivity acceleration can be fostered Dubois and Sielker [27]. Thus, digital service provision in rural areas requires suitable business models that consider the unique challenges and cost-benefit ratios of serving low-density zones Salemink et al. [28]. According to the Organization for Economic Co-operation and Development (OECD) OECD [29], by implementing strategies to improve rural service delivery, it becomes more enticing to invest in the necessary infrastructure and connectivity. This, in turn, accelerates the development of rural areas, bridging the digital divide and promoting equal opportunities for digital participation and economic growth.

2.2. Challenges in social and demographic context

The presence of the previous technical limitations leads to unequal opportunities, creating barriers to the adoption and acceptance of digital services in rural communities. As a result, the digitalization of rural areas becomes a social issue, as highlighted in the study by Zerrer and Sept [30]. This social issue is also influenced by the demographic composition of rural areas, particularly in Europe. To begin with, the population in rural areas of the EU tends to be older compared to urban areas, with a median age of 45.6 years. Also, only 23% of individuals aged 25–64 having tertiary education qualifications European Commission [9]. In addition to this, the EPSON report indicates that the EU faces significant demographic challenges, including a projected decline of 7.9 million people in predominantly rural regions by 2050 ESPON [31]. This population shrinkage can lead to imbalances in service supply and demand, scarcity of skilled labor, and decreased attractiveness of rural regions, perpetuating the disparities between urban and rural communities in terms of access to digital services, employment opportunities, and overall socio-economic development Malecki [32].

This "rural penalty" is exacerbated when basic digital skills are required to engage effectively with digital technologies and services. Unfortunately, rural areas face weakness in this regard, with only 48% of residents possessing basic digital skills, which is 14% lower than their urban counterparts (62%), as reported by EUROSAT [33]. The lower levels of education and older age demographics in rural communities are some of the reasons for the limited digital literacy and proficiency in these areas European Commission [9]. This lack of digital skills further increases the barriers to digital transformation in rural areas, hindering their ability to benefit from digital services and technologies. Moreover, fostering digital skills and literacy becomes crucial for promoting intergenerational social inclusion Robinson et al. [34]. Consequently, the social and demographic characteristics of rural areas influence the perceived attractiveness of these regions for investment in necessary infrastructures. Thus, it is vital to enhance interest, knowledge, and proficiency in digital skills and solutions, enabling rural citizens to engage with digital products and services, whether public or commercial in nature Gabrielli et al. [35].

Still, the adoption of digital technologies in rural areas is not only dependent on technology but also closely intertwined with trust and security concerns Jakku et al. [36]. Privacy and security concerns play a significant role in motivating rural actors to participate in digital transformation processes Degada et al. [37]. Furthermore, the primary threat to information security revolves around personal data and cybersecurity, despite the positive impact of the General Data Protection Regulation (GDPR). Insufficient digital skills create vulnerabilities, with the human factor often being the weakest link in cybersecurity Rahman et al. [38]. In this regard, enhancing digital literacy and providing educational resources can also bridge the gap between technology and trust.

Together with the previous challenges, understanding the impacts of digitization in rural areas is essential to understand their needs. The taxonomy developed by Ferrari et al. [39] provides valuable insights into these impacts, uncovering both anticipated and unexpected consequences. On the one hand, it is crucial to ensure that digital inclusion efforts accompany the adaptation to new markets to prevent any detrimental effects on traditional rural businesses Stojanova et al. [40]. On the other hand, the inclusion of new players from outside the community, who are unfamiliar and not physically present while offering new and uncommon services or goods, disrupts this trust dynamic Commission and for Informatics [41]. Finally, in addition to the challenges of trust and security, it is necessary to acknowledge the existence of legal barriers that can hinder the comprehensive and inclusive digital transformation of rural areas. Legislation, policies, regulations, and administrative restrictions vary significantly not only between countries but also within regions of the same country Martin [42]; Brunori et al. [43]. Addressing these legal barriers becomes vital for creating an enabling environment that supports the successful integration of digital technologies in rural communities.

2.3. Towards an integrated digital framework for rural areas

Based on the revised literature, it becomes apparent that promoting digitalization in rural areas necessitates addressing their unique contextual factors. Factors such as business opportunities, levels of digital skills, and trust in technology, among others, play a crucial role in

the successful definition of a digital framework Salemink et al. [28]. In fact, neglecting these factors when designing and implementing digital solutions can lead to inadequate policies that perpetuate social exclusion among vulnerable groups, such as older adults or individuals with low levels of digital literacy. Additionally, they may inadvertently impair local businesses, fostering dependence on digital providers who control both technologies and collected data Rolandi et al. [44]. Therefore, careful consideration needs to be given to these contextual factors when developing digital solutions for rural areas. This entails designing solutions that align with the specific business opportunities present in rural communities, while also considering the levels of digital skills and trust in technology among the local population.

Nonetheless, in addition to addressing the specific needs of the rural context, it is crucial to recognize and tackle broader technological challenges that extend beyond the scope of the rural sector. One common technological issue is the proprietary nature of many digital platforms, making integrating them with other platforms difficult. In the context of the rural sector and its limited digital resources, this can prevent the creation of enhanced service offerings that include a variety of standard services tailored to the needs of the rural ecosystem, such as mobility, logistics, or farming. To overcome this barrier, it is crucial to foster an environment where these services can be openly and equally shared. This calls for creating fair and trustworthy digital frameworks that facilitate seamless collaboration and cooperation among different platforms. By actively addressing these challenges, we can pave the way for the advancement and inclusive growth of digital platforms in the rural sector. For this reason, our work aims to contribute to this endeavor by considering the factors introduced throughout this section as insights to support the comprehensive and inclusive digital transformation of rural areas. In line with this objective, we propose an architecture that serves as a digital solution to contribute to creating new service ecosystems in these environments. By leveraging this architecture, we aim to empower rural areas with the necessary tools, resources, and infrastructure to promote a successful digital transformation, thereby promoting sustainable and resilient development.

3. Impact assessment for rural digital transformation

As introduced at the beginning of this paper, the main objective of the project in which this work is framed is to promote the digitalization of rural areas. Therefore, building upon the insights gained from the previous section, the AURORAL project aims to not only address the technological shortcomings but also improve access to digital services in rural areas considering their specific context and particularities. This involves the development of cross-sector digital service platforms that effectively match technology with the needs of people, ultimately driving the desired impacts on the different regions. To accomplish this objective, it adopts a comprehensive approach comprising two key components to understand better its adaptation to the different specificities: large-scale pilots in targeted domains and cross-domain demonstrators. The large-scale pilots are focused on specific domains, enabling higher readiness levels and a wider array of tools within those domains. Alternatively, cross-domain demonstrators leverage the tools and knowledge accumulated from the domain-oriented use cases, ensuring interoperability across different sectors. In the following sections, we will delve into the details of the AURORAL initiative, exploring how it envisions improved access to digital services in the participating regions and the evaluation and assessment framework designed to measure its impact.

The ecosystem of pilots and targeted domains conceived to asses this proposal is introduced in Fig. 1, which represents its distribution among regions. In particular, there are seven participating regions (Alentejo-Portugal, Hålogaland-Norway, Lapland-Finland, Penedès-Spain, Piedmont-Italy, Southern Burgenland-Austria and Västerbotten-Sweeden) in which eight different pilots are part of this digital transformation as the Norway region of Hålogaland is represented in two different pilots. Considering this number of pilots, 26 use cases were identified across the various domains represented in this distribution, focusing on associating the presented digital concept concerning different domains and evaluating its importance in rural areas.

Under this framework of domains, several use cases represent examples of how specific innovative solutions can enhance the provision of digital services, addressing each of the rural area's specific needs. Their

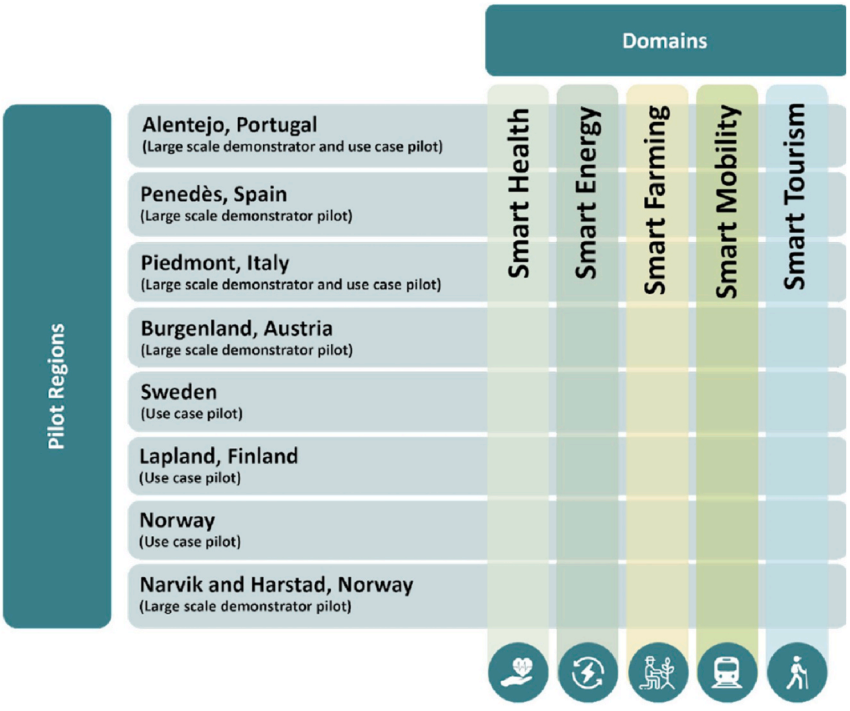

Fig. 1. AURORAL's ecosystem of pilot regions and (vertical) domains.

key features are the following:

- Smart Mobility. Integrate mobility offers into a digital platform, transport on-request, carsharing and bike sharing, or Intelligent communal logistic data system.
- Smart Energy. Agro-forestry residues valorization, Housing Energy retrofit, Zero emissions developments, renewable energy production or local energy communities.
- Smart tourism. Digital guiding system, virtual artistic performances/visits, booking and holiday planning, or promoting eco products and practices.
- Smart Farming. Local products acquisition, diary production management system, and livestock farming database.
- Smart Health. Autonomous drone transportation systems and remote healthcare and social assistance.

Nevertheless, in the same way, digital transformation requires considering the particularities of the rural sector, its impact can only be evaluated by addressing the needs and requirements of rural areas. For that, the first step is to define an Impact Measurement framework to accommodate those specific needs for the assessment of digitalization technologies in those environments. Under this context, the challenge is to adapt the existing impact frameworks of digitalization projects to rural areas, such as the regions taking part in the described AURORAL ecosystem. For this reason, the AURORAL impact measurement framework addresses the needs and requirements of rural areas. In this regard, Key Performance Indicators (KPIs) are essential for comparing initiatives that may appear dissimilar but are implemented in the same environment or with similar objectives. This is especially relevant considering the wide range of use cases that can be conceived for those areas, as the ones previously introduced. Nevertheless, defining and characterizing KPIs based on the objectives of the rural sector in different regions and domains can be challenging. To ensure proper identification and selection of KPIs, it is essential to establish general and specific taxonomies, including hierarchy, dimensions, and layers encompassing them. The one proposed for this KPIs assessment framework is included in Fig. 2.

The first criterion of definition and readiness of KPIs is associated with whether the KPIs apply to a certain vertical domain or several/all of them. To address this, as has been introduced, the AURORAL project has identified five different dimensions or domains, including energy, tourism, mobility, health, and farming. Some KPIs can be applied across all dimensions, while others are specific to one or a few dimensions due to their objectives or particular characteristics. Therefore, the taxonomy distinguishes between cross-domain and domain-specific KPIs. On the one hand, cross-domain KPIs are flexible and adaptable, allowing for comparison between different pilot sites and regions. On the other hand, domain-specific KPIs consider the use case objectives, business stakeholders, and technologies of interest, proposing specific KPIs for each domain. KPIs can also be assessed at the region, regional demonstrator, or platform performance level to consider the scale of those indicators' impact.

In addition, three dimensions associated with key sustainable development principles (economic, social, and environmental) were identified as KPIs characterization criteria. Those principal dimensions can be found in Fig. 3. First, the economic dimension evaluates the business efficiency of each pilot proposition and contains indicators related to the economic benefit of different operational scenarios in the rural sector. For example, a use-case to increase the use of data-driven agriculture techniques may be evaluated regarding the cost savings achieved by reducing the amount of water, fertilizer, or pesticides used. The environmental dimension focuses on evaluating impacts on the surrounding environment and using natural resources, contributing to identifying areas where improvements can be made to promote sustainability. That is, a use-case aimed at promoting sustainable energy practices could be evaluated in terms of the reduction of CO2 emissions or the increase in the percentage of renewable energy sources used in the region. Finally, the social dimension is important for evaluating the impact of pilot propositions on various stakeholders within the rural sector, including tourists and residents. Hence, a pilot to promote rural tourism by providing online services for suggestions on eco-friendly transportation or connecting to local cultural heritage sites may be evaluated in terms of the number of tourists who engage with sustainable tourism practices to preserve local ecosystems and cultural

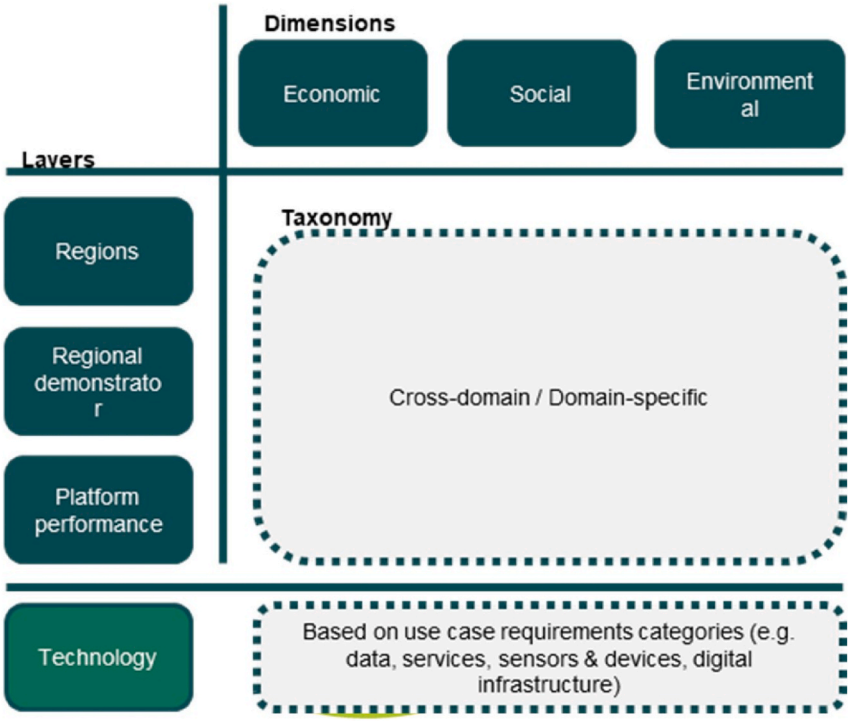

Fig. 2. KPIs assessment framework.

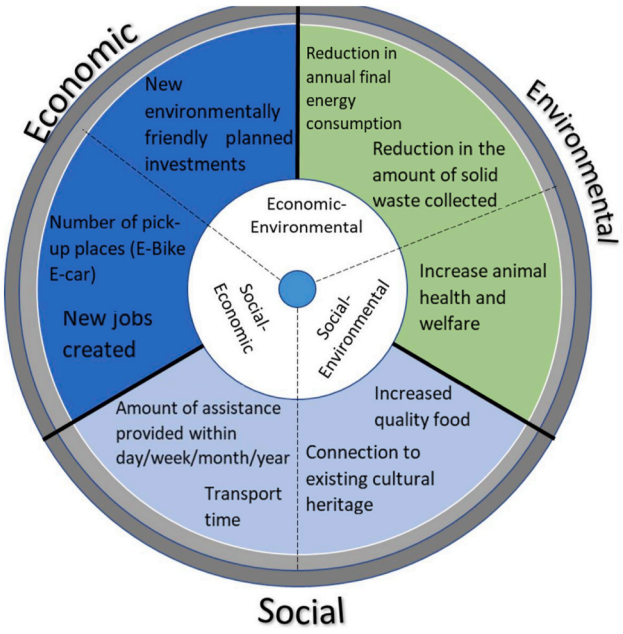

Fig. 3. Matrix with types of KPIs according to each layer and dimension.

heritage.

In summary, the AURORAL approach and its evaluation framework aim to implement transformative strategies and processes that enable rural ecosystems to leverage the potential of digitization for their resources, products, and services. Under this context, the success of the proposed ecosystem needs to be evaluated based on the specific objectives of the rural sector in different regions and domains, with the ultimate goal of empowering them to take advantage of digital opportunities. To achieve this, the described evaluation framework assesses the impact of tools and services on the performance of stakeholders, focusing on promoting economic development, social equity, and improved quality of life. Those tools and services will be explained in the remaining of this work.

4. The AURORAL proposal

To bring advanced technology to rural areas, we require a solution to connect diverse data types and empower technology and service providers to drive digital transformation. This is where our proposal comes in. AURORAL offers solutions that contribute to making services and technology easily integrated, reducing the barriers and costs associated with adopting technology in rural communities. Nonetheless, it is crucial to prioritize certain principles that address the unique social challenges and requirements of these regions. Hence, such a solution must foster inclusivity, trustworthiness, and user-friendliness for capacity building and digital literacy. From a technical perspective, those challenges translate into a solution that promotes interoperability to prevent fragmentation and favour this inclusion, ensures security and privacy to build trust, and empowers users with easy control over their data to encourage its adoption. By aligning with these principles, we seek to facilitate the transformation of rural areas, fostering their growth, competitiveness, and socio-economic well-being. Therefore, in the remainder of this section, we will present the relevance of those principles in detail. Then, we will introduce our proposal for a digital platform for facilitating the digital transformation journey of rural areas.

4.1. Key principles for a secure and interoperable digitalization

As has been introduced, the principles of interoperability, security, privacy, and data sovereignty are essential components in the development of innovative digital rural ecosystems.

First, interoperability is crucial for rural ecosystems to prevent application silos and reduce the cost of creating service infrastructures from scratch Barnaghi et al. [45]. In the context of digitalizing rural areas, the lack of interoperability, standards, and collaborative frameworks poses a common challenge that hinders the effectiveness of digital transformation efforts. Interoperability between platforms, sensors, and data analysis tools is crucial for maximizing the potential of advanced digital technologies and increasing productivity sustainably Klingenberg et al. [46]. Therefore, prioritizing interoperability principles such as openness, transparency, reusability, and technological neutrality, becomes necessary to enable the integration of different services and the gap between smart object platforms, fostering digital innovation and enabling new business opportunities Kouroubali and Katehakis [47]. Hence, interoperability creates new opportunities in rural areas and reduces cost-benefit barriers, allowing easier development of innovative digital solutions. In other words, the benefit of incorporating interoperability is preventing fragmented markets and improving user experiences, leading to increased adoption and participation from rural communities. This way, by addressing interoperability challenges through interoperability-by-design Charalabidis et al. [48] and adopting open standards, secure and trustful interactions can be promoted while allowing local entities to participate in online marketplaces. Under this context, we must ensure that all infrastructures or services connected to a digital system can adapt to the network and communicate in a common way and language.

Once a common language is agreed upon, establishing a shared communication network becomes crucial to facilitate interactions among users and organizations within the ecosystem. However, the interconnected nature of the digital environment brings forth additional challenges that need to be addressed. Indeed, traditional Internet of Things (IoT) architectures often adopt a hierarchical or centralistic approach, which may not be suitable for open communities with multiple stakeholders, diverse data owners, and various applications, especially in rural areas Noaman et al. [49]. Thus, alongside interoperability, it is essential to prioritize security and privacy considerations to alleviate concerns regarding privacy violations, data protection, and data misuse, which are particularly relevant in rural areas Deep et al. [50]. By incorporating mechanisms that guarantee security and privacy, we can ensure the integrity of the information created, transmitted, received, or maintained within the ecosystem. For that, it becomes imperative to specify components that enable identity-based control and access to data and services, thereby enhancing the overall security and privacy of the system Alanzi and Alkhatib [51]. This approach fosters trust among users and mitigates risks associated with data breaches that could prevent rural areas from confidently embracing and benefiting from digital services.

In this line, the notion of data sovereignty holds significant importance in the digitalization of rural areas. It involves crucial considerations such as determining which data should be collected and shared or understanding the associated benefits and recipients when sharing this data Jakku et al. [36]. Hence, it becomes essential to empower users to actively and independently control the utilization of their data Hummel et al. [52]. So, users participating in a digital ecosystem must have the ability to control, manage, and set the visibility and status of their objects, services and personal information, ensuring consent and clear rules for data storage, use, and privacy Karale [53]. This recognizes the need for fair solutions that emphasize democracy among actors participating in a digital ecosystem. Additionally, openness and transparency regarding data management become essential for building trust and facilitating data-sharing agreements among different parties Kranz [54]; Khan et al. [55]. Compliance with relevant legal and regulatory requirements, such as the GDPR, further enhances transparency, reliability, and governance concerning data security and sovereignty Voigt and Von dem Bussche [56]. This approach empowers rural users and strengthens their data control and promotes their interests in

cross-cutting services, ultimately safeguarding their rights, protecting their privacy and improving their trust.

4.2. The AURORAL architecture

The AURORAL system has been specifically designed to enable the seamless connection of different physical objects, data sources and services. By incorporating the key design principles previously explained, this system aims to address the challenges of rural digitalization and deliver substantial benefits to rural Smart Communities. For that, this architecture comprises two main components: the Node and the Middleware/Cloud. Thanks to these components, it can be described as a decentralized network of nodes that interact among them coordinated by the cloud, as shown in Fig. 4. Those components are responsible for the main functionality and information exchange within the system. Furthermore, they allow accessing to common tools offered by the platform.

On the one hand, the nodes are gateways owned and managed by users, facilitating the integration of IoT devices and services into the network. That is, their role in the architecture is to provide functionality to integrate data and communicate with other nodes in the platform. For that reason, the Node plays a crucial role in connecting local infrastructures and enabling interaction with other stakeholders that are also participating in the platform. Thanks to the nodes, the architecture follows a decentralized and distributed approach, in which IoT objects and services can interact with each other without the need for a central authority. This decentralized approach enhances scalability, autonomy, and resilience in rural environments, enabling users to share data and leverage value-added services easily. On the other hand, the Middleware/Cloud serves as the management entity for these interactions. It acts as a user interface, known as the "Neighbourhood Manager," providing users with a convenient and easy way to configure their accounts, access their assets, and find other users (also connected through their nodes) for potential collaboration. Besides, this part of the system ensures the security of the decentralized network and protects user data during communication. For that, it incorporates Distributed Ledger Technology (DLT) as a network layer, providing an additional level of data access authorization and verification based on the access rules defined by users.

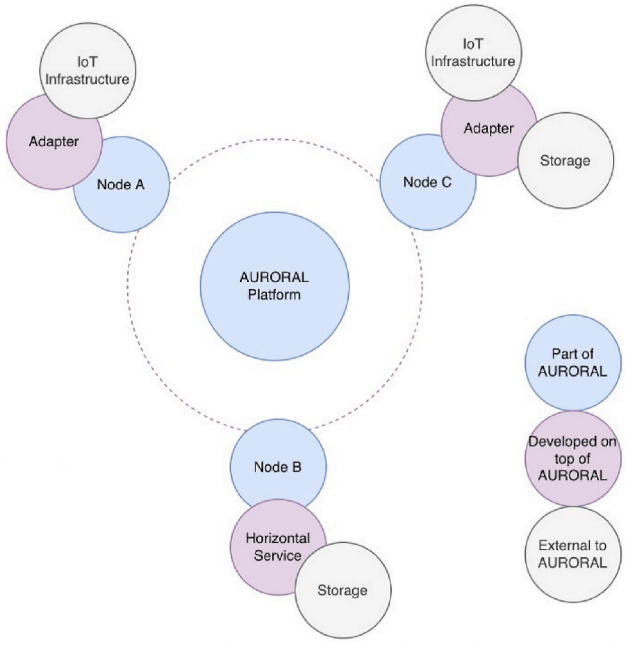

Fig. 4. The AURORAL network is composed of nodes that can interact among them.

In other words, together, the nodes and the cloud configure the AURORAL data interoperability platform, allowing for the integration of heterogeneous infrastructures owned by different stakeholders. Fig. 5 illustrates how this proposal can be applied in different ecosystems. For instance, an intelligent farm (actor 1) and a smart logistics system (actor 2) can each operate their specific services, devices, or virtual instances (digital twins) that can be integrated into the system through the Node and the adapter. This adapter is, indeed, a key piece in this architecture as it transforms different data sources into a common format that all devices and services can understand Cimmino et al. [57]). This way, the Node serves as the entry point to the system, enabling communication across the network and accessing data from remote IoT devices or objects based on privacy and visibility preferences set and managed by the Cloud. From the point of view of each of the actors, once this integration is done, they can establish data-sharing agreements and collaborate in various ways while accessing common horizontal services or marketplaces to enable new business opportunities. This way, in the context of this example, they can streamline their operations to improve efficiency in the agricultural supply chain. For instance, the intelligent farm could benefit from optimized logistics processes, enabling the timely delivery of products and reducing transportation costs. Simultaneously, the smart logistics system could also leverage real-time agricultural data to optimize its transportation routes, ensuring the freshness and quality of products.

This previous scenario illustrates the potential of creating a common ecosystem that efficiently connects different stakeholders. But to foster this digital innovation, the functionalities of the Node and the Middleware/Cloud need to be aligned with the addressed principles of openness, interoperability, security, privacy, and data sovereignty. In this sense, this system relies on shared standards and collaborative frameworks to support semantic interoperability and open data. The system promotes this through open Aplication Programing Interfaces (APIs) and standard vocabularies proposed by organizations like ETSI[5] or the World Wide Web Consortium (W3C).[6] These open standards, combined with the adapter and the created AURORAL ontology for representing data and concepts,[7] ensure that devices and services can understand and communicate with each other, overcoming language or protocol differences. In this sense, the platform's interoperability and open standards foster collaboration and partnership regardless of the actors' infrastructure, creating new opportunities for new digital services targeting rural communities. Additionally, this solution guarantees that none of the information generated by connected infrastructures is stored without the owner's consent, thus enabling users to maintain control over their sensitive data. Within this framework, users are empowered to establish rules and criteria for data usage, including restrictions on viewing, transmission, and data combination, thereby ensuring their consent and privacy. On top of that, the decentralized architecture and incorporation of the DLT network provide trustworthiness and security. The system also guarantees that users and organizations maintain ownership and control over their data and registered objects, reinforcing the principles of data sovereignty. These combined features create a secure and reliable ecosystem for Smart Communities.

Overall, this solution effectively addresses the challenges and barriers of digitalization in rural areas by prioritizing security, privacy, and data control. With its user-friendly design and emphasis on easy integration of services, the platform eliminates the need to create solutions from scratch, making technology readily accessible and reducing barriers and costs associated with technology adoption in rural communities. As a result, it not only fosters trust, encourages active participation, and promotes responsible data utilization, but also

[5] https://www.etsi.org/.
[6] https://www.w3.org/.
[7] https://auroral.iot.linkeddata.es/.

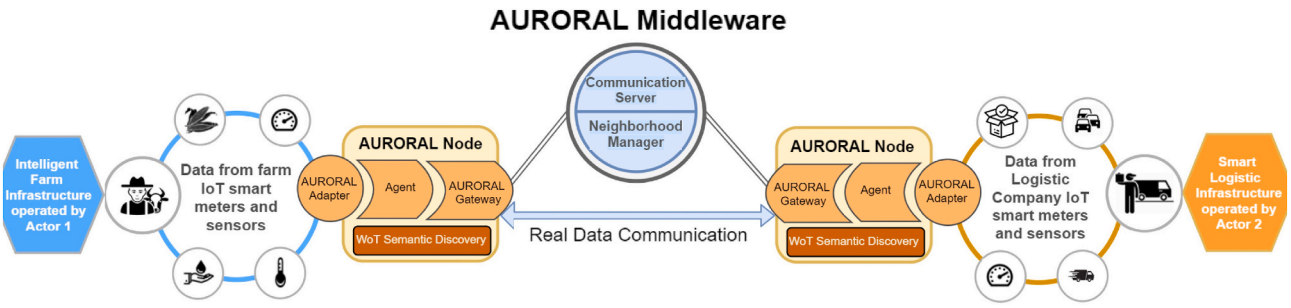

Fig. 5. AURORAL concept and functionality between two ecosystems.

empowers rural regions to shape their digital future and drive inclusive growth through customizable services and support for local development initiatives. Further details on the technical aspects of the solution can be found in the AURORAL documentation[8]

5. A digital ecosystem for services and marketplaces

To support the envisaged digital ecosystem and bring real value to the Smart communities, AURORAL needs to tackle the orchestration of a plethora of multi-owner horizontal and vertical building blocks. This means tackling both sector-agnostic and specific functionalities to deliver next-generation rural apps and services over which multi-stakeholder business models can be approached. On the one hand, this means providing sophisticated horizontal services that are sector-independent digital services (such as Data Analytics, data processing pipelines, process optimization, and monitoring) to external technology and application providers to obtain insights from rural ecosystem data, including new online marketplaces. On the other hand, the AURORAL reference architecture aims to facilitate the integration of specific rural-oriented vertical tools and services to meet AURORAL and rural context requirements from a variety of rural domains (e.g., farming mobility, energy, tourism, and health).

Horizontal services that are expected to be offered in the platform have significant importance on the usefulness of the entire system. In addition to that, vertical services deploy commodity services to share knowledge, experience and solutions, allowing different stakeholders to cooperate seamlessly and transparently. The presented ecosystem is designed so that any node can exchange data with any other (data source to service or service to service), provided that the appropriate permissions are in place (same organization, contract, etc.). These controlled-data exchange capabilities are one of the strengths of AURORAL. Within this environment, the services can flourish, and leverage the fact that the data integrated into the system should follow the AURORAL data models and be highly interoperable and reusable. In this way, a vertical service created for farm A, for example, could be reused by a hypothetical farm B, if farm B registers all its sensors and data sources using an adapter and Node. In addition, regarding cross-cutting or horizontal services, the interoperability concept recognizes and supports several interoperability layers allowing the utilization of horizontal services for several heterogeneous users and applications.

Hence, AURORAL horizontal services and tools, together with the Vertical services, could be considered as the part of the system that gives meaning to the ecosystem, adding value to several cross-domains in multiple rural areas. To illustrate it, this subsection introduces the use case and demonstrator of a particular digital platform called oHA, which is integrated as a service into the Cloud and provides a solution in different domains. Nevertheless, the final goal of implementing such services is supporting open collections of digital services where 3rd party providers can offer their services to different rural domains. Thus, this section also introduces the AURORAL Services Store, conceived for service/application providers to offer their tools and create a match between the needs of the rural areas and the existing solutions, making services, such as oHA, easily accessible by developers, service providers and user communities.

5.1. Services & tools: the oHA use case

The platform oHA is one of the cross-horizontal services that are integrated and that takes advantage of the AURORAL middleware. In particular, oHA covers and improves domains such as tourism, public service, mobility, and energy. For that, it provides a bundle of digital services for end users like tourists or inhabitants. These are available, for example, in the form of a web app that contains services like booking and payment, information, mobility, navigation or IoT, which are accessible in AURORAL as white label oHA instances and/or widgets for websites, suitable for all kinds of organizations like tourist service

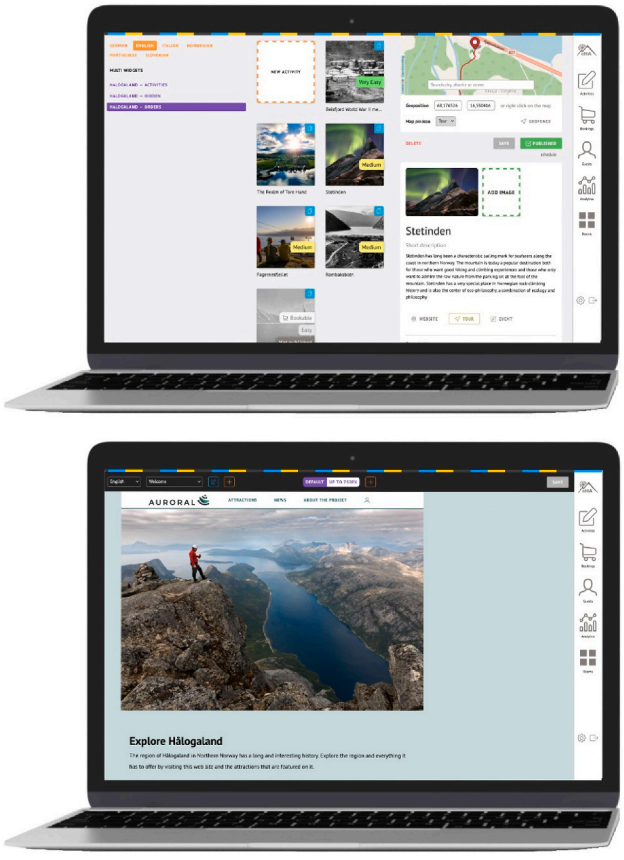

Fig. 6. Graphical visualization of oHA Base managing tool for the web app oHA. Copyright and resources: halogalandattractions.myoha.net.

[8] https://auroral.docs.bavenir.eu.

providers, local businesses, or municipalities, as Fig. 6 illustrates. In this regard, organizations get access to oHA Base, which is the management tool for oHA instances. oHA Base consists of a web app editor like established website builders[9,10] but with the distinction that web apps with several cross-domain services can be built there. Thus, a wide-ranging process coverage, e.g. in the tourism domain from destination management till management for accommodation providers, can be established. On top, user behavior statistics are provided, for example, to distinguish best-selling from non-selling products and services.

5.1.1. Integration with AURORAL ecosystem

Thanks to oHA capabilities, the creation of local Smart Communities based on the AURORAL concept is enabled. These communities rely on horizontal and vertical smart services, integrating data from oHA into the AURORAL Middleware. By doing so, this facilitates cross-cutting services in different domains, where data and services are shared between oHA instances and with third-party services via a standardized API which is accessible from the Middleware. This way, one of its notable advantages is its ability to foster an open ecosystem for applications and innovations.

The integration of oHA with AURORAL creates an open ecosystem for applications and innovations in various domains that require, for example, location-based information such as events or tours with GPS coordinates. This allows data and services from oHA to be accessible across communities and beyond. For instance, in the tourism domain, an oHA instance can integrate mobility services from the Cloud, such as e-car sharing, e-bike sharing, and shuttle services for tourists and inhabitants. Different third-party services, such as a different e-bike sharing service, can also be integrated. For this integration, the AURORAL Tourism Ontology[11] was defined, which includes the definition of classes and properties which specify how tourism data looks like in the Middleware. Therefore data like tours, events, or touristic activities are specified. Following the interoperability principles, this makes these data accessible to other stakeholders or service providers participating in the AURORAL ecosystem.

In the following, the applicability of this approach in different domains will be explained in more detail.

5.1.2. The oHA use-case for different domains

One of the core purposes of the digital platform and web app oHA is the tourism domain and the support of tourism service providers. In this sector, oHA serves as a destination management system and guest portal for accommodation providers that cover a variety of services (reservation, booking of activities and products, digital guest cards, GPS navigation, push notification, PDF news, time planning, recommendations, car-sharing, organization of childcare, IoT, tourist information and many more) for end users. For instance, to extend the tourism services in oHA, providers of it can create storytelling tours with a digital outdoor guiding system in oHA Base. This service allows uploading GPX files and self-creation of touristic tours with live navigation via GPS for end users, e.g., tourists or inhabitants. Along these tours, pins for activities can be set in oHA Base to highlight sights and attractions. When using the service in navigation mode, pop-up alerts notify the end users about informative content in the form of images, texts, videos, audio files, or bookable products and services, related to a particular attraction. Optional, the individual attractions can be hidden from the end-user on the map on the tour to provide a better storytelling experience. Only if an end-user is near a set radius around such a hidden activity and pin, a pop-up alert appears, and the end-user is able to view the particular part of the story, which is an activity in oHA. This service also provides end-users with daily touristic and relevant information about the Smart Community and the particular region. This is beneficial for rural areas to guide end users to specific attractions and to enhance their promotion.

Moreover, together with its role in the tourism sector, the digital platform and web app oHA also offers valuable support in the public sector. Municipalities can leverage this service to provide tailored, smart digital public services to their communities. In this sense, in the public sector, municipalities can use oHA to provide a regional web app for their inhabitants and Smart Communities with tailored, smart digital public services like digital information from the whole region and municipality, bookable local products or services, provided by the municipality or from local companies, arrangement of appointments with local authorities based on actual availabilities, news with notifications, or waste management. An example of those, which will be related to the different rural domains represented in AURORAL, is showcased in Fig. 7.

In this regard, due to its high interoperability, oHA instances can be enriched from different instances, where one of them contains, for example, a car-sharing service from the mobility domain. Thus, as explained before, particular services like this one can be accessible for tourists and inhabitants from a different oHA instance or the AURORAL Middleware. All the different services are then bundled in one app. In the particular case of car-sharing, this contributes and supports the potential needs in the mobility domain thanks to its integration with ZEMTU[12] and CARUSO.[13] Thus, together with other external mobility services integrated through the Middleware, the web app oHA provides end users with a bundle of bookable and available mobility services from a region. In this line, mobility providers can also control their fleets and customize their services individually, based on available contingents and needed constraints. Finally, the versatility for different domains is also represented in the potential capabilities of the presented service for the energy domain and their energy communities, which are often part of municipalities. This includes measuring energy consumption or production and statistics on energy community data, as well as an instructive visualization, which can be provided by this horizontal service. Therefore, energy services can be regionally integrated and promoted. For example, oHA is capable of, by using AI integration, to identify the best times to charge e-cars and thus improve mobility services.

This way, those examples demonstrate the business benefits of having an infrastructure ready to host such services. The cross-cutting service and tool oHA is used for specific pilot use cases in the mentioned domains. Furthermore, municipalities can enhance their service offerings, regarding the needs of both tourists and local inhabitants. For instance, end-users can utilize digital public services or directly order local products from regional providers. Following the previous examples, users could rent e-bikes or navigate through tours, and then directly order local products from regional providers or book a ride using a local shuttle service. This way, it serves as a digital marketplace for bookable products and experiences, providing a platform and customer portal where regional businesses can showcase their offers. Distinct from the AURORAL marketplace, which will be explained later, the oHA marketplace offers services specific to different web app instances, such as for a municipality, a hotel, or a region. Each instance can be customized to meet the specific design and purpose requirements of local providers. Bookable products are available in the AURORAL Middleware, which enables third-party apps to utilize data and services from oHA, like the booking and payment process.

Overall, the versatility of the oHA approach extends its applicability to various domains, offering immense value and benefits across different sectors.

[9] https://www.jimdo.com.
[10] https://squarespace.com.
[11] https://auroral.iot.linkeddata.es/def/tour/index.html.
[12] https://www.zemtu.com.
[13] https://www.carusocarsharing.com.

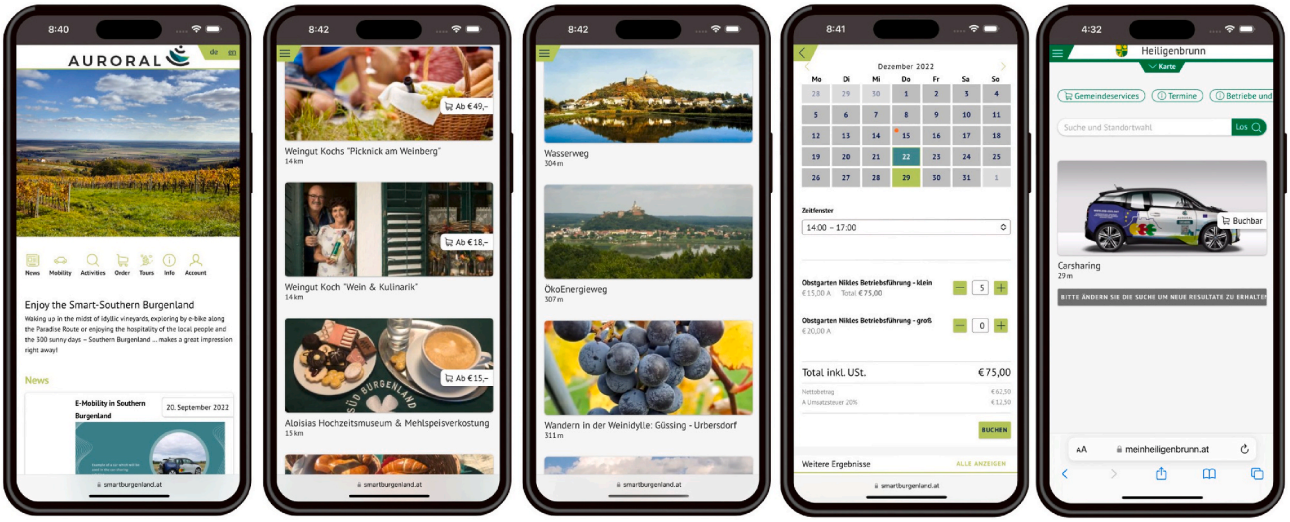

Fig. 7. Graphical visualization of the oHA web app with bookable tourists' services, products and experiences, and the car-sharing service. Copyright and resources: smartburgenland. at, myerlebnisparadies. at, halogalandattractions.myoha.net.

5.2. The AURORAL Service Store

The Service Store[14] is an extension integrated into the AURORAL middleware with the sole purpose of acting as a search engine for available applications in the ecosystem. In it, users can easily identify applications that positively impact their activities and infrastructures. That is, the Service Store is a simple application that displays a list of available services in the form of a catalogue. From the user side, it corresponds to a publicly accessible web page that provides a comprehensive list of the available services, which can be easily searched and filtered based on the user's specific needs. The filters categorize and describe each service, making it easy for the users. This platform is designed to be user-friendly and accessible to anyone, regardless of their technical expertise or familiarity with digital platforms.

In terms of its integration with the middleware, this application is designed to communicate with the ecosystem of integrated services by means of the communities, which are partnership spaces created in the Neighbourhood Manager. The retrieval of existing services in the nodes participating in the community is done by specific and standardized discovery queries (SPARQL query) to each community, which in turn queries all its underlying nodes and requests the metadata that describes the services.

Each service provider has full control over the information of their service. For that, several needs should be covered in the context of its integration into the AURORAL solution to fulfil the described functionality, both functional and non-functional. On the one hand, to make this information available, a mandatory requirement is that the Service Store should allow automatically discovering and displaying of all the services integrated into AURORAL from the catalogue, such as the previous oHA service. A search engine is deployed for the discovery of services. Besides, services should be made publicly available so that they can be consulted by any user accessing the Service Store. On the other hand, specific requirements and aspects should be taken into account to fulfil the addressed AURORAL's principles for interoperability, security, data sovereignty, and transparency, described at the beginning of Section 4. Thus, following the definition of the proposed ecosystem, the Service Store needs to be integrated into the AURORAL node, the entry point to the overall architecture. Then, now as part of this ecosystem, it must respect the privacy policies, which entails that data should not be stored in any part of the Service Store. In the same line, clear management of the consent to process service description data and its public visibility is implemented so that every third-party service owner has the right to decide whether they can make their services discoverable or not, aligning it with the idea of data sovereignty. On top of that, a security layer for communication to the Service Store is also implemented using specific web protocols for access to the web, exposing the Service Store.

Finally, accessibility is key for the final end-users. Thus, a user-friendly graphic interface that complies with AURORAL's visual identity is conceived with this purpose. This interface is included in Fig. 8. As can be observed, it presents a set of filters that have been defined to help users find the right service according to their needs. These filters represent the information according to the AURORAL Ontology[15] to represent information in a common format Poveda-Villalón et al. [58]. Thanks to this, the Service Store is able to "talk" to other systems in the AURORAL network and share information in a common format, which is needed to make the Service Store interoperable with the services integrated into AURORAL and, by means of this, facilitating users to find all the information of the services they may need.

5.2.1. The AURORAL marketplace

The presented ecosystem enables participation in a dynamic online marketplace where commodities services and online platform operators are involved. Thus, as a part of the AURORAL ecosystem, the Marketplace is devised to promote local citizens and entities' cooperation and cohesion by contributing to the digitalization of common farm markets while promoting rural communities (or any organized communities) to participate in the exchange, sale, or trading of their resources. So, the marketplace and its accompanying services are part of the architecture and allow easy service interaction and exchange across multiple domains. For this reason, the same principles intrinsic to the solution in terms of data management and availability are applied to this marketplace, covering the specific needs of this service. Besides, it should be part of the solution as a service, receiving and sending data between the marketplace and involved vertical services through the middleware.

The marketplace is conceived as an open-source solution that promotes its spread, avoiding market fragmentation while ensuring the security and privacy of the transactions that are made through it. That is, allowing transactions and trading activities needed to enable community cohesion and collaboration. Furthermore, the marketplace enables

[14] https://AURORAL.elliotcloud.com/service-store.

[15] https://AURORAL.iot.linkeddata.es/def/core.

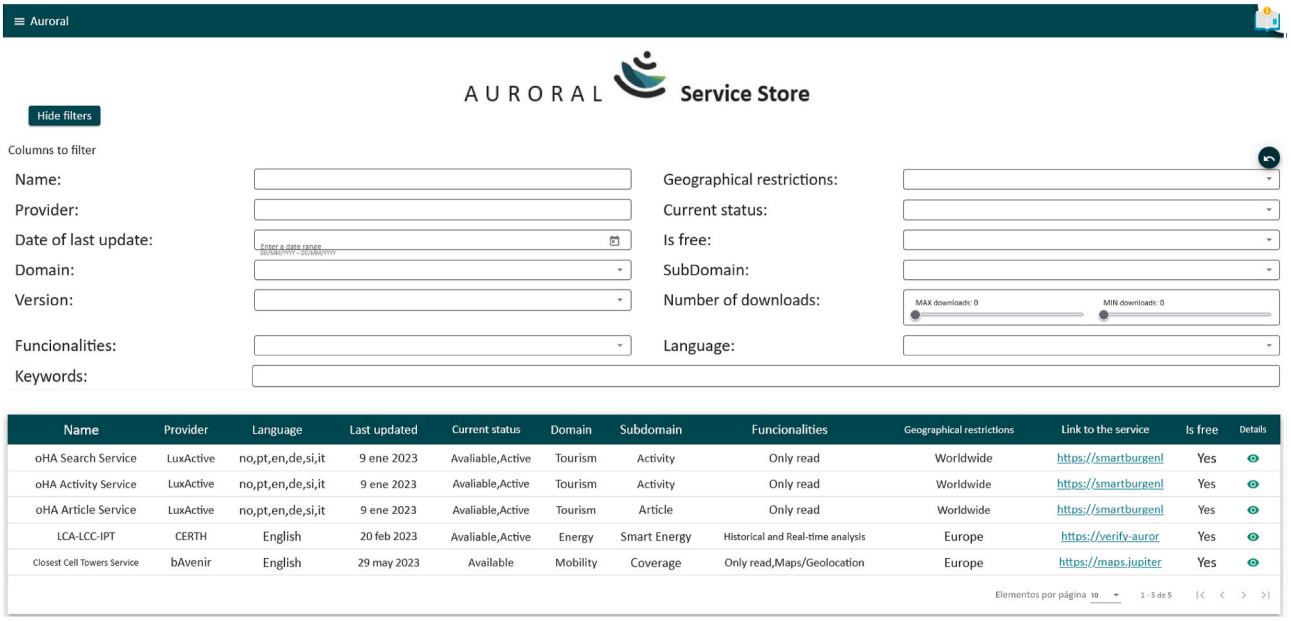

Fig. 8. Graphical user interface (GUI) of the AURORAL service store.

the definition of exchange rules and agreements on the delivery of goods and services based on interoperability with auxiliary and/or external services. At the same time, it manages the consolidated data and trade results from and to (respectively) vertical systems. As part of the AURORAL solution, the marketplace takes advantage of its components and the DLT Tool for managing and facilitating its transitions. Besides, it ensures security and privacy through the use of public/private authentication mechanisms. At the same time, the AURORAL Node and adapters automate transactions between verticals and the marketplace through explicit buyer-seller agreements.

Thanks to the described functionalities, the main use cases that AURORAL foresee for the marketplace are:

1. Users Management: Before a user can access the benefits of a local marketplace, she/he must be registered and authorized to interact with it. Once registered, the user has access to all options related to her/his profile. The process applies to community users and AURORAL's users (understood as the owners of a vertical involved in the marketplace).
2. Barter management: To enable sharing and exchange of goods and services, all users need to have assigned market-related tokens, which will be used as exchange currency inside the marketplace to facilitate trades while promoting transparency.
3. Rules management: Enable communities (users of a local marketplace) to define exchange rules for the goods and services available in the marketplace, e.g., maximum profit, cost of professional services, etc.
4. Offering management: Services to enable marketplace users to register a product/service (good) offer and prepare deals with existing demands.
5. Demand management: Services to enable marketplace users to register a good (product/service) need. It also includes the functionality to select specific offers available in the marketplace and propose deals.
6. AURORAL integration: APIs (Application Programming Interfaces) required to receive/send data be-tween the marketplace, and the AURORAL Middleware as the main provider of consolidated data and the trade results from and to (respectively) vertical systems (e.g., logistic services).

6. Discussion and open challenges

Digitalization has proven to be an asset for rural areas. Technology implementation is crucial for its citizens and end users' cohesion, competitiveness and empowerment. In this line, Zaki et al. [59] demonstrate that any digitalization strategy should adopt an interdisciplinary approach to consider the context in which it will be enacted. For it to succeed, its design must consider the external context and the social, economic, and technological environment. For this reason, it must be comprehensive, well-structured, and evaluate the complexity of the organizational context and the technologies and solutions that will be implemented. A good digitalization strategy goes through several steps, where barriers, activities, and goals must be well outlined. Furthermore, it requires good engagement and active participation in the process of co-creation by the end users of these technologies to be implemented, which is the culmination of the implementation of strategies. Thus, while promoting digitalization in rural areas, efforts in identifying the main barriers to digital transformation through interaction with stakeholders and end-users are needed, along with a literature review to complement and support such interactions and expand on that knowledge AURORAL [60].

As has been outlined, our work places a strong emphasis on understanding the relevance of barriers to digital transformation, as it serves as the foundation for our proposed digitalization strategies. AURORAL, as described throughout the paper, is dedicated to the digital transformation of rural areas, with a specific focus on creating Smart Communities. The success of such initiatives relies heavily on fostering collaborations among diverse stakeholders, including government organizations, community leaders, technology providers, and residents. By working together, we can identify specific needs, develop tailored solutions, and implement effective strategies that consider the unique characteristics and contexts of rural areas. In addition, it is crucial to recognize the pivotal role of people as the primary agents of transformation Zerrer and Sept [30]. Therefore, to truly incorporate technology into the daily lives of rural communities and bring about a profound transformation in these regions, addressing the open challenge of engagement is crucial. Engagement is a key measure of how valuable people find a product or service, and tracking user activities can provide insights into its effectiveness and areas for improvement. Nonetheless, traditionally, rural citizens have relied on face-to-face agreements and

personal references when accessing services. Therefore, enhancing their interest, knowledge, and literacy in digital skills and solutions becomes imperative. This will foster greater engagement and connection with the delivery of digital products and services, allowing rural communities to benefit from the advantages they offer fully. Activities such as selecting a service or sharing information can be considered positive engagement and contribute to the wider adoption of digital solutions in rural areas.

In the same line, the popularization of technology, that is, promoting and marketing newly developed solutions for end-users in Smart Communities, is vital to contribute to its acceptance and adoption. The content of the message to the potential user of the new solutions needs to be understandable and reach them. Nevertheless, just as knowledge of digital tools is vital, so is the capacitation to use this technology. Capacitation can be understood as developing digital skills, creating digital inclusion, and assimilating digitalization to communities regardless of socioeconomic background. Capacitation is often seen as one of the solutions to diminish the digicap or digital divide between people in communities, which remains unresolved. Although capacitation tools and measures can be used in communities with different levels of digital development, the target group and their skill level regarding digital capacity must be defined to identify correct procedures. By combining our efforts to popularize technology, provide capacitation measures, and create an enabling environment, we aim to ensure that Smart Communities are equipped with the necessary skills and resources to embrace digital transformation fully.

At the same time, defining a suitable model for deploying and operating digital services in rural areas is crucial for their adoption Salemink et al. [28]. The technological aspect of capacity building, such as connectivity and open software development, plays a vital role in this process. In this regard, interoperability is a key consideration that remains an open technological issue, particularly in integrating data sources within a digital ecosystem. The proper description of data is essential to ensure semantic interoperability. As previously mentioned, AURORAL solutions are designed to be interoperable, allowing for high reusability and easy integration of new services, which encourages the participation of service providers and actors, including small businesses. This is particularly important as small businesses are often overwhelmed by the infrastructure required to create digital assets and services. Hence, utilizing existing solutions and technologies with open-source software and collaborative development platforms is necessary to reduce this barrier. Therefore, fostering openness is pivotal in increasing the usage of digital services, such as through the utilization and continuous improvement of open government data and sovereignty. Users of open government data need to have a voice and be actively engaged in the development process by local, regional, and central administrations.

Additionally, the role of local governments in driving digitalization efforts should not be overlooked. Local authorities can play a pivotal role in advocating for digital inclusion, establishing supportive policies, and allocating resources for digital infrastructure development. By actively engaging with their constituents and understanding their needs, local governments can create an ecosystem that enables innovation and fosters the growth of digital entrepreneurship in rural areas. Thus, in the European context, the EU is taking measures to support the development of digital solutions and services targeting these areas. This includes improving digital infrastructure in rural areas by implementing initiatives that support the rollout of very-high-capacity networks, promoting digital skills and literacy, and providing lifelong learning opportunities for rural residents. Those actions are being developed under the scope of the already introduced Rural Vision and other mechanisms such as the Digital Europe Programme Ragonnaud [61].

In essence, addressing the challenges specific to each context requires active engagement with local communities and stakeholders. We also recognize the importance of involving these stakeholders in identifying their needs and co-creating solutions that are well-suited to their particular contexts. From a social perspective, overcoming resistance to adopting new digital solutions requires addressing four key pillars that underpin a truly inclusive and equitable digital transformation. Those have been considered in the context of the proposed digital solution:

- Trust, by offering solutions that do not aim to store or use their end users' data in any way other than what the end-users require. In other words, AURORAL does not store information in the cloud except the minimum required to identify users and route data from point to point.
- Support and capacity building, by offering online materials such as video tutorials in the form of the AURORAL academy, thorough documentation, a blog with usage examples, and support materials for developers and system integrators. The consortium maintains the platform, and different partners offer assistance to help users leverage the available services effectively.
- Openness by embracing the concept of openness, allowing for transparency, collaboration, and community-driven innovation. By leveraging open-source technologies, AURORAL reduces the monetary gap in developing digital solutions, making it more accessible and cost-effective for rural areas.
- Reliability, achieved by building a system that addresses typical problems such as security and performance while also adapting to specific issues related to rural areas, such as limited connectivity. AURORAL aims to provide a dependable and robust infrastructure that ensures consistent service delivery even in challenging rural environments.

Furthermore, from a technological standpoint, two additional pillars need to be considered:

- Interoperability, by providing solutions that promote seamless integration and communication between different systems and services. AURORAL ensures that its components can effectively interact with existing technologies and infrastructure, enabling smooth data exchange and collaboration between diverse stakeholders.
- Customizability, by designed to be customizable and adaptable to the specific needs and contexts of different rural areas. It offers a range of ready-to-use services that can be tailored to suit the requirements of each individual rural region.

In this context, Table 1 highlights the key barriers and challenges in promoting digital transformation in rural areas, along with the ways to overcome them and the specific contributions of the AURORAL solution in this direction. The table encompasses both social and technological perspectives, addressing important aspects such as community engagement, cost-effectiveness, interoperability, and more. Incorporating the last pillars into the digital transformation process makes it possible to foster inclusive and equitable development in rural areas possible. In this sense, the presented solution is aligned with EU's digital policies and strategies, such as the Shaping Europe's Digital Future European Commission [62] and Europe's Digital Decade strategy [63], which aim to promote a human-centered, sustainable, and prosperous digital future. In fact, the focus of our proposal on open APIs, decentralized architecture, trustworthiness, and security aligns with the EU's push for a more trustworthy and secure digital ecosystem, contributing to the objectives of the Digital Single Market European Commission [64]. In this regard, by facilitating the adoption of new technologies and interoperable services that align with the day-to-day activities of rural communities, we aim to contribute to developing new business models and services that enhance the socio-economic well-being of targeted areas in line with these strategies.

In summary, the present work represents our effort to create a digital platform that unlocks the full potential of rural areas and contributes to a resilient and prosperous digital future. It addresses key barriers to digital transformation and fosters inclusivity, cohesion, and empowerment, supporting the objectives of the Digital Europe Programme. The

Table 1
Summary of barriers, solutions, and AURORAL's Contributions in Rural Digital Transformation.

Category	Challenges	Ways to Overcome	AURORAL's Contribution	Pillar(s)
Social	Demographic gap	Create easy-to-use technologies for digital skills training	User-friendly interfaces and intuitive features	Support and Capacity Building
	Lack of digital skills	Provide inclusive digital skills training programs and promote lifelong learning for rural residents	Capacity-building in rural communities through workshops, webinars, and online resources	Support and Capacity Building
	Privacy and security concerns	Foster trust through transparent data handling and privacy education for rural communities	Data privacy and security by only storing necessary user data and ensuring transparent communication	Trust, Openness
	Socioeconomic inequalities	Implement inclusive policies to reduce socioeconomic disparities	Ready-to-use services that can be adapted to the specific needs of rural regions	Customizability
Technology	Insufficient infrastructure	Improve technological infrastructure in rural areas through broadband expansion and reliable network coverage	Leveraging a decentralized architecture to promote digital service deployment and investment	Interoperability, Customizability, Reliability
	Integration of data sources and devices	Enable interoperability between different data sources and devices	Develop standardized protocols and frameworks for seamless integration of data	Interoperability
	Cost-benefit barriers	Develop innovative business models that consider the unique challenges and benefits of serving rural communities	Empower rural areas with cost-effective tools and resources to promote the creation of new digital services	Reliability, Openness
Other	Legal and regulatory barriers	Update legal frameworks and streamline regulations to support digital transformation in rural areas	Alignment with EU digital policies, initiatives and strategies	Openness
	Disruption of community trust	Promote community engagement and participation in the digital transformation process	Co-creation, continuous support and maintaining open communication channels	Trust, Openness, Support and Capacity Building

system bridges the digital divide and reduces socio-economic inequalities through user-friendly interfaces and intuitive features, empowering rural residents to participate in the digital era. Aligned with EU digital policies and strategies, the AURORAL system contributes to the overall vision of a digitally inclusive and resilient future, promoting lifelong learning opportunities, and supporting the development of Smart Communities in rural areas. Nevertheless, we acknowledge that there are still significant social and infrastructure gaps in the presented challenges that need to be bridged. Challenges like connectivity issues are still present and require further attention and action. However, we are hopeful that with the implementation of the EU's rural vision and proposals, such as the one outlined thought this work, progress can be made towards using information, communication technologies and data to provide new opportunities in rural areas and contributing to an ecosystem of services that improve the lives of their inhabitants.

7. Conclusions and future work

This work aims to provide rural areas with new digital tools for driving their digital development. Hence, we present the AURORAL system, a comprehensive platform designed to address the specific context of rural communities. The objective of AURORAL is to advance a just, equitable, and open digital revolution, with a focus on empowering Smart Communities as the driving force behind this transformation. To successfully achieve this objective, it is crucial to address the digital divide, particularly in large, sparsely inhabited, and distant locations. The presented solution offers an open environment that fosters enhanced cooperation, communication, and interaction among stakeholders within and between rural regions. It provides a reliable, secure, and privacy-preserving framework with advanced interoperability and commoditization capabilities, enabling the seamless integration of digital tools and services from different domains.

At the same time, a technological solution cannot succeed if it fails to adapt to the unique needs and barriers of each community. For this reason, alongside this paper, we have identified the multifaceted challenges faced by the rural sector and the guiding principles that must support the development of new digital solutions. In this regard, digital solutions like the one presented should promote a suitable ecosystem for fostering collaboration and engagement among stakeholders, strengthening trust and facilitating widespread adoption of services. In this line, tailored evaluation strategies for rural contexts are also needed. Thus, we also propose a framework to assess the potential impact of the proposed digitalization approach and its meaningful outcomes.

In future work, we aim to assess the impact of the AURORAL ecosystem using the described framework, focusing on how well the proposed solution enables communities to overcome the barriers and disparities between rural and urban areas, making the concept of Smart Communities a reality. In summary, this work reflects our dedicated efforts to understand the unique needs and challenges specific to rural areas while developing digital platforms that enhance rural citizens' access to information and services. Through our endeavors, we strive to drive the comprehensive and inclusive digital development of rural communities, contributing to their overall growth and progress.

Credit author statement

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Data availability

No data was used for the research described in the article.

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