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Use of open-source P2P energy sharing platforms for energy Democratization

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Open-source tools assessment

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Disclaimer

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[1] https://u2demo.eu/

Executive Summary

Task 1.3 conducted within Work Package 1 of the *U2Demo* project, aims to assess the mapping and interoperability of existing *Open-Source Software* (OSS) tools supporting active energy consumers. This work contributes directly to the project's overarching objective of enabling scalable and replicable digital solutions across the EU energy communities' ecosystem.

The task combined several methodologies: a comprehensive literature review, pilot site interviews, input from stakeholders, methodological developments, and technical assessments. A thorough review of relevant tools and their specifications was conducted and classified by domain, category and application. Insights gathered from the pilot sites and their respective academic partners supported the creation of a harmonised overview of the OSS landscape relevant to energy communities and helped identifying specific solution development requirements in the digital infrastructures across the pilots. As a result, the task produced a **detailed catalogue of 204 existing OSS tools**, systematically classified into domains, categories, and applications, and characterized by 18 KPIs. This catalogue, including all results obtained from this Task 1.3, is available in the *U2Demo* Zenodo repository [1].

The mapping and assessments were conducted in three stages. First, the maturity and ***Technology Readiness Level* (TRL)** of all the 204 identified tools were evaluated, focussing on the 30 tools with the highest TRL by prioritised application, as identified by the demonstration sites. Next, a **functionality mapping** was performed to analyse the tools' capabilities across applications, their technical robustness, flexibility in terms of the range of offered functionalities, and to determine their readiness for deployment in demonstration environments.

This was followed by an **interoperability assessment**, which examined the extent to which selected tools can integrate into the existing digital infrastructures of energy communities. Particular attention was given to each tool's potential to operate as part of a larger, scalable and interoperable digital ecosystem. Additionally, a *Smart Grid Architecture Model* (SGAM), framework under the European Mandate M490 for Smart Grids, was developed for "*Open Remote*" [2], the only OSS tool that is already in use at the demonstration sites as per the date of this assessment.

In the conclusion, recommendations regarding the most promising tools are provided for pilots according to their highly prioritised categories. For example, "*OpenEMS*" [3], in the *Energy and Distribution Category*, emerged as the best performing and interoperable tools of the present analysis. Tools classified within the category *Energy Management and Monitoring Tools*, identified as Priority 1 across all demonstration sites, achieved consistently high scores, such as "*Volttron*" [4] and "*Open Remote*" [2] for *Community Energy Management Systems (CEMS)* applications, both with excellent interoperability and functionality capabilities. Besides, "*EVCC*" [5] in *Integration with EVs*, achieved one of the best scores, assigned with the highest interoperability level among all analysed tools. Overall, it has been found that no single tool meets all the mapping and interoperability criteria within the *U2Demo* research objectives. This highlights the need of relying on a combination of tools based on their maturity, functionality and interoperability level.

Finally, these findings provide a harmonised and strategic perspective on the landscape of OSS solutions applicable to energy communities. By identifying, classifying, and assessing these OSS tools, Task 1.3 lays the groundwork for informed decision-making in the upcoming phases of the *U2Demo* project, particularly regarding tool integration, and further development.

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Acronyms

AI	Artificial Intelligence
CEMS	Community Energy Management System
DER	Distributed Energy Resources
DR	Demand Response
DSO	Distribution System Operators
EC	Energy Community
EU	European Union
EV	Electric Vehicle
HEMS	Home Energy Management System
HV	High Voltage
KPIs	Key Performance Indicators
LV	Low Voltage
ML	Machine Learning
MV	Middle Voltage
OSS	Open-Source Software
RES	Renewable Energy Systems
SGAM	Smart Grid Architecture Model
TRL	Technology Readiness Level
TSO	Transmission System Operator
WP	Work Package

1 Introduction to Task 1.3

1.1 Scope and Objectives

This document conducts an extensive mapping and interoperability assessment of existing *Open-Source Software* (OSS) solutions proposed in scientific research and industry.

A comprehensive literature review of these solutions and their standards, classified by domain, category and application, provides a harmonized overview and a valuable insight into the various modules that will be integrated to create *U2Demo* solutions.

The mapping of the OSS solutions is divided into three parts. The maturity and *Technology readiness Level* (TRL) of the reviewed solutions are assessed, and the most promising tools within the *U2Demo* scope are selected based on this assessment. Besides, the selected tools' functionalities, and their operations in different domains are analysed through a functionality mapping. This is followed by an interoperability assessment of the selected tools with high technical maturity to develop an outlook of the integration of the selected tools with existing digital architectures of the energy communities. Finally, a *Smart Grid Architecture Model* (SGAM) of OSS tools for active consumers in energy communities that are already in use in the demonstration sites is presented.

The research objectives are summarised as follows:

I. A framework development for OSS tools assessment: a comprehensive literature review of OSS solutions, their standards, and main *Key Performance Indicators* (KPIs) classified by domain, category, and application, and prioritized according to academic literature, feedback and data collected from the demonstration sites interviews.

II. A *Technology Readiness Level* (TRL) assessment of the identified OSS solutions, followed by functionality mapping of the tools with the highest maturity level.

III. An interoperability assessment of the relevant OSS solutions as identified in objective II, and a *Smart Grid Architecture Model* (SGAM) methodology of the OSS solutions already in use at the demonstration sites within the *U2Demo* project.

1.2 Introduction to Mapping of OSS Solutions

The various OSS tools that exist to support one or more functionalities in local energy communities do not typically concentrate on the operation of a single function. In certain instances, there are specialised tools that are required to function either with the existing platform or in conjunction with other tools. Alternatively, there are complex tools that take into consideration the development of multiple functionalities within a single comprehensive platform. The mapping of such OSS tools provides a comprehensive overview of their functionalities in different domains and categories, as well as their compatibility with other existing tools and solutions.

Mapping is an overarching term, and there are various methods which collectively constitute the mapping of OSS solutions. In this report, the mapping of solutions is defined as composed of the following three types of assessments, delineated as follows:

1. **TRL Assessment**: it provides information regarding the maturity of the analysed OSS tools, thus supporting decision makers and stakeholders in making an informed decision regarding the adoption of these tools.

2. **Functionality Mapping**: it provides a broad overview of the specialised capabilities of each tool, in addition to the other supported functionalities associated with the existing tool. For example, "*Home Assistant*" [6] is a mobile application that is also available as an energy monitoring tool, with the capacity to support home automation.
3. **Interoperability Assessment**: it provides insights into the potential integration of a specific tool with an existing platform, tool or solution. The purpose of this insight is to establish synergies between these elements.

The combination of these three analyses constitutes the framework for the mapping and interoperability assessment of the selected OSS solutions for active consumers in energy communities.

1.3 Structure of the Deliverable

The structure of this deliverable has been designed to reflect the logical flow of the analysis and to support the understanding of the key findings, in alignment with the research objectives outlined in Section 1.1.

Following the Introduction (**Chapter 1**), the report is organized in four core chapters.

Chapter 2 describes the framework developed for OSS tools assessment. It constitutes of a comprehensive literature review, and a methodology used to identify and classify open-source tools relevant to the research scope. To identify and rank (from Priority 1 to Priority 3) the most valuable applications, a classification – by domain, category, and application – is used. This classification is combined with data and feedback collected from interviews with the four demonstration sites and their academic partners in the consortium. Once the applications are selected, the corresponding OSS tools are identified by application type and prepared for subsequent analysis.

The analysis of mapping open-source tools is conducted in Chapters 3, 4, and 5.

Chapter 3 builds upon the review in Chapter 2 by conducting a *Technology Readiness Level* (TRL) assessment of the identified tools. A novel methodology for calculating the TRL of open-source solutions has been developed. The assessment is thus carried out using a set of key metrics, each providing insights into the different aspects of the tools' maturity. The metrics, grouped into categories, are then weighted to calculate an overall TRL score for each OSS solution. The resulting TRL scores, represented with a heat map, inform the selection of high-maturity tools for further functionality and interoperability analyses.

Chapter 4 focuses on functionality mapping of the high-TRL open-source solutions. This analysis evaluates how well each tool supports the previously prioritised applications for each demonstration site. The goal is to assess their potential integration into the sites' existing digital architecture frameworks.

In the last section of the mapping, **Chapter 5** presents the interoperability assessment. The selected tools are further analysed to understand their interoperability with both existing infrastructures and other OSS solutions. Key interoperability metrics are defined to assess critical characteristics of these tools. The assessment is then conducted using the *Smart Grid Architecture Model* (SGAM) framework as defined by the European Commission. The mapping of existing OSS solutions at the demonstration sites onto the SGAM layers is explained in detail in Section 5.3.

Finally, **Chapter 6** concludes the report by summarising key findings and highlighting cross-cutting challenges and next steps relevant for the upcoming *Work Packages* (WPs).

1.4 Relationship with other Deliverables

The mapping and interoperability assessment of the existing OSS solutions for active consumers provides direct and indirect benefits to the following WPs and Tasks within *U2Demo*. These following insights are specified:

1. **WP2 & WP4:** The mapping of different OSS solutions provides an outlook for the research and development of decision-support tools to be undertaken in the mentioned WPs.
2. **WP3:** The development of a platform to host all the tools and solutions may draw inspiration from the existing OSS community platforms. This can be done by focussing on the integration of pre-existing solutions into the *U2Demo* platform, based on their level of interoperability, as presented in this Task.
3. **WP 5:** The demonstration sites will be provided with OSS solutions developed within the project. Nevertheless, certain tools which are not the focus of development in *U2Demo*, but which already exist with a certain degree of technical maturity, may be integrated by energy communities into their existing or evolving digital infrastructure.
4. **WP6:** Several KPIs will be used to evaluate the solutions developed in the *U2Demo* project. These KPIs may be informed by this report, which has already defined certain criteria for evaluating existing OSS solutions.

Finally, this deliverable provides a harmonised perspective and a valuable reference on the various modules of OSS solutions that are expected to be integrated into the *U2Demo* project. By identifying and assessing these tools, the document establishes the foundation for informed decision-making in the subsequent phases of the project.

2 Framework for OSS Tools Assessment

In this chapter a framework for assessing existing OSS tools is reported. Firstly, the literature review presented in Section 2.1 establishes the foundations for the development of a methodology – outlined in Section 2.2– for the identification and classification of OSS tools relevant for the management of local energy communities. This process initially led to the definition of several categories and application areas, structured by domain, which are important for the operation of such communities (see Section 2.3).

Following expert validation, bilateral interviews were conducted with each demonstration site to identify their specific needs, interests, and – if available – any tool already in use within the scope of the current project (see Section 2.4). In the next phase, the collected inputs were processed using a prioritisation methodology and normalized in order to identify the most commonly relevant categories and application areas across the demonstration sites (see Section 2.5).

Finally, for each of the highly prioritised applications, a thorough search and evaluation of existing OSS tools was carried out (see Section 2.6), leading to the identification of the most relevant solutions which will consequently be subjected to the mapping and interoperability assessment.

2.1 Literature Review

It is crucial for energy communities to equip their active consumers with the necessary tools to facilitate seamless participation in various aspects of their daily activities, and to enable effective management of community operations.

In this Section 2.1, an extensive review of the existent academic literature has been conducted for the purpose of categorising the various tools and applications that are currently in use within different energy communities.

For instance, Minuto et al., [7] describes diverse renewable OSS tools and categorizes them as commercial, EU-funded, and freeware. Deb et al., [8] emphasizes the importance of local energy systems in enhancing local energy generation and utilization, curtailing reliance on transmission infrastructures, and improving community welfare. Another study [9], presents the results of an activity within the H2020 project "*eNeuron".* The objective of this activity was to address the identified gap by introducing the "Integrated Local OSS" definition and conducting an in-depth review of the multiple factors influencing the future development of these emerging systems. The review encompassed three levels: political priorities, technical overview and limitations plus barriers.

In addition to the abovementioned literature, there are several review papers that explore a variety of tools and solutions employed in different aspects of local energy communities. Mahmud et al., [10] offers an extensive list of computational tools for the design, analysis, and management of residential energy systems. A comprehensive review by Ponnaganti et al., [11] is carried out about designing flexibility provisions for local energy communities in the context of existing and emerging flexible electricity markets. The review also discusses the need for social arrangements, technical designs, and their impact on energy communities. The following paper by Trivedi et al., [12] sets out to present state-of-the-art microgrid solutions for smart energy communities along with the motivation, advantages and challenges, comprehensibly contrasted between the recommended generic architecture and every other reported structure. Again, Capper *et al.,* [13] reviews twelve energy modelling tools suitable for evaluating

Renewable Energy Communities, while Groissböck [14] assesses 31 OSS energy system optimisation tools, highlighting their maturity for serious use. In Capper *et al.*, [15], 139 peer-reviewed journal articles were reviewed to examine the market designs employed in the energy trading models. Finally, Körber et al., [16] presents a tool chain that functions as a decision support tool for techno-economic and ecological design choices, providing essential insights into a holistic energy concept for the renewable energy communities.

This review emphasises that comprehensive overviews of OSS tools and solutions for energy communities are often conducted only for specific applications or use-cases. In this regard, the present study aims to develop a systematic framework for the taxonomical definition, classification, identification and subsequent evaluation of OSS tools for an exhaustive list of applications within the specific field of energy communities as prioritised by the demonstration site responsible partners. Successively, this process facilitates in-depth exploration of the identified use cases. In this instance, the requirements for the four demonstration sites of the *U2Demo* project are explored.

2.2 Methodology

The conducted literature review provided a systematic benchmark for the exploration of various OSS tools and their applications within the context of local energy communities. The methodology for identifying and evaluating these tools is structured into four distinct steps, ensuring a systematic and reproducible approach. This methodology integrates academic insight, expert validation, stakeholder engagement, and result processing. The methodological steps are illustrated in Figure 1 and explained below.

Figure 1 – Four methodological steps for the identification of existing OSS Tools

1. **Taxonomy Definition:** Building upon insights from the literature review, project websites related to local energy communities, and other relevant resources, a classification framework comprising categories and application areas was developed. This resulted in the identification of 34 categories – such as *Energy Management & Monitoring*, *Energy Distribution*, and *Settlement & Billing* – detailed in APPENDIX A: Categorization of OSS Tools, Table I. These categories were further broken down into 144 applications to capture the functional dimensions of each category – such as *Community Energy Management Systems (CEMS)*, *Real-time Energy Monitoring Platforms*, *Automated Billing Platforms,* also described in Appendix A Table II (see Section 2.3).
2. **Expert Validation & Stakeholder Engagement:** The proposed classification of categories and applications underwent an internal review by project partners within the *U2Demo* consortium. This validation process aimed to ensure the classification's comprehensiveness and practical relevance for other WPs within the project (see Section 2.4). Following the internal review, semi-structured interviews were conducted

with the managers of the four demonstration sites participating in the *U2Demo* project – located in the Netherlands, Belgium, Portugal, and Italy – as well as their respective academic partners. These interviews aimed to contextualise and to prioritise the categories and applications according to each site's specific interests, with respect to technical maturity, stakeholder roles, digital infrastructure, regulatory environment, and other contextual factors.

3. **Results Prioritisation & Normalization:** Insights gathered from the interviews formed the basis for selecting high-priority categories and applications, as explained in Section 2.5. For each demonstration site, the interviewees were asked to assign a priority level – from Priority 1 to Priority 3 – to each of the 34 categories. Additionally, they indicated their interest in each of the 144 applications using a "Yes", "No", or "Maybe" scale, reflecting the potential for further development in those areas. Subsequently, these priority ratings and scores were normalized to identify the most relevant applications for further investigation and tool mapping.
4. **Tool Identification & Documentation:** Following the prioritisation process, an extensive research and evaluation of relevant OSS tools was conducted. Each tool was assessed based on KPIs, including, among others, license type, functional scope, development activity, and interoperability features. The definition of these metrics and the evaluation process are detailed in Section 2.6. The complete table of OSS tools is reported in APPENDIX C: OSS Tools Complete List, Table IV and it is available in the *U2Demo* Zenodo repository [1].

This methodological framework was designed to ensure a rigorous academic approach and alignment with the objectives of the *U2Demo* project, while also addressing the specific needs and priorities of the local energy communities involved in the demonstration sites.

2.3 Taxonomy Definition

As explained in Section 2.2, all aspects of local energy systems were classified into 34 categories, encompassing all operations of local energy communities that are digitally managed. These categories were further subdivided into 144 applications to capture the full range of functionalities within each category.

As a means of explicating the interrelationships between the various taxonomy groups that have been utilised in this report, Figure 2 provides a visual representation of the hierarchical correlations between Domains, Categories and Applications and the respective examples.

While **domains** describe the broader context (e.g. *Operations, Communication, Technology*), **categories** specify the type of tool or service offered –such as *Energy Management & Monitoring Tools*, *Energy Distribution Tools*, *Settlement & Billing Tools*, *AI & Machine Learning Tools*, or *Communication & Collaboration Tools*. These categories thus facilitated the identification of the functional grouping of tools within each domain, reflecting their primary role or contribution (e.g., management, forecasting, trading, billing) and the classification of tools based on their general purpose, functionality, or role within the OSS ecosystem. The detailed list of categories, along with their definitions, can be found in Table I of APPENDIX A: Categorization of OSS Tools.

Furthermore, **applications** refer to the specific functional purposes, use cases, or problem areas that OSS tools are designed to address within each category. This classification highlights the practical application of a tool – such as for *AI-powered energy forecasting*, *Peer-to-Peer Energy Trading Platforms*, *Anomaly Detection* or *Automated Billing Platforms* –

underlying its technical implementation. The detailed list of applications, along with their definitions, is provided in Table II of APPENDIX A: Categorization of OSS Tools.

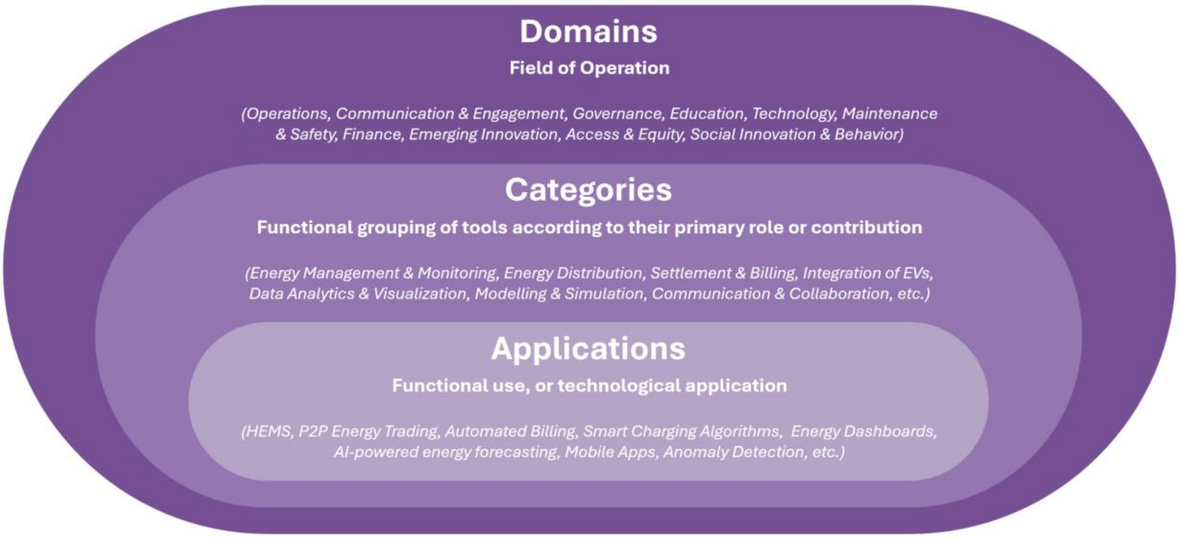

Figure 2 – Taxonomy diagram: Domains, Categories, Applications

The classification of various operations of local energy systems was developed from academic literature, consultations with experts and consortium partners, and inputs provided by the four demonstration sites.

In particular, the extensive literature review conducted in Section 2.1, including also other academic works such as [17], [18], [19], [20], and [21], contributed to the definition of the presented list of categories and applications. This list is intended to be exhaustive and mutually exclusive within the specific domain of local energy communities' applications. It is evident that there are applications which can be classified into diverse categories. For instance, *AI-Powered Energy Forecasting* and *Machine Learning Algorithms applications* could be used for the *Energy Management & Monitoring* and/or *Modelling & Simulation* categories. Nevertheless, since the directly related tools may have not been specifically designed primarily for these functional groups, they have been classified into an even more specific category, in this example *Artificial Intelligence & Machine Learning Tools*.

It is also noteworthy that several tools are compatible with multiple categories and may offer a variety of functionalities in different areas of application. However, in order to ensure a consistent evaluation process, it was decided that each tool would be allocated a single primary application for which the tool was principally developed.

Furthermore, the classification of all categories was conducted under ten domains, based on the definitions of the category. Also in this case, despite the possibility of one category being classified under multiple domains, the most prevalent feature of each category has been utilised for its classification. Finally, following a thorough process of review, the consortium experts have provided their feedback on the classification framework of OSS tools.

This work resulted in the identification of 144 applications across 34 categories, which were subsequentially classified according to their respective 10 domains, as defined above. The following Figure 3 illustrates the distribution of these applications across categories and domains.

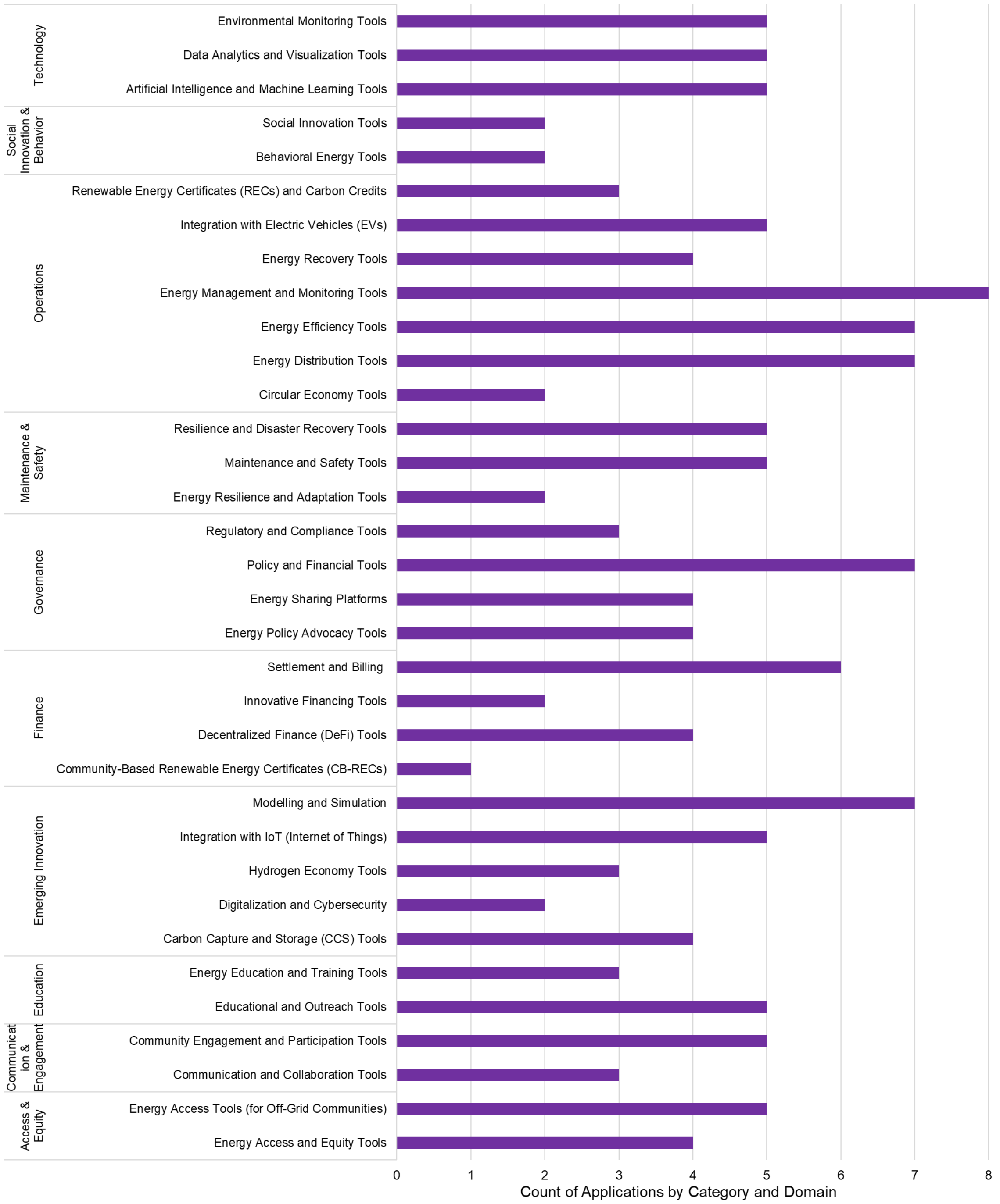

Figure 3 – Distribution of all 144 Applications by their associated Category and Domain

2.4 Expert Validation and Stakeholder Engagement

Following the classification of different operations of local energy communities, the subsequent stage of the study involved engagement with the four *U2Demo* demonstration sites, which are distributed across Europe. The objective of this engagement was to guarantee the relevance and applicability of the OSS tools that are planned to be scouted as part of this work to real-world energy communities.

The details of the demonstration sites can be observed in Table 1:

Table 1: Description of the four pilots in the *U2Demo* project

N.	Demonstrator	Location	Type of Site	Coordinating Partner	Remarks
1	Dutch Pilot	Scheveningen, Netherlands	Living Lab, Hague Smart City	Den Haag, TNO	Collaboration with local DSO, includes 22 solar prosumers
2	Belgian Pilot	Mechelen, Belgium	Citizen Energy Community	Klimaan	197 prosumer households with hybrid PV installations (only 17 buildings planned for active EC)
3	Portuguese Pilot	Valverde, Portugal	Innovation Hub (H2020)	EDP	Regulatory sandbox with 10 households
4	Italian Pilot	Vallevignale, Italy	Renewable Energy Community	EnGreen	10 buildings (5 prosumers and 5 consumers)

Each demonstration site is representative of a distinct geographical location, technical challenge, socio-economic policy, and regulatory context. These offer a diverse pool of requirements and priorities used to validate the complete spectrum of classification of categories and applications described in Section 2.3.

The objectives of this stakeholder validation and engagement process were threefold:

1. Contextualizing the digital landscape of individual demonstration sites, including an examination of OSS tools and their immediate digital challenges.
2. Assessing the priorities of individual demonstration sites regarding the application areas and functionalities of the OSS solutions to be collected.
3. Collecting qualitative and quantitative data on the key metrics, essential to support the evaluation process before and after the selection of OSS tools.

The following sections detail the approach and key findings from the interviews with the four demonstration sites.

2.4.1 Approach and Methodology

The data collection framework from the demonstration sites was structured to ensure that the inputs received could be standardized and that the prioritisation could converge on certain functionalities. The objective of this approach aimed to identify the most critical applications to be investigated further in the subsequent steps.

The methodology included the following steps:

1. **Database Setup**: a database of functionalities was created and organized into categories and applications. Each category item was assigned a priority level – from 1 to 3 – to be selected by the demonstration sites prior to the interviews.
2. **Semi-Structured Interviews**: semi-structured interviews were conducted with each demonstration site. Participants were asked to justify their priority level selection for each category, as described in the previous point, and subsequently classify the

applications using a “Yes”, “No”, or “Maybe” scale, reflecting the interest for potential further development in those areas for their pilots, if not yet in place (see Section 2.5).

3. **Feedback from Academic Experts**: feedback was gathered from academic partners within the consortium, including experts from *EIFER*, and the interviewees, in order to review and comment on the interview process and on the prioritisation outcomes.
4. **Stakeholder Mapping and Validation**: a final consolidated table was developed, combining the results and feedback from the interviews across the four demonstration sites into a unified prioritisation structure. The results were then shared with all demonstration sites and academic partners, and feedback was received and incorporated prior to the collection of OSS tools related to the prioritised applications. This process led to the final stakeholder mapping of the OSS tools.

2.4.2 Demonstration Site Interviews

The interviews with the demonstration sites were all conducted by *EIFER* and included the participation from representatives of the demonstration sites, as well as their academic partners within the *U2Demo* consortium.

The primary aim of these interviews was to identify the priorities and digital challenges faced by each demonstration site, assess the proposed short-term developments within the scope of the *U2Demo* project, and support the creation of a harmonized framework for the exploration of OSS solutions.

The complete version of these findings can be found in the *U2Demo* Zenodo repository [1] and extracted in Appendix B Table III. A summary of the individual discussions, thematic insights, and key findings is presented below:

- **Dutch Pilot** (interviewed on 28th March 2025)

  Responsible: *Municipality of The Hague*. Academic support: *TNO*.

The subjects of scalability and interoperability were identified as the highest priority narrative for the Dutch pilot, also validated by their academic support partner. The demonstration site's primary focus is on modular OSS components, which can be integrated into its system architecture and replicated in other locations, thereby obviating the need to develop niche tools for each site.

The demonstration site currently utilises “*Open Remote*”[2], an OSS solution for energy monitoring that also holds a number of additional functionalities. However, the functionalities with highest prioritisation for the demonstration site were *Demand Forecasting*, *Price Forecasting*, and *Decision-making Algorithms*, with a primary focus on *Dynamic Pricing* scenarios. The highlighted primary objective is to respond to the dynamic price signals of the market and to utilise tools that facilitate the exploitation of various market mechanisms.

- **Belgian Pilot** (interviewed on 24th April 2025)

  Responsible: *Klimaan*.

The Belgian pilot’s primary focus was on identifying solutions that could facilitate *Settlement and Billing*. Their long-term objective of establishing an 800-household energy community necessitated two key metrics: automation and scalability at low cost. The representatives expressed significant interest in tools that could assist them in automated mandate processing, real-time billing and payments, and social housing integration.

The team also briefly mentioned about their interest in various gamification strategies to enhance engagement in the community and increase self-consumption. The barrier of digital literacy levels among the community's citizens prompted the adoption of simple gamification and dashboards rather than a full-fledged platform-based gamification strategy.

A further point of discussion was the requirement for real-time data accessibility, aggregation, and visualisation. The representatives are undertaking focused research to ascertain whether real-time data are essential for the demonstration site's objectives. Should this be the case, subsequent investigation will determine the most suitable tool that complies with high privacy standards for social housing tenants.

- **Portuguese Pilot** (interviewed on 8th April 2025)

  Responsible: *EDP*. Academic support: *INESC ID*.

The highest priority for the Portuguese pilot is the development of tools and solutions that would enable them to establish an in-house *Energy Monitoring System*, with the objective of reducing their reliance on third-party infrastructures. This was identified as a major prospective advancement for the operations at the demonstration site, increasing autonomy and facilitating direct oversight of data streams.

A pivotal insight derived from the academic support was the necessity for *Billing and Settlement* instruments for the pilot. These instruments would facilitate the calculation of energy sharing initiatives, DSO feedback integration, and the management of payment systems within the demonstration site.

The representatives also made mention of the establishment of a regulatory sandbox environment, the purpose of which would be to facilitate research activities. These activities would be used to test technologies, tools, governance, and financial models that are not yet part of Portuguese regulations, providing the necessary support for the suggestion of regulatory changes though the demonstrators.

- **Italian Pilot** (interviewed on 16th April 2025)

  Responsible: *EnGreen*

The Italian pilot responsible has indicated that the *Energy Management* and *Monitoring Tools* are among the highest priorities for the demonstration site. Currently, there are no OSS solutions implemented on the demonstration site. However, the present study has demonstrated an evolving interest in the deployment of OSS solutions, as well as the development of OSS solutions from the *U2Demo* project in the demonstration site.

The second priority area of investigation for the pilot is the *Energy Distribution Tools.* The purpose of these tools is to support the pilot with *Peer-to-peer energy sharing*, and *Load distribution and balancing* in the energy community. The pilot responsible has also showcased an increasing interest in exploring tools that may provide behavioural analytics and community engagement platforms. However, these tools are part of their long-term strategy to improve scalability and better integration and is not of immediate exploratory interest.

2.4.3 Key Insights and Observations

The key insights and observations that may be deduced from the interviews and expert feedback are summarized as follows:

- **Common Priority 1-Categories**: All the demonstration sites expressed their high priority for two categories: *Energy Management and Monitoring Tools*, and *Settlement and Billing Tools*.
- **Common Applications' Needs**: For the category *Energy Management and Monitoring Tools*, all surveyed demonstration sites expressed a collective interest ("Yes") in the development of *Community Energy Management Systems*, and *Home Energy Management Systems*. However, within the category *Settlement and Billing Tools*, there was no common or specific demand for a particular application. The only other application that received a common consensus among all pilots was *AI-powered Energy Forecasting* in the category *Artificial Intelligence and Machine Learning Tools*.
- **Tool Modularity**: The majority of demonstration sites expressed their interest in the modularity of the tools. This is due to the fact that they already have existing or planned platforms, and the modularity and interoperability of OSS solutions that can enhance their efficiency on the existing platforms are of major importance.
- **Local Governance Relevance**: Community-driven demonstration sites showed a higher level of interest in budgeting, community budgeting, and educational platforms with gamification (*Educational and Outreach Tools*, or *Energy Access and Equity Tools* categories) in comparison to DSO-supported applications.
- **Limited AI Readiness**: The subject of *Artificial Intelligence* (AI) for forecasting and optimization is of significant pertinence; however, the prevailing digital architecture of most of the demo sites poses a substantial challenge to its seamless integration. Yet, the application of *AI-powered Energy Forecasting* was identified as a high priority for all the pilots.
- **OSS Tools already in use**: only the Dutch Pilot is currently using an OSS tool to carry on operations of *Energy Management and Monitoring*: "*Open Remote*" [2]. The Belgian pilot is using "*EnergyID*" [22] for smart metering and real-time monitoring, together with other supplementary not-OSS tools that contribute, beside others, to crowd funding activities.

The complete datasets and answers obtained from the interviews with the four pilots are reported in Appendix B Table III and can be found in the *U2Demo* Zenodo repository [1].

The main conclusions derived from these rounds of interviews and stakeholder engagement, offered the foundation for the development of a prioritization framework. After being normalized, the results facilitated the identification of the most relevant categories and applications, to investigate the available OSS solutions in those domains as explained in the following Section 2.5.

2.5 Prioritisation

The results obtained from the interviews conducted with the demonstration sites' representatives were compiled and synthesised. The approach used to select categories is referred to as "*Priority Criteria*", whereby each selected priority per pilot is assigned a value, which is then summed together to form a total score.

The following subsections will provide a detailed explanation of the methods that were utilised for the purpose of results prioritisation and normalisation, in order to facilitate the selection of the prioritised categories and applications, respectively.

2.5.1 Prioritised Categories

The selection of the most relevant categories – rated from Priority 1 to Priority 3 – was determined by assigning a value to the answers of each demonstration site as follows:

- *Priority 1*: 1 point
- *Priority 2*: 0,5 points
- *Priority 3*: 0 points

The total sum of the answers could thus score from 0%, indicating that no pilot prioritised the category (e.g. *Carbon Capture and Storage Tools*, and *Hydrogen Economy Tools*), to 100%, indicating that all pilots selected the category (only *Energy Management and Monitoring Tools* and *Settlement and Billing*).

Consequently, a common priority was reassigned to all categories that scored above 50%. One exception was constituted by cases where a category was listed as Priority 1 by one single demonstration site, and Priority 3 by the other partners – such as *Regulatory and Compliance Tools* selected by the Italian Pilot, and *Policy and Energy Efficiency Tools* selected by the Portuguese Pilot. In this particular instance, after validation from the consortium partners, an additional level of Priority 3 was designated for a total of three extra implicated categories.

The table below (Table 2), presents the complete list of the 14 selected categories and their assigned priority level, as determined by the aggregate score derived from the four demonstration sites. It can be observed that six categories have been identified as Priority 1.

Table 2: List of prioritised categories by priority level, with allocated score

N.	Priority Level	Categories	Score
6	Priority 1	*Energy Management and Monitoring Tools*	>75%
		Settlement and Billing	
		Artificial Intelligence and Machine Learning Tools	
		Data Analytics and Visualization Tools	
		Energy Sharing Platforms	
		Modelling and Simulation	
2	Priority 2	*Energy Distribution Tools*	60% to 75%
		Energy Access and Equity Tools	
3	Priority 3	*Environmental Monitoring Tools*	≥50%
		Integration with Electric Vehicles (EVs)	
		Decentralized Finance (DeFi) Tools	
3	Priority 3	*Energy Efficiency Tools*	Exception: 1 Demo Site selection of Priority 1
		Communication and Collaboration Tools	
		Regulatory and Compliance Tools	

Following the identification of the prioritised categories, the normalisation of results is similarly performed on the applications of each of these categories.

2.5.2 Prioritised Applications

The preference of certain applications by the pilots' representatives was determined using a "*Yes*", "*No*", or "*Maybe*" scale, reflecting the interest in potential further development in those areas for their demonstration projects, if OSS tools are not already in use.

The initial normalization of results was conducted utilising a "*Technology Criteria*" encompassing all applications that received a "*Yes*" response, in addition to those that received a minimum of two "*Maybes*". However, the outcome of this process counted a total of 49 applications among all selected Categories in Table 2. In order to further refine the analysis, the "*Priority Criteria*" (see Section 2.5.1) was applied in addition to the considerations from the evaluation just described.

Subsequently, in a similar manner to the categories, the results from the four pilots were normalised using the following assigned values:

- *Yes*: 1 point
- *Maybe*: 0,5 points
- *No*: 0 points

The total sum of the answers could thus again score from 0%, indicating that no pilot is currently interested in developing the applications, to 100%, indicating that all pilots are interested in developing that application.

A total of three applications were identified that were mutually agreed upon by all parties involved, resulting in a 100% consensus score: *Community Energy Management Systems (CEMS)*, *Home Energy Management Systems (HEMS)*, both of which are classified in the *Energy Management and Monitoring Tools* category, in addition to *AI-Powered Energy Forecasting*. In contrast, five applications were not selected at all (0% score), including *Big Data Platforms*, *Biodiversity Monitoring Tools*, *Air Quality Sensors*, *Time-Series Data Analysis Tools* and *Permitting Tools*.

As was the case with the "*Priority Criteria"* used for the Categories, a common priority was reassigned to all applications which scored above 50%. The data was then categorised into three distinct ranges: those with scores above 75%, those with scores between 60% and 75%, and finally, those with scores above 50%.

It was observed that only one from all applications from the exception Priority 3 categories, as outlined in Section 2.5.1, was selected by this method: *Mobile Apps* from the *Communication and Collaboration Tools* category. Besides, two applications were identified from the Priority 3 categories, namely *Environmental Monitoring Tools* and *Integration with EVs*. An additional case is worthy of note: three categories (*Energy Efficiency Tools*, *Regulatory and Compliance Tools* and *Decentralized Finance Tools*), classified as Priority 3 in Table 2, have not been assigned any application.

Moreover, despite being designated as Priority 1 category by all pilots' representatives, *Settlement and Billing* is assigned only one commonly prioritised application: *Automated Billing Platforms*. On the other hand, the *AI and Machine Learning Tools* category, which is also classified as Priority 1, has been assigned all its applications.

The following Table 3 illustrates the outcome of the normalization and prioritisation phase, wherein all the complete array of applications and their corresponding scores are presented as systematized and classified according to the identified prioritized levels and by category.

The applications with the highest rating are reported, according to the results of the interviews conducted with the representatives of the four demonstration sites.

Out of the total 29 applications selected, 12 applications have been assigned a high importance rating (above 75%), 9 applications have been assigned a medium-high importance rating (between 60% and 75%), and 8 applications have been assigned a medium-low importance rating (above 50%).

Table 3: List of prioritised applications classified by categories, with allocated scores

N.	Priority Level	Applications	Category	Applications Score
12	Priority 1	Community Energy Management Systems (CEMS)	*Energy Management & Monitoring Tools*	>75%
		Home Energy Management Systems (HEMS)		
		Demand Response Systems		
		Community level Modelling	*Modelling & Simulation*	
		Automated Billing Platforms (dynamic pricing billing systems)	*Settlement & Billing*	
		AI-Powered Energy Forecasting	*AI & Machine Learning Tools*	
		Machine Learning Algorithms		
		AI-Driven Energy Optimization		
		Anomaly Detection in Energy Systems		
		Energy Dashboards	*Data Analytics & Visualization Tools*	
		Data Visualization Tools (e.g., Tableau, Grafana)		
		Energy Sharing Apps	*Energy Sharing Platforms*	
9	Priority 2	Real-Time Energy Monitoring Platforms	*Energy Management & Monitoring Tools*	60% to 75%
		DSO level modelling	*Modelling & Simulation*	
		Individual Unit modelling		
		Collaborative Decision-Making Platforms		
		AI for Predictive Maintenance	*AI & Machine Learning Tools*	
		Virtual Power Plants (VPPs)	*Energy Distribution Tools*	
		Grid Balancing Tools		
		Dynamic Pricing Platforms		
		Smart Charging Algorithms	*Integration with Electric Vehicles (EVs)*	
8	Priority 3	Energy Analytics Platforms	*Energy Management & Monitoring Tools*	≥50%
		Energy System Simulation Tools (e.g., HOMER, PLEXOS)	*Modelling & Simulation*	
		Energy Pooling Platforms	*Energy Sharing Platforms*	
		Peer-to-Peer (P2P) Energy Trading Platforms	*Energy Distribution Tools*	
		Energy Trading Tool		
		Community-Based Energy Access Programs	*Energy Access & Equity Tools*	
		Mobile Apps	*Communication and Collaboration Tools*	
		Weather Forecasting Tools	*Environmental Monitoring Tools*	

It should be noted that this methodology resulted in the prioritisation of certain applications over others. Consequently, not all needs of the demonstration sites –particularly those falling into generally less critical categories, were prioritised in the development of this Task 1.3.

The prioritisation phase was pivotal in determining the areas of interest for the pilots, prior to conducting the subsequent in-depth search of OSS tools (Section 2.6). It should be noted that this search will be conducted exclusively for the selected categories and applications as indicated in Table 2 and Table 3.

2.6 Tool Identification and Documentation

As demonstrated in Section 2.5 and evidenced by interviews and expert feedback, the demand for exploration of certain applications of OSS tools applied in local OSS systems is vast. This demand motivated the performance of a thorough academic literature and internet research, in addition to suggestions from partners of the consortium, of available OSS tools. The result consists of a long list of 204 solutions, of which 154 within the identified 29 applications (see APPENDIX C: OSS Tools Complete List, Table IV).

The following subsections offers a detailed exposition of the process and conclusions of the tools search, followed by the limitations of the performed analysis.

2.6.1 Methodology

The objective of this review of OSS solutions is to develop an in-depth understanding of the existing tools for identification, classification and evaluation that would support the defined applications of priority interest to the demonstration sites. These include, as shown in Table 3, for example *Automated Billing Platforms*, *Home Energy Management Systems, Energy Sharing Apps, Data Visualization Tools etc*.

The evaluation of all available OSS solutions is founded upon a comprehensive dataset, which has been assembled through a systematic scan of OSS *GitHub* repositories, academic publications, OSS foundations' websites and portals –such as *Linux Foundation*, *energy*, *NREL* and others–, various public-funded projects (e.g. *EU Horizon 2020*, and national public projects), and expert feedback. The set of solutions that had been collected was structured in accordance with a standard spreadsheet format and comprised 22 key metrics (KPIs) with the purpose of quantifying the efficiency of each tool in terms of technical, functional, organisational and developmental dimensions. The KPIs may be grouped in different dimensions as follows:

- **Tool Metadata:** OSS Tool Name, Domain, Category, Application, Affiliated Project –if any–, Use Cases, Year since inception, Github and Website link, and Developer – Host Organization.
- **Functionality Language:** Core Functionality, Key features, Programming Language, Level of Documentation.
- **Maintenance Interoperability:** License Type, Maintenance & Update Frequency, Standards compliance – Interoperability (e.g., REST APIs, MQTT, IEC 61850).
- **Community Environmental Aspects:** Community Support, Environmental Impact (e.g., blockchain energy use), Ease of Use, Cost, Forum presence.
- **Use Cases Limitations:** Limitations as known constraints (e.g. real-time capability, scalability), and typical deployment contexts.

Following the extraction of the key metrics for each OSS solution, a mapping was created according to the different prioritised categories and applications, bringing the number of selected solutions from 204 to 154. Besides, in the interest of maintaining a selective approach, tools that had already been archived, where core information was unavailable, or were too early in development, were excluded from the list from further assessment.

The outcome of this tools' review is providing an extensive catalogue of OSS solutions, along with a comprehensive review of their functionalities, maturity level, and community interest in terms of further development (see the Excel File found in the *U2Demo* Zenodo repository [1]).

The information from the catalogue of OSS solutions forms the basis for the mapping and interoperability analysis, core objective of Task 1.3, composed of a TRL assessment (Chapter 3), Functionality Mapping (Chapter 4), and Interoperability Assessment (Chapter 5).

The following subsections provides an overview of the overall number of tools, classified by domains, categories and applications that have been found, together with an explanation of the OSS tools matrix.

2.6.2 Analysis of the Identified OSS Tools

The OSS tools collected have been summarised in this subsection and counted based on the correspondent domain and category. In line with the 29-application selection, the 154 OSS solutions encompass 7 domains – namely *Access & Equity, Communication & Engagement, Emerging Innovation, Finance, Governance, Operations and Technologies*–, and 11 categories, as illustrated in Figure 4.

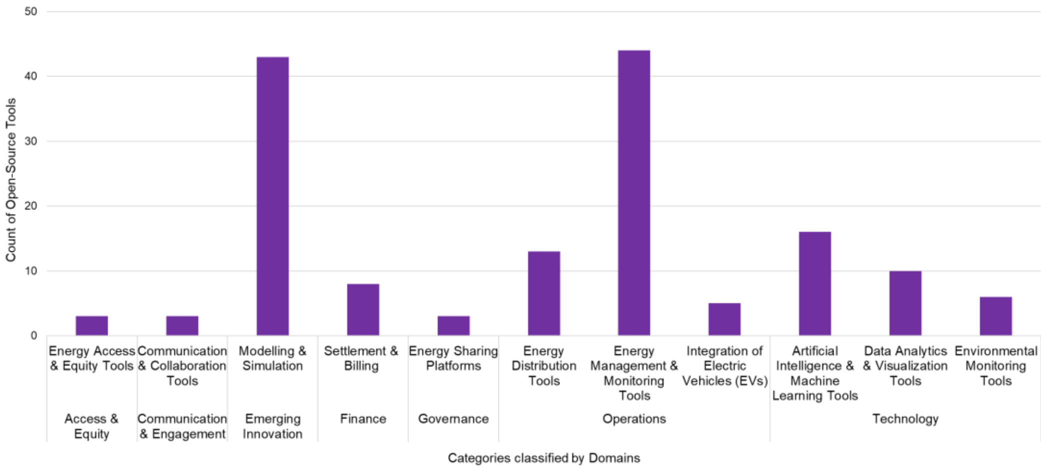

Figure 4 – Count of OSS Tools in each prioritised category and domain

It is evident that *Modelling & Simulation*, and *Energy Management & Monitoring Tools* are the two most prevalent categories, with each category having more than 50 OSS tools identified in the review. Contrarily, the least represented categories are *Communication & Collaboration Tools*, *Energy Access & Equity Tools and Energy Sharing Platforms*, with only a few of OSS solutions identified.

Similarly, an investigation can be conducted into the quantity of OSS solutions classified by applications (see Figure 5). In this case, the most represented applications are *Energy System Simulation Tools, Community level Modelling (*in the domain of *Emerging Innovation), and Energy Analytics Platforms, and Community Energy Management Systems (CEMS)* (domain of *Operations*) and, with 11 OSS tools each or above. Other numerous OSS solutions' applications are *Automated Billing Platforms, Demand Response Systems, Home Energy Management Systems and Data Visualization Tools*.

Among the seven domains, the most represented are *Operations*, *Emerging Innovations* and *Technology*.

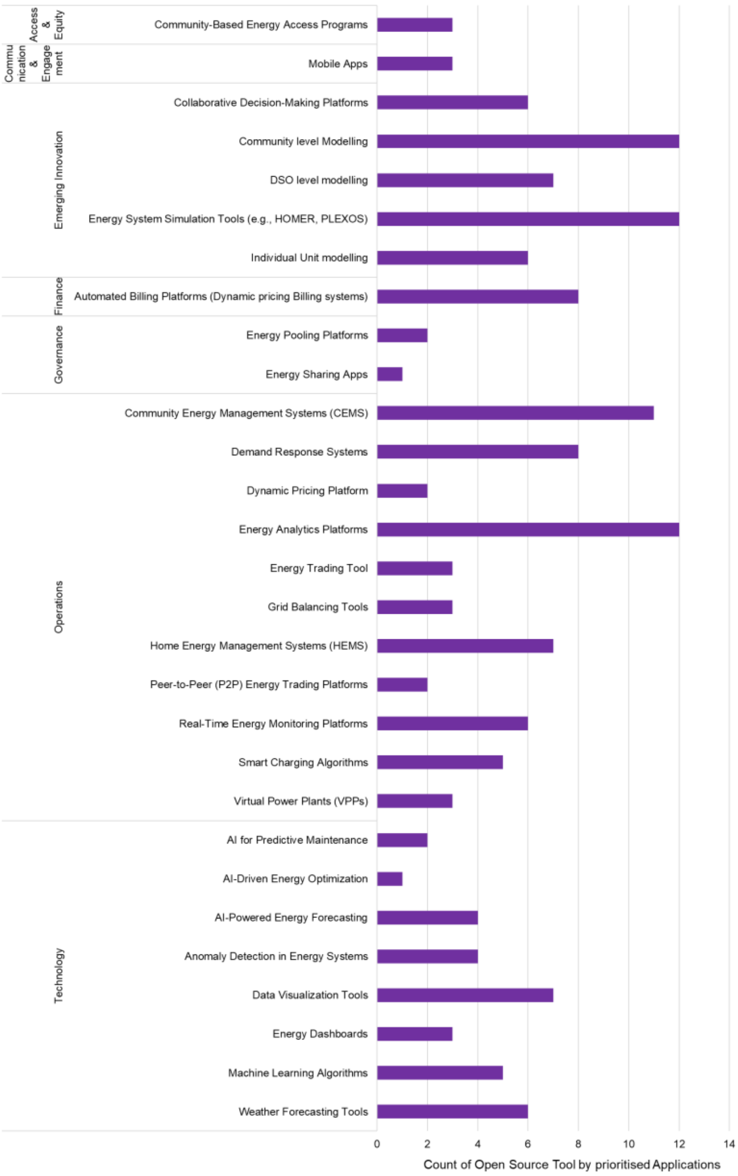

Figure 5 – Count of OSS tools in each prioritized application by domain

The number of OSS solutions is not expected to have a direct impact on the following steps of the mapping and interoperability. As it will be explained in Chapter 3, in order to ensure a more general representation of the interests of the demonstration sites in the field of local energy communities, only one tool per prioritized application will be selected for the following assessments.

2.6.3 Other Relevant Solutions for Stakeholders

In the context of *U2Demo,* additional OSS operational tools will be developed to implement proposed solutions in the demonstration sites. Indeed, while available OSS tools allow to deliver proven end-to-end solutions, the research context of *U2Demo* at the interface of energy communities and researchers encourages the development of tailor-made yet generalisable tools.

It is therefore essential that these developed tools themselves rely on open mathematical engines and modelling languages. Amongst the available modelling toolkits, the following two from the Python ecosystem will play a fundamental role in further developing OSS tools in *U2Demo WP4:*

- "*Pyomo*" [23]: a software package which allows to formulate, solve, and analyse optimisation models. It translates mathematical formulations into problem instances which can be used as inputs to either commercial or OSS optimization solvers to solve the problems. OSS solvers include *GLPK* (GNU Linear Programming Kit) and *CBC* (Coin-or brand and cut) for LP/MIP problems, *Bonmin and Couenne* for MINLP, amongst others.
- "*Pyoptinterface*" [24] : a new modelling language for mathematical optimization, which showcases promising performance features in terms of model generation time before passing it to the solver. Although less established than "*Pyomo"* to this day, it is interfaced with several OSS solvers, such as *HiGHS* for LP/MILP problems and *Ipopt* for NLP problems.

By combining the features of these different OSS modelling languages, a large variety of optimisation problems can be addressed in the context of *U2Demo*.

2.6.4 OSS Tools Catalogue: excel file review

The Excel File found in the *U2Demo* Zenodo repository [1] contains a matrix in sheet "*OSS Tools*" with a structured list of the 204 OSS tools identified as explained in Chapter 2.

Each of these solutions is classified across several domains, categories and application areas. The matrix also includes 22 KPIs to support comparative assessment (see Section 2.6.1). Users can filter or sort the table using built-in Excel functions (e.g. filters, or dropdown menus) to easily identify relevant tools based on specific categories, applications, or KPI priorities. This enables targeted exploration and analysis, especially useful for selecting tools aligned with a particular use case or functional need for the demonstration sites as indicated during the interviews.

A zoom on the matrix is shown in Figure 6 for representative reasons, while the entire matrix can be found extracted in Appendix C Table IV.

Open-Source Tools for Local Energy Communities classified by Domanin, Category, and Aplication

Domain	Category	Application	Open Source Tool Name	Developer	Project – if any	Core Functionality	Programming Language	Maintenance & Updates	Interoperability	Cost	License Type
Operations	Energy Distribution Tools	Energy Trading Tool	**POMATO (Power Market Tool)**	Richard Weinhold, Reiner Lemoine-Foundation, the		comprehensive analysis of the modern electricity	Python, Julia	Archived	Interfaces with Pyomo, pandas, NumPy	Free	LGPL 3.0
Operations	Energy Distribution Tools	Energy Trading Tool	**AMIRIS**	Helmholtz Digital Services for Science, GFZ Helmholtz-	ENERGOOD, Man0EUvRE, InvestAgent etc.	Agent-based simulation of electricity market	Java, Python	Frequently updated, active academic/resear	Limited, designed for research	Free	Apache-2.0
Operations	Energy Distribution Tools	Energy Trading Tool	**Grid Singularity (d3a.io)**	Grid Singularity	Energy Web Chain	Blockchain-based energy data exchange and grid	Python, HTML, SCSS, JavaScript,	Actively maintained	Based on Ethereum and Energy Web	Free	GPL-3.0
Operations	Energy Distribution Tools	Distribution Network Operat	**eDisGo(eGo^n)**	open_eGo		Low-voltage distribution grid simulation and	Python	Actively maintained	based on PyPSA	Free	AGPL-3.0
Operations	Energy Distribution Tools	Distribution Network Operat	**Pandapower – Python for Power System Analysis**	University of Kassel and Fraunhofer IEE	Forschungsprojekt RobustPlan, HybridBOT_FW	Distribution network modeling and analysis	Python	Actively maintained, regular updates	Excel, MATPOWER,	Free	BSD 3-Clause
Operations	Energy Distribution Tools	Grid Balancing Tools	**PowSyBl**	PowSyBl	PowSyBl project	grid analysis, visualization, and simulation.	Java	Actively maintained, regular updates	CGMES, IIDM, Rest APIs	Free	MPL 2.0
Operations	Energy Distribution Tools	Grid Balancing Tools	**OpenRAO(Open Remedial Actions Optimizer)**	PowSyBl	FARAO (OpenRAO)	toolbox for remedial actions optimisation	Java, Gherkin	Actively maintained,	CGMES, IIDM, Rest APIs	Free	MPL 2.0
Operations	Energy Distribution Tools	Grid Balancing Tools	**PowerDynamics.jl**	Potsdam Institute for Climate Impact		Modeling and simulation of	Julia	Moderately maintained	JuliaEnergy packages	Free	GNU GPL-3.0
Operations	Energy Distribution Tools	Dynamic Pricing Platform	**OpenEMS**	Open EMS Association e.V.	BloGPV, Delfine, EASY-RES,	Real-time energy management and	Java, HTML, TypeScript,	Actively maintained,	MQTT, Modbus, REST APIs,	Free	GNU AGPL-3.0, EPL-2.0
Communication and E	Communication and Collaboration Tools	Community Platforms	**Decidim**	City Council of Barcelona	NYC Civic Engagement Commission	participatory democracy platform	Ruby	Actively maintained with regular updates	REST API, OAuth2,	Free	AGPL-3.0
Communication and E	Communication and Collaboration Tools	Community Platforms	**Friendica**	Friendica community	networking with Mastodon,	community communication and	PHP	maintained with regular updates	Diaspora*, OStatus, RSS,	Free	AGPL-3.0

Figure 6 – Zoom on the OSS Tools Matrix

2.7 OSS Solutions Limitations

The scope of this review of OSS solutions has encompassed all the most relevant applications of local energy communities. Nevertheless, an evaluation of the fundings has exposed significant deficiencies and developmental lacunae, which impede the solutions' scalability and mass adoption, as will be addressed in the next Chapters of this report.

The limitations of OSS tools observed at this stage of the analysis may be summarized as follows:

- **Fragmentation Across Tools:** several tools operate as stand-alone and are not equipped with standardized interfaces, with the effect of creating a barrier for interoperability with larger platforms. This is one of the primary obstacles hindering the development of a modular system architecture.
- **Uneven Maturity Levels:** several tools lack active community engagement, evidenced by non-continuous updates, inadequate documentation and inactive community support. Despite the evident quality of innovation encouraged in several tools, there is a clear absence of any progressive development.
- **Lack of Localised Support:** only a limited number of tools have exhibited the necessary robustness of application in various regulatory environments, or grid connectivity across EU member states.
- **Under-Representation in Key Categories:** some categories, identified as high priority by the demonstration site managers and experts, are under-represented due to limited development of OSS solutions in those areas. Some categories' examples include *Communication & Collaboration Tools*, *Energy Access & Equity Tools, Energy Sharing Platforms, Integration with Electric Vehicles, and Environmental Monitoring Tools.*
- **Barriers for Adoption by Non-Technical Users:** a significant challenge for most of the OSS solutions consists of their constrained capacity for adoption by non-technical users. The complexity of the installation process, the absence of user interfaces, and the limited documentation available for onboarding create a barrier to their adoption in citizen-led initiatives, where digital expertise is generally expected to be limited.
- **Sustainability and Governance:** the absence of a governance structure in many of the tools is a matter of concern, as it poses a threat to the long-term development of those tools. An interesting case was observed in several EU-funded and national project initiatives throughout Europe, where the advancement of tools' development frequently ceased following the termination of project funding. This phenomenon results in the premature abandonment of innovative instruments prior to reaching high TRLs.

Despite the challenges faced by the OSS ecosystem, it still holds significant potential. The promotion of an environment that fosters interoperable, innovative, and sustainable community-focused local energy systems is a key benefit.

Finally, the limitations identified in this section form the basis for the Mapping and Interoperability Assessment of the OSS tools identified in Chapter 2.

The mapping is presented in the next three chapters: TRL assessment (Chapter 3), Functionality Mapping (Chapter 4), and Interoperability Assessment (Chapter 5).

3 Technology Readiness Level (TRL) Assessment

The TRL framework was originally developed by NASA and later adopted by the European Commission to assess the maturity of different technologies, tools, solutions, software, and hardware. It is now widely accepted as the standard measure of maturity level of different technologies. TRL assessments provide a standardised scale for evaluating any type of tools and categorize them as being in the early research phase, live systems, pilot site demonstrations, or market-scale deployments.

OSS tools and solutions can vary significantly in terms of their technical maturity, documentation, community support, application at specific demonstration sites and market-scale deployment. Some solutions are mature enough to have strong community and developer support, proper documentation, and integration into large-scale demonstration sites. Others are at a varying degree of development, ranging from early-stage concept design and research with low validation, to others with more developed features and documentation, and growing popularity and community. In this case, the TRL assessment will support stakeholders and new adopters of these solutions by:

- **Identifying and comparing** various OSS tools and solutions to find the best one for the pilots' specific use cases.
- **Analysing the gaps** in the present architecture and focusing on technical development and validation on those specific parts.
- **Prioritizing technical and economic support** for community-relevant technologies.

In this Chapter 3, the final TRL scores are assigned to each of the identified OSS tools after an analysis performed using a scoring and weightage methodology, and not only a binary inclusion / exclusion filter. This methodology is further explained in the next Section 3.1, to provide a clear picture of each tool selected as part of the literature search in Section 2.6.

3.1 Methodology

The TRL assessment was based on a novel methodology developed by EIFER to evaluate OSS solutions. As an upcoming journal article on the topic is in progress, only the general approach of this methodology will be explained in this section.

The evaluation process was conducted on each of the OSS tools that were identified in Section 2.6. The detailed steps used for the TRL assessment are described below:

- **Step 1**: A set of four principal criteria was developed for the purpose of assessing different aspects of technological maturity: *Development & Maintenance, Integrability & Deployment, Technical Robustness, Use Case Demonstration.* The description of each criterion is presented in Table 4.
- **Step 2**: Weightings were allocated to each individual category, according to their relevance for the current assessment within *U2Demo* (see Table 4). The assigned weightings contribute to the calculation of the final TRL scores and can be calibrated according to the purpose of the OSS tools analysis. In the present study, the most relevant criterion has been identified in the *Use Case Demonstration* (50% weightage). This is because one the objectives of *U2Demo* is the implementation of OSS solutions at the demonstration sites, therefore it is important to identify tools that are already being applied in other pilots or projects.

Table 4: Criteria for TRL assessment, description and weightage

Criteria	Criteria Description	Weightage criteria	Weightage
Development & Maintenance	Measures the level of active development, quality of technical documentation, and the availability of support for maintenance and updates.	Weight is set higher if reliance on ongoing community updates	15%
Integrability & Deployment	Evaluates the tool's readiness for integration with external systems and ease of deployment in real-world environments.	Weight is set higher for integration in open-source ecosystems (typical for tools with mid-TRLs 5–7)	20%
Technical Robustness	Assesses the maturity and reliability of the tool's core features, including code quality, development practices, testing coverage, and adherence to open-source standards.	Weight is set higher for research tools (typical for tools with low TRLs 3–5)	15%
Use Case Demonstration	Determines the extent to which the tool has been applied or validated in operational settings relevant to energy communities or similar real-world contexts.	Weight is set higher for tools to be implemented or public funded projects (typical for tools with high TRLs 7–9)	50%

- **Step 3**: A set of metrics was internally defined for each category to facilitate the quantification of the analysis, as will be presented in the upcoming journal article. A total of 20 key metrics were identified with the objective of quantifying the respective criteria and thereby reducing qualitative assessments and any potential biases. Then, as for Step 2, each metric was assigned a weightage based on its relevance to the assessment (see Table 5).

Table 5: Metrics for TRL assessment by criteria, and description

N.	Metric	Criteria	Scoring Description
1	*Stars*	Development & Maintenance	Community popularity
2	*Forks*	Development & Maintenance	Cloning/customization signal
3	*Watchers*	Development & Maintenance	Ongoing interest indicator
4	*Pull Requests*	Development & Maintenance	Community collaboration
5	*Active Contributors*	Development & Maintenance	Community sustainability
6	*Last Push Date*	Development & Maintenance	Update frequency proxy
7	*License Type*	Integrability & Deployability	Legal reuse permission
8	*Languages / Tech Stack*	Integratability & Deployability	Code modularity/complexity
9	*API Interface Readiness*	Integrability & Deployability	Swagger/OpenAPI, CLI readiness
10	*User & Developer Documentation*	Integrability & Deployability	Docs for setup, APIs, diagrams
11	*Open Issues*	Technical Robustness	Unresolved issues volume
12	*Closed Issues*	Technical Robustness	Total resolved issue count
13	*Issue Resolution Rate*	Technical Robustness	Closed vs total issue %
14	*CI/CD Workflows*	Technical Robustness	Automated build/deploy maturity
15	*Testing Frequency*	Technical Robustness	Automated test validation frequency
16	*Commits (Est)*	Technical Robustness	Codebase development activity
17	*Real-World Deployments*	Use Case Demonstration	Active usage in projects/pilots
18	*Public Project Inclusion*	Use Case Demonstration	Horizon Europe /National project deliverables or links
19	*User Base or Adoption*	Use Case Demonstration	Evidence of community or user base
20	*Use in Energy Community*	Use Case Demonstration	Referenced in local energy/grid deployments

- **Step 4**: The scoring threshold was defined. The data were normalized between 1 and 5, named average metric score, with 1 representing the lowest possible score and 5 the highest (see Table 6).
- **Step 5**: The averaged metric scores were calculated with consideration for the weightage first of each metric and then of each criterion, in order to determine the ultimate TRL score of each solution. The TRL scores range from TRL2 to TRL9. For high TRLs (6 to 9), the increment in TRL score correspond to an increment of 0.5 in the average metric score. However, for low TRLs (3 to 5), the increment is set to 0.3. In fact, the original TRL definition, as provided in [25], describes the progression of TRL from proof of concept to validation in a relevant environment, which signifies a smaller leap for the use case of energy communities. The TRL scores according to the metric score ranges and their description are presented in Table 6.

Table 6: Thresholds definition for the final TRL score

TRL Score	Average Metric Score	Description
TRL 2	1.0 – 2.0	Initial concept or basic principles observed
TRL 3	2.0 – 2.3	Proof of concept or early-stage prototype
TRL 4	2.3 – 2.6	
TRL 5	2.6 – 3.0	Validated in relevant or operational environments
TRL 6	3.0 – 3.5	
TRL 7	3.5 – 4.0	Piloted or deployed in real-world projects
TRL 8	4.0 – 4.5	
TRL 9	4.5 – 5.0	Fully mature technology, widely adopted

- **Step 6**: A TRL heatmap was created to illustrate the highest TRL score's OSS solutions for each prioritised application, as outlined in Section 2.5.

3.2 TRL Assessment Results

The TRL scores were calculated for all 204 identified OSS tools from Section 2.6. Each tool received a corresponding TRL depending on the threshold definition as provided in Table 6. The complete TRL evaluation is reported in the Excel File found in the *U2Demo* Zenodo repository [1].

In this excel, the sheet "*TRL metrics Score*" shows the score of all the 204 selected OSS solutions based on the metrics as demonstrated in Table 5, along with the weightage calculation for each criteria as mentioned in Table 4.

For the purposes of this Task 1.3, the final selection of OSS tools has been conducted only for the highest TRL scores for each prioritized application to represent the general interest emerged from the interviews of the demonstration sites.

The following Figure 7 illustrates the 30 OSS tools that achieved the highest TRL scores out of the complete 204 solutions' list, being identified as the most complete OSS tools for deployment. The heatmap showcases a snapshot of the most mature solutions and their level of development in the four weighted criteria: *Development & Maintenance, Integration & Deployment, Technical Robustness, and Use Case Demonstration*.

N.	Open Source Tools		TRL	Development & Maintenance	Integratability & Deployment	Technical Robustness	Use Case Demonstration
1	*Hyperledger Fabric*	Blockchain Technology (or DLT)	9				
2	*Home Assistant*	Mobile Apps	9				
3	*PyTorch*	Machine Learning Algorithms	9				
4	*QGIS*	GIS (Geographic Information Systems)	9				
5	*ThingsBoard*	Energy Dashboards	9				
6	*Grafana*	Data Visualization Tools	9				
7	*InfluxDB*	Time-Series Data Analysis Tools	9				
8	*Prometheus*	Time-Series Data Analysis Tools	9				
9	*MISP*	Cybersecurity Tools for Energy Systems	9				
10	*pvlib python*	Energy Analytics Platforms	9				
11	*OpenHAB*	Home Energy Management Systems (HEMS)	9				
12	*Wetterdienst*	Weather Forecasting Tools	9				
13	*Metabase*	Data Visualization Tools	8				
14	*EnergyPlus*	Energy Analytics Platforms	8				
15	*Chart.js*	Data Visualization Tools	8				
16	*PyPSA*	Community level Modelling	8				
17	*EnergyID*	Remote Monitoring Tools	8				
18	*Darts*	Time-Series Data Analysis Tools	8				
19	*Apache Flink*	Big Data Platforms	8				
20	*EVCC*	Smart Charging Algorithms	8				
21	*Decidim*	Community Platforms	8				
22	*Apache Superset*	Data Visualization Tools	8				
23	*OpenCTI*	Cybersecurity Tools for Energy Systems	8				
24	*OpenStudio*	Community level Modelling	8				
25	*Loomio*	Collaborative Decision-Making Platforms	8				
26	*ERPNext*	Automated Billing Platforms	8				
27	*IOTA*	Blockchain Technology (or DLT)	8				
28	*Open-Meteo*	Weather Forecasting Tools	8				
29	*Netdata*	Remote Monitoring Tools	8				
30	*PostHog*	Energy Analytics Platforms	8				

Figure 7 – Heat Map of OSS tools with the highest TRL score

It is evident that there are certain industry-grade tools that have been demonstrated to possess a high TRL score and maturity. This is indicative of their practical real-world commercial application, extensive adoption across a diverse range of sectors, not only limited to energy communities, and their inherent technical robustness.

In the field of *Blockchain*-based energy transactions and *Mobile Apps* for home automation, two solutions have demonstrated particularly high levels of mature integration within energy communities, respectively: "*Hyper Ledger Fabric*" by IBM [26] and "*Home Assistant*" [6]. "*Hyper Ledger Fabric*" is a modular, open-source blockchain framework that enables plug-and-play components like consensus and membership services, supporting scalable and privacy-preserving enterprise applications. "*Home Assistant*" is a home automation platform that provides a modular architecture for integration of IoT devices, protocols, and APIs. These solutions have achieved amongst the highest *Use Case Demonstration* score of 4.92, reflecting their advanced capabilities in this criterion (TRL 9). *"PyTorch"* [27], also TRL 9, represents another noteworthy example of a general-purpose *machine learning* framework. It has been extensively utilised by ECs exclusively for energy forecasting and the deployment of other machine learning algorithms within their digital architecture.

Other TRL 9 tools which are worthy of mentioning include, but not limited to, "*Things Board*" [28], "*Grafana*" [29], "*InfluxDB*" [30], and "*QGIS*" [31]. As all part of the category *Data Analytics and Visualization Tools*, these tools form the skeleton of the data infrastructure for energy monitoring and visualisation due to their mature technical ecosystem (high *Technical Robustness* scores above 4.75). In particular, the latter is an OSS *Geographic Information System* (GIS) platform, which plays an important role in the realm of geospatial energy planning and mapping. Meanwhile, "*MISP*" [32] and "*Prometheus*" [33], both TRL 9 with a high score on *Use Case Demonstration (*above 4.83*)*, contribute extensively to improve the cybersecurity and time-series data analytics in decentralised energy systems, playing an important role in resilient grid management.

In addition, an active role in *Energy Management and Environmental Monitoring*, as home energy management, photovoltaic modelling, and weather data integration is demonstrated by tools such as "*OpenHAB*" [34], "*pyLib Python*" [35], and "*Wetterdienst*" [36], respectively. These tools' cumulative role is of great importance to the development of the demand-supply balance and forecasting in ECs.

The collection of these high TRL solutions engenders a comprehensive outlook of the most mature segment of the OSS tools available for local energy communities. This segment of TRL 9 tools is characterised by its immediate deployment, scalability, and integration with existing and emerging digital infrastructure in ECs.

However, several tools have also been calculated to have achieved TRL 8, thus still demonstrating their high active community support in *Use Case Demonstrations* and high-scale *Interoperability and Deployment*. Nonetheless, these tools fail to meet the highest threshold of complete deployment in local energy systems as defined by the methodology employed, particularly for the criteria of *Development and Maintenance*. It is interesting to note that a number of these tools are recognised as industry-grade solutions and qualify for TRL 9 in the general context. However, the tools in question are assigned a lower score in the assessment process due to their inherent limitations about direct application in decentralised energy community environments, a key component of the methodology used.

To illustrate this point, consider "*PyPSA*" [37]. This is one of the most widely utilised OSS tools with a well-established presence in national and regional-scale energy systems modelling. However, its integration within community-level energy architecture remains limited, and the utilisation within this context remains inadequately documented and acknowledged, resulting in a score that corresponds to TRL 8.

3.2.1 Highest TRL scores per prioritised applications

After having a look at the tools with overall highest TRL scores, the most relevant part of the analysis for the scope of this Task 1.3 is to collect the results from the TRL assessment by choosing one solution per application based on the priority list, and insert into a heat map (see Figure 8). This allows to visualize the level of maturity of the highest ranked OSS tools by prioritised application (29 applications). Besides, "*Open-Remote*" [2] has been added to the list of analysed tools being the one in use in the Dutch demonstration site.

As illustrated in Figure 8, 11 of the tools with the highest TRL per application correspond to the highest TRL score tools, all having TRL 9. These include "*Home Assistant*" [6], "*PyTorch*" [27], "*OpenHAB*" [34], "*Wetterdienst*" [36], "*Things Board*" [28] and "*Grafana*" [29], which have been already described in Section 3.2. A subsequent analysis will be conducted for the remaining tools.

N.	Open Source Tools	Applications	TRL	Development & Maintenance	Integratability & Deployment	Technical Robustness	Use Case Demonstration
1	*Volttron*	Community Energy Management Systems (CEMS)	8				
2	*OpenHAB*	Home Energy Management Systems (HEMS)	9				
3	*OpenLEADR*	Demand Response Systems	8				
4	*Smart Citizen Kit*	Real-Time Energy Monitoring Platforms	7				
5	*pvlib python*	Energy Analytics Platforms	9				
6	*OpenModelica*	DSO level modelling	8				
7	*PyPSA*	Community level Modelling	8				
8	*ResStock*	Individual Unit modelling	8				
9	*MATPOWER*	Energy System Simulation Tools	8				
10	*Loomio*	Collaborative Decision-Making Platforms	8				
11	*ERPNext*	Automated Billing Platforms	8				
12	*OpenSTEF*	AI-Powered Energy Forecasting	8				
13	*PyTorch*	Machine Learning Algorithms	9				
14	*MESMO*	AI-Driven Energy Optimization	6				
15	*Anomalib*	Anomaly Detection in Energy Systems	7				
16	*Predictive Maintenance with AI Azure*	AI for Predictive Maintenance	7				
17	*ThingsBoard*	Energy Dashboards	9				
18	*Grafana*	Data Visualization Tools	9				
19	*Local Energy Sharing Simulator (LESS)*	Energy Sharing Apps	4				
20	*Enflow*	Energy Pooling Platforms	4				
21	*PowerMatcher*	Peer-to-Peer (P2P) Energy Trading Platforms	7				
22	*REScoopVPP*	Virtual Power Plants (VPPs)	7				
23	*Grid Singularity (d3a.io)*	Energy Trading Tool	8				
24	*PowSyBl*	Grid Balancing Tools	8				
25	*OpenEMS*	Dynamic Pricing Platform	8				
26	*Reopt*	Community-Based Energy Access Programs	8				
27	*Home Assistant*	Mobile Apps	9				
28	*Wetterdienst*	Weather Forecasting Tools	9				
29	*EVCC*	Smart Chargin Algorithm	8				
30	*OpenRemote*	Community Energy Management Systems (CEMS)	8				

Figure 8 – Heat Map of OSS tools with highest TRL score per prioritised Application

"*OpenEMS*" [3] and "*Grid Singularity*" [38] (TRL 8) have been identified as platforms for *Dynamic Pricing* and *Energy Trading* applications in the category of *Energy Distribution*. However, the application of these technologies within the domain of energy communities is still emerging. Despite their commercial-grade architecture, their evaluation suffered from a lack of development in publicly verifiable ECs.

Besides, it has been observed that "*PowSyBl*" [39], *"Open Modelica"* [40], *"MATPower"* [41], and "*Energy Plus"* [42] (see Figure 7 of top TRL scores), also present with analogous issues. The utilisation of these tools by utilities and TSO/DSO in commercial-level applications is indicative of their high *Integrability* and *Technical Robustness*. However, the methodology employed by the present study resulted in a slightly lower TRL for said tools, a consequence of the inadequate documentation of their applications in community-owned or cooperative energy setups.

Conversely, tools such as "*OpenLEADR*" [43] are either nascent in terms of maturity or specialised in one specific application. This is appropriately marked as TRL 8. "*OpenLEADR*" [43] is a particular instrument designed for demand response automation, yet it has not been adopted extensively, particularly among smaller ECs.

Collaborative decision-making tools such as "*Loomio*" [44] – but also some other governance tools as "*Decidim*" [45] from Figure 7 –, facilitate public participation and support governance. These are of particular pertinence to collectives with a focus on cooperation and prosumers.

Nevertheless, a direct connection to the energy workflows is not established, which curtails the full demonstration of their value, resulting in a marginally diminished TRL value: TRL 8.

Tools like "*Home Assistant*" [6], "*PyTorch*" [27], "*Grafana*" [29], and "*ThingsBoard*" [28] demonstrates their wide-spread development on the metrics and criteria chosen for the analysis. As showed by their evaluation against the criteria of *Use Case Demonstration*, it is evident that they have a significant degree of application in real-world deployments, particularly within the EC domain. Conversely, a number of tools with optimal *Technical Robustness*, including "*PyPSA*" [37], "*OpenModelica*" [40], "*Volttron*" [4] and "*ResStock*" [46], exhibit a marginally diminished TRL. This is not attributable to a lack of technical maturity, but rather to their integration within community-scale implementations.

Furthermore, "*PowerMatcher*" [47] and "*REScoopVPP*" [48], which are pertinent to the concept of energy democracy, received low TRL scores (TRL 7) due to limited further development, an absence of support from the community, and limited active contributors. This demonstrates that even tools which show strong potential for large-scale adoption can be lost due to a lack of financial and developmental resources, a phenomenon which is particularly prevalent in the non-commercialised OSS solutions.

Tools assessed TRL 7 or below represent a heterogeneous group, including technically mature solutions that are widely accepted in industry, as well as context-specific tools or those that rely heavily on third-party components for full deployment. While certain tools—such as modelling platforms, data frameworks, and monitoring solutions—may reach TRL 9 in general applications, they fall short under our methodology due to its specific focus on community energy contexts. Furthermore, some tools exhibit lower TRLs despite being used commercially, primarily because their OSS development has either stagnated or diverged into proprietary versions. As our assessment relies exclusively on publicly accessible data (e.g., GitHub repositories, official websites, community forums, and academic sources), tools behind paywalls or restricted licenses are excluded from full evaluation.

Overall, the heatmap analysis highlights that community deployment and technical robustness constitute fundamental pillars for the success of any OSS tool. The observed trends suggest that tools intended for deployment within ECs must not only exhibit technical robustness but also possess well-developed features that support usability across diverse EC contexts. These findings are particularly valuable for stakeholders, community managers, and architecture developers engaged in the development and deployment of tools for energy communities, as they provide guidance for selecting context-appropriate solutions and for assessing the technical, economic, and integrative requirements necessary for successful implementation.

This assessment constitutes the first part of the Mapping and Interoperability Assessment (see Section 1.2), providing an evaluation of the technological maturity of the collected OSS tools to further screen and select the most advanced solutions for the next step of the analysis: functionality mapping.

4 Functionality Mapping

The functionality mapping of each chosen high TRL OSS tool is conducted in order to assess the extent to which these tools fulfil the application requirements of each demonstration site, which are considered to be of high priority as outlined in Section 2.5.

Specifically, the breadth, depth, and usability of each solution are evaluated in the functionality mapping assessment, with possible implementation in the demonstration sites. While the TRL assessment is distinguished by its emphasis on the maturity of each OSS solution, the functionality mapping places greater emphasis on the scope. The relevance and quality of the functionalities delivered by each individual tool in its intended application are of great importance.

The following three core requirements guided the analysis of these OSS solutions:

1. How each individual tool fulfils the specific requirements of the demonstration sites.
2. What is the level of maturity required to complement the prioritised functionality in the demonstration sites.
3. What is the level of ease with which these individual tools and solutions can be adopted, utilised, and scaled up.

4.1 Methodology

The functionality mapping of each individual tool was conducted in accordance with the following steps:

- **High TRL Score:** as outlined in Section 3.2, the TRL assessment yielded a selection of OSS solutions with a high level of maturity that may be applicable to individual demonstration sites. These same tools were selected for the functionality mapping.
- **Key Functionality Metrics:** these correspond to the applications selected based on the interviews conducted with the demonstration sites and their academic counterparts as reported in Section 2.4, and according to the prioritisation in Section 2.5.
- **Scoring Mechanism:** a scoring mechanism – from 1 to 3 – was developed to evaluate how well each selected OSS tool performs in the most relevant identified functionalities, including their main application area.

4.1.1 Key Functionalities Metrics

The evaluation criteria on which the key metrics were devised are based on the following:

- **Core Functionality:** the tool's capacity to deliver on its core functionality in accordance with its asserted specifications.
- **Feature Completeness:** the extent to which the tool under analysis offers additional features that serve to supplement its core functionality.
- **Modularity and Scalability:** the capacity of each individual tool to support and communicate with an external environment. The extension of this criterion is also explored in the Interoperability Assessment in Chapter 5.

- **Useability:** the level of support mechanisms that have been developed for the purpose of facilitating the ease of use of the tools in existing architecture for technical as well as non-technical users.
- **Deployment Readiness:** the level of ease with which each solution can be installed and configured, besides the presence of guides and other forms of support for each tool.
- **Documentation and support resources:** the existence of documentation, availability of tutorials, community forums and other forms of support.

In accordance with the aforementioned criteria and the interviews conducted with the demonstration sites, the subsequent functionality requirements, corresponding to the selected applications with Priority 1 from Section 2.5.2, were chosen to analyse how each of the identified OSS tools performs in those application area. The 12 selected functionalities are:

1. Community Energy Management System (CEMS)
2. Home Energy Management System (HEMS)
3. Demand Response Systems
4. Community Level Modelling
5. AI-Powered Energy Forecasting
6. Machine Learning Algorithms
7. AI-driven Energy Optimization
8. Anomaly Detection in Energy systems
9. Energy Dashboards
10. Data Visualization
11. Energy Sharing Apps
12. Automated Billing Platforms

After the functionalities have been decided, a scoring system for evaluation has been developed, described in Section 4.1.2.

4.1.2 Scoring Mechanism

Following the establishment of the framework, a scoring system was devised for the purpose of mapping all selected functionalities. This system was developed to establish the overall ability of a tool to meet the operational requirements of individual demonstration sites of *U2Demo*.

Each of the 12 prioritized applications listed in Section 4.1.1, is assigned a score ranging from 0 to 3, based on how well this functionality is developed within the tool.

The scoring scale framework utilized for this purpose is described in the following Table 7.

Table 7: Scoring framework for functionality mapping of OSS tools

Score	Definition	Criteria Description
0	Not Available	The functionality is not available
1	Limited	Basic or partial functionality available or implemented
2	Adequate	Core functionality is available and useable. However, lacks advanced features, documentation, or ease of use
3	Comprehensive	Fully implemented functionality with proper documentation and community support

Therefore, the total functionality score for each tool ranges from 0 to 36. It is widely accepted that tools with a high functionality score, particularly when combined with the TRL assessment conducted in Chapter 3, are to be regarded as robust, more flexible in terms of the range of offered applications, and ready for deployment at the demonstration sites. Conversely, tools with a lower functionality score may be regarded as mature (high TRL) but not directly deployable in those areas of analysis.

The evaluation and scoring selection of the individual tools were conducted through a manual review of the following:

- Official project websites and GitHub repositories.
- Discussion with demonstration sites, available documentation, or user interfaces.
- Deployment instructions or docker files.
- Visual aids such as screenshots, walkthrough videos, and community forums.
- Academic literature and EU-project references.

Finally, following the completion of the framework development, the results were compiled, as illustrated in the subsequent section.

4.2 Functionality Mapping Results

As illustrated in Figure 9, the functional mapping of 12 (Priority 1) applications of OSS tools is demonstrated. The comprehensive functional mapping of all 29 tools, encompassing all application scenarios of Priority1, Priority 2, and Priority 3, in conjunction with "*Open Remote*" [2] being the one utilised in the Dutch pilot, is presented in the Excel File found in the *U2Demo* Zenodo repository [1], in the sheet named "*Functionality Mapping*". A table of complete results can also be found in Appendix D – Table V.

The analysis evaluates the alignment of each individual tool with the requirements of local energy communities in general, and more specifically with the four demonstration sites of *U2Demo*. These include among others, *Community Energy Management Systems*, *AI-Powered Energy Forecasting*, *Data Visualisation* and *Energy Sharing Apps*.

The following Figure 9 is a heat map, with the darkest colour denoting the highest score of 3, of the individual scores for each functionality for the OSS tools. These are classified according to the same ordered applications (e.g. “*OpenLEADR*” [43] is classified for the *Demand Response* application, and “*PyPSA*” [37] under the application *Community Level Modelling*). It has thus been demonstrated, looking at the darker coloured diagonal in the heat map, that each of these tools performs optimally within the applications for which they are designed, as would be expected.

	1	2	3	4	5	6	7	8	9	10	11	12	
Open-Source Tools	**CEMS**	**HEMS**	**DR Systems**	**Community level Modelling**	**AI-powered Forecasting**	**ML algorithms**	**AI-Driven Energy Optimization**	**Anomaly Detection**	**Energy Dashboards**	**Data visualization**	**Energy sharing Apps**	**Automated Billing Platforms**	**SUM**
Volttron	3	2	3	2	1	2	2	2	1	1	2	1	22
OpenHAB	1	3	1	0	0	1	1	0	2	3	1	0	13
OpenLEADR	2	1	3	0	0	1	1	1	1	1	1	0	12
PyPSA	1	0	2	3	2	2	2	1	1	2	1	0	17
OpenSTEF	2	1	2	2	3	3	1	1	1	2	1	0	19
PyTorch	0	0	0	0	3	3	3	1	0	1	0	0	11
MESMO	2	1	2	3	2	2	2	2	1	2	1	0	20
Anomalib	0	0	0	0	0	3	1	3	0	1	0	0	8
ThingsBoard	2	2	2	1	2	2	1	2	3	3	1	1	22
Grafana	0	0	0	0	0	0	0	1	3	3	0	0	7
Local Energy Sharing Simulator (LESS)	1	0	0	2	0	0	1	0	1	1	3	2	11
ERPNext	1	0	0	0	0	0	0	0	0	2	0	3	6

Figure 9 – Functionality Mapping of the 12 tools with highest TRL score per prioritized application

It is evident that “*Volttron*” [4], “*ThingsBoard*” [28], “*OpenEMS*” [3] and “*Open Remote*” [2], tools which obtained the highest overall functionality mapping score with 22 points, but also “*MESMO*” [49] (score 20), demonstrate a strong coverage across key application areas suitable for energy communities. For instance, “*Volttron*” [4] has been shown to demonstrate notable efficacy in its function as a *community energy management system*, but also in the context of *demand response*, and in the implementation of *AI-driven forecasting*. Furthermore, the application has been identified as a strong contender for adoption within energy communities.

It is to be noted that, for the case of *AI-driven energy optimisation*, no such tool has been identified with native energy optimization as part of their Github repository. However, there are AI-extendable platforms available, such as “*OpenEMS*” [3], “*MESMO*” [49], “*OpenSTEF*” [50], “*PyPSA*” [37]. For example, “*Volttron*” [4] mentions the availability of customisable agents which may be integrated with external AI-based systems. But given its categorization in *Community Energy Management System*, “*MESMO*” was chosen as an alternative to it. Nevertheless, “*MESMO*” is a mathematical optimisation platform which may be integrated with external AI-agents to derive AI-based optimisations. Besides, despite tools like “*Pytorch*” [27] and “*Predictive Maintenance by Azure*” [51] have AI frameworks incorporated in them, they are better suited for other functionalities which are also priority for the demonstration sites. Tools like “*Volttron*” [4] have customizable agents and can incorporate python libraries for AI optimization but their demonstration in energy communities have not been observed yet. Similarly, for automated billing platforms, apart from “*ERP next*” which has inherent architecture for automation of billing and customer relationship management, other tools and solutions don’t have this functionality as one of their KPIs. For example, the capacity of automated agents in "Volttron" to perform billing when connected to external billing agents remains unproven as such a capability has not yet been demonstrated in any project, as per the review.

It is evident that certain tools are specialised within a specific field of application. For instance, "*PyPSA*" [37] primary focus is on *modelling and simulation*, with application in *community-level modelling*. However, it also demonstrates its affinity for adopting *AI-driven forecasting and optimisation* in its architecture. Conversely, certain tools, including "*Grafana*" [29] (score 7), "*ERPNext*" [52] (score 6), "*Loomio*" [44] (score 3), and "*Wetterdienst*" [36] (score 2), are characterised by their specialisation in selected key application areas within energy communities and scored poorly (see also Appendix D Table V). Nevertheless, the high technical robustness (high TRL scores) and interoperability of these systems renders them a suitable choice for adoption in ECs, particularly in conjunction with other OSS solutions.

The following Figure 10, reports the radar charts of the six OSS tools with the highest functionality mapping score (all 22 points each, except from "*MESMO*" [49] and "*REScoopVPP*" [48] with 20 points).

Figure 10 – Radar Chart of the 6 tools with highest functionality mapping scores

In consideration of each key application area, the functional mapping provides several alternatives that can be incorporated into the overall architecture of energy communities. However, analysis of the radar chart (see Figure 10) and the heatmap of Priority 1 applications (see Table 7) indicates that no single tool can meet all the requirements of the ECs. However, a combination of two or more solutions is likely to be effective in meeting the requirements of individual communities.

In conclusion, the functional mapping demonstrates a healthy ecosystem of OSS solutions that collectively address all the strategic high-priority requirements of energy communities. It is evident that no single instrument is capable of addressing all 12 key application domains. However, certain instruments offer comprehensive solutions for 4-5 key domains. In addition, there are instruments that exhibit high maturity in 1-2 key domains. When employed in conjunction, these instruments may not only fulfil the majority of requirements but also provide substantial technical maturity and robustness to the digital infrastructure of the demonstration sites.

With the Functionality Mapping, the first two parts of the Mapping and Interoperability Assessment (see Section 1.2), have been performed. Firstly, the TRL assessment (Chapter 3) has evidenced the technological maturity of the collected OSS tools. Secondly, the functionality mapping (Chapter 4) has identified which tools support best which set of high priority application areas for local energy communities. In the following Chapter 5, the interoperability of the highest performing OSS tools is finally tested.

5 Interoperability Assessment

As energy communities increasingly rely on digital platforms for the production, consumption, storage and trading of decentralized energy, interoperability of various tools and solutions has become paramount for achieving scalability, modularity and long-term sustainability. In the scope of this present study, OSS solutions for local energy communities, the concept of interoperability is examined in order to provide a comprehensive outlook on the implementation of a tool that can seamlessly exchange information with its existing counterparts. The analysis also explores the ability of the solution to act accordingly with software, middleware or hardware systems across all frontiers of its specifications.

In contrast to TRL assessments and functionality mapping, which prioritise respectively the maturity of the tool and its functionalities in accordance with application areas, interoperability places greater emphasis on a specific OSS tool's capacity to operate effectively as part of a larger digital ecosystem. This issue is of primary importance, particularly in the context of local OSS initiatives. Such initiatives are often required to incorporate a range of components into digital architecture, such as for example from smart meters, home energy management system, automated billing, demand response, and trading platforms.

The overall outlook for interoperability performance is structured to evaluate all the selected high TRL tools based on key metrics, including, but not limited to, communication protocols, data format compatibility, interface availability, and integration mechanisms. The analysis is based on the study provided by European frameworks such as the *Smart Grid Architecture Model* (SGAM), as well as other academic literature and EU projects insights.

The main objective of this Chapter 5 is to identify well-developed interoperable tools with high maturity level and evaluate them in terms of their capacity to mitigate common integration bottlenecks. In addition, a harmonized outlook on the existing OSS tools in the demonstration sites will be proposed to check if these tools may be integrable to other sites as well and to other OSS solutions.

The evaluation of the tools is conducted in two distinct aspects: firstly, their individual interoperability when operated in isolation, and secondly, their position and role within layered interoperability models. The latter consists of the various layers of the SGAM-based mapping architecture. Following the delineation of the methodological approach (Section 5.1), the results are exhibited in Section 5.2. Ultimately, the SGAM architecture model will be implemented in the only OSS tool that is currently utilised in the *U2Demo* demonstration site: "*Open Remote*" [2].

5.1 Methodology

The interoperability of OSS tools for energy communities with a high level of maturity was systematically evaluated through the development of a multi-criteria framework which considers technical, semantic, and organisational dimensions. This framework is based on the Interoperability Standards as defined by the EU Commission and the IEC. This includes, but it is not limited to, the *Smart Grid Architecture Model* (SGAM) framework, the Horizon EU project *InterConnect,* and other guidelines that have been presented in academic literature.

The following points delineate the steps involved in the interoperability assessment of the selected tools.

- **Step 1: Identification of Interoperability Metrics**

The initial step entailed the formulation of ten metrics to be employed for the assessment of the interoperability of the OSS tools. The following Table 8 presents an overview of the 10 selected metrics and their definitions.

Table 8: Key Metrics for Interoperability Assessment

Metric	Definition	What It Indicates
MQTT Support	Whether the tool can publish/subscribe using the Message Queuing Telemetry Transport protocol	Used in energy IoT, lightweight telemetry communication
API Availability	Whether the tool exposes a RESTful API for external control or integration	Flexibility for dashboards, services, mobile apps
OpenADR Support	Supports Open Automated Demand Response protocol	Demand response readiness & DSO compatibility
OPC-UA Support	Uses Open Platform Communications – Unified Architecture	Industrial integration in SCADA, BMS, DERs
EEBUS Compatibility	Interfaces with the EEBUS standard for device-to-device energy management	Compatibility with European smart home/EV standards
IEC 61850 Support	Implements this protocol for substation and DER communication	Utility-grade electrical system interoperability
Data Format – JSON/XML/CSV	Can output or consume data in JSON format	Common for web APIs, visualizations, data platforms
Cloud Integration (APIs)	Has SDKs or plugins for AWS, Azure, Google Cloud	Cloud-readiness and ecosystem integration
Interoperability Plugin System	Offers a modular plugin architecture for adding interfaces	Extensibility for future protocols
Docker / Containerization	Tool is containerized or offers Docker images	Simplifies deployment and API gateway integration

- **Step 2: Scoring Methodology**

A scoring mechanism was developed to evaluate the selected OSS tools for each of the above listed metrics, similarly to the one used for the Functionality Mapping described in Section 4.1.2. The score ranges from 0, indicating the unavailability of data, to 2, denoting full functionality and compliance with existing standards. The following Table 9 provides a summary of the described scoring mechanism. The total maximum score associated to an OSS tool is thus 20.

Table 9: Scoring metrics for Interoperability Assessment

Score	Definition	Criteria Description
0	Not Available	The interoperability metric is not available
1	Limited	Basic or partially available with custom implementation
2	Fully functional and compliant	Completely documented and compliant with existing standards.

- **Step 3: Tool-Level Evaluation**

For a comprehensive comparison of results, the interoperability assessment is performed on the OSS tools selected in the previous parts of the analysis. These are the 29 tools with the highest TRL score per application, in addition to "*Open Remote*" [2] being the OSS tools in utilization in the Dutch Demonstration Site. The evaluation of these solutions against the defined key metrics was conducted using the scoring criteria, in accordance with the aforementioned framework. The results are presented in Section 5.2.

- **Step 4: SGAM Architecture Integration**

Following the interoperability assessment, the SGAM architecture is presented. The analysis is conducted on the "*Open Remote*" [2] tool, being the one in place at the Dutch Demonstration Site. The tool was mapped in the different domains, zones and layers of the SGAM architecture model, as explained in Section 5.3.

5.2 Interoperability Assessment Results

As explained in Section 5.1, a set of 10 key metrics for interoperability was utilised to evaluate the selected highly mature OSS tools and solutions. The metrics of each tool were manually evaluated based on the available documentation, GitHub repositories, websites, existing projects and community forums.

The assessment of the selected 30 OSS tools revealed the interoperability readiness of each tool. It was evident that certain tools exhibited elevated levels of interoperability, accompanied by substantial support and industry-standard harmonisation. In addition, these tools demonstrated docker deployment capabilities. Conversely, other tools demonstrated deficiencies in terms of interfaces and essential integration mechanisms. The detailed assessment can be found in Figure 11.

Among the analysed tools, "EVCC" [5], "*OpenEMS*" [3], "*Volttron*" [4] and "*Home Assistant*" [6] are regarded as the most advanced in terms of interoperability metrics, scoring respectively a total of 17, 15, 14 and 14 points. Other tools that presented high scores are "*Open Modelica*" [40], "*ThingsBoard*" [28], "*Open Remote*" [2] and "*OpenHAB*" [34]. It is evident that these tools exhibit considerable plugin-based modularity, robust API integration with cloud architecture, and containerisation support. This demonstrates their aptitude for deployment in scalable and interoperable energy communities.

"*Grid Singularity*" [38] (score 11), "*Power Matcher*" [47] (score 10), "*REScoopVPP"* [48] (score 10) and "*PyTorch*" [27] (score 10), despite their advanced development and their considerable technical robustness, were assigned a high-moderate rating in the present assessment. Despite their capacity to facilitate fundamental interoperable measures, such as containerization and API availability, these tools exhibit deficiencies in specific domains of interoperability. "*PyPSA*" [37] itself has options for external containerisation; however, it is important to note that "*PyPSA-Eur*" and "*PyPSA-Earth*" have full docker containerisation capabilities.

Finally, it can be noticed from the results of the interoperability assessment that tools such as "*MESMO*" [49], "*Reopt*" [53], and "*Enflow*" [54] have been found to score poorly in this assessment, respectively score 5, 5, and 4. This is indicative of the fact that, despite their high TRL, OSS solutions are difficult to integrate in energy communities.

	1	2	3	4	5	6	7	8	9	10	
Open Source Tools	MQTT Support	API Availability	OpenADR Support	OPC-UA Support	EEBUS Compatibility	IEC 61850 Support	Data Format – JSON/XML/CSV	Cloud Integration (APIs)	Interoperability Plugin System	Docker / Containerizatio n	Sum Score
Volttron	2	2	2	0	0	0	2	2	2	2	14
OpenHAB	2	2	0	0	1	0	2	1	2	2	12
OpenLEADR	0	2	2	0	0	0	2	0	0	2	8
Smart Citizen Kit	2	2	0	0	0	0	2	0	0	0	6
pvlib python	0	2	0	0	0	0	2	1	0	0	5
OpenModelica	2	2	0	2	0	0	2	1	2	2	13
PyPSA	0	2	0	0	0	0	2	2	1	2	9
ResStock	0	0	1	0	0	0	2	2	0	2	7
MATPOWER	0	1	0	0	0	0	2	0	0	2	5
Loomio	0	2	0	0	0	0	2	2	2	2	10
ERPNext	0	2	0	0	0	0	2	2	1	2	9
OpenSTEF	0	2	0	0	0	0	2	2	2	2	10
PyTorch	0	2	0	0	0	0	2	2	2	2	10
MESMO	0	2	0	0	0	0	2	0	0	1	5
Anomalib	2	2	0	0	0	0	2	1	1	2	10
Predictive Maintenance with AI Azure	1	2	0	0	0	0	2	2	2	2	11
ThingsBoard	2	2	1	0	0	0	2	2	2	2	13
Grafana	2	2	0	0	0	0	2	2	2	2	12
Local Energy Sharing Simulator (LESS)	0	1	1	0	0	0	2	1	2	2	9
Enflow	0	2	0	0	0	0	2	0	0	0	4
PowerMatcher	2	2	0	0	0	0	2	0	2	2	10
REScoopVPP	1	0	2	0	0	0	2	2	1	2	10
Grid Singularity (d3a.io)	1	2	1	0	0	0	2	2	1	2	11
PowSyBl	0	1	0	0	0	0	2	0	2	2	7
OpenEMS	2	2	1	2	0	0	2	2	2	2	15
Reopt	0	2	1	0	0	0	2	0	0	0	5
Home Assistant	2	2	2	0	0	0	2	2	2	2	14
EVCC	2	2	1	0	2	2	2	2	2	2	17
Wetterdienst	0	2	0	0	0	0	2	2	0	2	8
OpenRemote	2	2	1	0	0	0	2	2	2	2	13

Figure 11 – Interoperability Assessment of the OSS solutions

Other key insights that can be drawn from this functionality mapping are described as follow:

- **Dockerization:** it is available in most of the OSS solutions which demonstrate that there is a strong trend among the developers of OSS to provide container-ready tools.
- **API Availability and Cloud Integration:** API is found available in most solutions. However, the possibility for Cloud integration varies significantly. Some tools, such as "*Open EMS*" [3], "*Open Remote*" [2] and "*WetterDienst*" [36], demonstrate mature interfaces. Others focus more on internal pipelines or offline operation.
- **EEBUS and IEC 61850:** The support for these metrics was rarely observed in any of the tools. "*OpenHAB*" [34] alone exhibited some degree of availability, though IEC 61850 was not present in any of the selected OSS solutions. This finding highlights a substantial gap in alignment with industry protocol. One of the important factors of non-inclusion of the IEC 61850 standard is that this standardization measure is quite complex and requires expert intervention to fulfil all the requirements of the mentioned standard. Nevertheless, its adherence is important for making a particular tool interoperable for communication networks and systems used in electrical substations which is a key factor for integration of ECs to the electricity network.

- **Interoperability Plugins:** several OSS solutions demonstrated the availability of Plugin attributes. These attributes have the potential to support the customisation of the OSS tools, thereby enabling their integration into the digital infrastructure of energy communities.

The presented interoperability assessment is subject to several limitations. Firstly, the scoring was qualitative and discrete, which may have resulted in two or more tools being placed in the same level of maturity for interoperability, which may have led to inaccurate results. Moreover, the study was contingent upon the accessibility of information within the GitHub repositories and community forums, which may have missed the undocumented features.

It is acknowledged that standard support mechanisms such as EEBUS and IEC61850, where the performance of the tools is poor, may have been implemented through the utilisation of external libraries. However, it should be noted that the scope of this report did not encompass any research on these libraries. Moreover, the evaluation demonstrates the affinity of these tools for its readiness and modular structure. Yet, it does not showcase the run time performance or the ease of integration due to the complexity of the code or documentation in their integration with energy communities.

5.3 SGAM architecture

The *Smart Grid Architecture Model* (SGAM) is a three-dimensional interface framework developed under the European Mandate M490 for Smart Grids[2]. It offers an innovative, structured approach to the representation of maturity and availability of each solution, with this representation being conducted along three axes: Domains, Zones and Interoperability Layers. The utilisation of the SGAM architecture has been documented in a multitude of academic literature and EU projects dedicated to standardisation and harmonisation. It acts as an academic and industrial benchmark, serving as a criterion for evaluating the interoperability of different tools for integration within digital platforms and other services in the domain of smart grids.

As illustrated in Table 10, the three axes represent different dimensions of interoperability, hereunder further defined.

Table 10: Definition of the three axes of the SGAM architecture

Axis	Criteria	Definition
X-axis	Domain	Represent the physical energy value chain from centralized generation to *Distributed Energy Resources* (DER) and end-use customers
Y-axis	Zone	Reflect the operational hierarchy from real-time process control to enterprise and market-level decision-making
Z-axis	Layer	Define how systems interact, from physical hardware to abstract business rules

[2] *https://www.cencenelec.eu/media/CEN-CENELEC/AreasOfWork/CEN-CENELEC_Topics/Smart%20Grids%20and%20Meters/Smart%20Grids/2_sgcg_methodology_overview.pdf*

As mentioned, each of the three axes is sub-divided into multiple levels of progression. The following tables (Table 11, Table 12, and Table 13) provide a comprehensive overview of these levels.

Table 11: Domains of SGAM architecture

SGAM Domain	Description	Assessment Question	Examples
Generation	Centralized Power Plants (wind farms, coal, etc.)	Is the tool applied at centralized generation plants?	Wind farms, Hydro, Solar PV plants
Transmission	High-Voltage (HV) Electricity Transport	Is the tool used in HV electricity transport?	TSO-level SCADA, HV asset monitoring
Distribution	Medium/Low Voltage (MV / LV) Grids and Substations	Is the tool used in MV/LW grid environments?	DSO tools, MV/LV grid models
DER	Distributed Energy Resources (PV, batteries, EVs, etc.)	Is the tool used to manage decentralized assets like batteries or PV?	HEMS, battery controller, EVSE
Customer	Homes, Buildings, Prosumers, End-user interfaces	Is the tool used at residential, commercial, or prosumer level?	Energy apps, Dashboards, access tools

Table 12: Zones of SGAM architecture

SGAM Zone	Description	Assessment Question	Examples
Market	Energy trading, policy, external stakeholders	Does it interface with external market actors or tariffs?	Billing platform, market platforms
Enterprise	Utility-level decision-making, asset management	Is it part of utility enterprise systems?	Asset management, decision support, dashboards
Operation	Grid operations and system monitoring	Does it support grid operations or dispatch?	Forecasting tools, scheduling systems
Station	Substation automation systems	Is it deployed at substation level or SCADA node?	Substation automation, relay config tools
Field	Local equipment (controllers, sensors)	Does it interact with local field devices or remote terminal units?	RTUs, gateways, mobile apps
Process	Direct energy conversion (inverters, meters)	Does the tool operate at the physical energy conversion level?	Sensors, inverters, controllers

Table 13: Layers of SGAM architecture

SGAM Layer	Description	Assessment Question	Examples
Business	Business goals, regulations, market roles, and policies	Does the tool express or operate on business rules, tariffs, contracts, or roles?	Automated Billing, DR schemes, Access Control
Function	Application functions and logic, including automation and operations	Does the tool implement logical or decision-making functionality?	AI engine, load scheduler, billing calculator
Information	Data models, semantics, payload structures	Does the tool define or exchange structured data formats?	API responses, data exchange, data schemas
Communication	Protocols and technologies for data transport	Does the tool use communication protocols?	REST API, MQTT broker
Component	Physical devices, systems, and platforms	Is the tool a software or hardware component deployed on a device?	HEMS controller, BEMS, VPP edge unit

Currently in the four demonstration sites of *U2Demo*, only "*Open Remote*" [2] is being used as an OSS tool for their operation. This OSS solution has been employed as a demonstrative example for the comprehensive assessment and mapping utilising the SGAM architecture. The analysis is presented in Section 5.3.1.

5.3.1 SGAM of Open Remote

As delineated in Section 5.3, the application of the SGAM architecture is employed to facilitate a comprehensive interoperability assessment of "*Open Remote*" [2].

The selection of "*Open Remote*" as only tool to be assessed in this analysis is due to two main factors. Firstly, because developer inputs and testing of the claims are necessary when developing a SGAM architecture. At the time of the report, "*Open Remote*" had indeed already been deployed in an existing community and tested by a partner of the consortium, the Municipality of The Hague, as Dutch pilot responsible. Secondly, OSS tools are sometime mentioned as being standard compliant, however when tested, certain modules of these tools do not comply with the existing standards of interoperability. This could result in the development of a non-reliable SGAM architecture.

In order to avoid such complications, this report only covers the analysis of "*Open Remote*" as representative of the identified OSS tools, supported by the feedback and review of partners of the consortiums. Besides, it should be noted that other tools that may be deployed under the *U2Demo* project could be investigated for interoperability using the same methodology as described in Section 5.3.

The process of evaluation of SGAM architecture for "*Open Remote*" is illustrated in the present Section and graphically represented in Figure 12. "*Open Remote*" is deployed in the Dutch pilot and is being utilised for the purposes of community-based flexibility and monitoring systems.

The detailed assessment of "Open Remote" is presented in Table 14, Table 15, and Table 16, respectively reporting the three axes for the evaluation: domain, zone and layer.

Table 14: Domain coverage of "*Open Remote*"

Domain	Does "Open-Remote" apply?	Reasoning
Customer	Yes	Used in smart buildings, homes, and user-facing dashboards
DER	Yes	Controls distributed energy devices: EVs, batteries
Distribution	Yes	Can integrate into DSO or facility-level microgrids
Transmission	No	Not designed for HV grid operation
Generation	No	No application in centralized power plants

Table 15: Zone coverage of "*Open Remote*"

Zone	Does "Open-Remote" apply?	Reasoning
Process	Yes	Interfaces with physical sensors/actuators (via BLE, Modbus, etc.)
Field	Yes	Edge deployments on gateways, local control of field devices
Station	No	Not typically used in substations
Operation	Yes	Rule engine does automation and operational scheduling
Enterprise	Yes	Includes user dashboards and analytics
Market	No	No direct energy market integration or tariff engine

Table 16: Layer coverage of "*Open Remote*"

Layer	Does "Open-Remote" apply?	Reasoning
Component	Yes	Can run on edge devices, servers, gateways
Communication	Yes	Uses MQTT, HTTP, CoAP, WebSocket, Modbus
Information	Yes	Handles JSON data, device models, stateful payloads
Function	Yes	Built-in rule engine for automation logic
Business	No	It can model business logic, but lacks formal tariffs and contracts

Finally, the complete assessment of "*Open Remote*" tool is projected on the SGAM, as a three-dimensional representation of its layers in Figure 12.

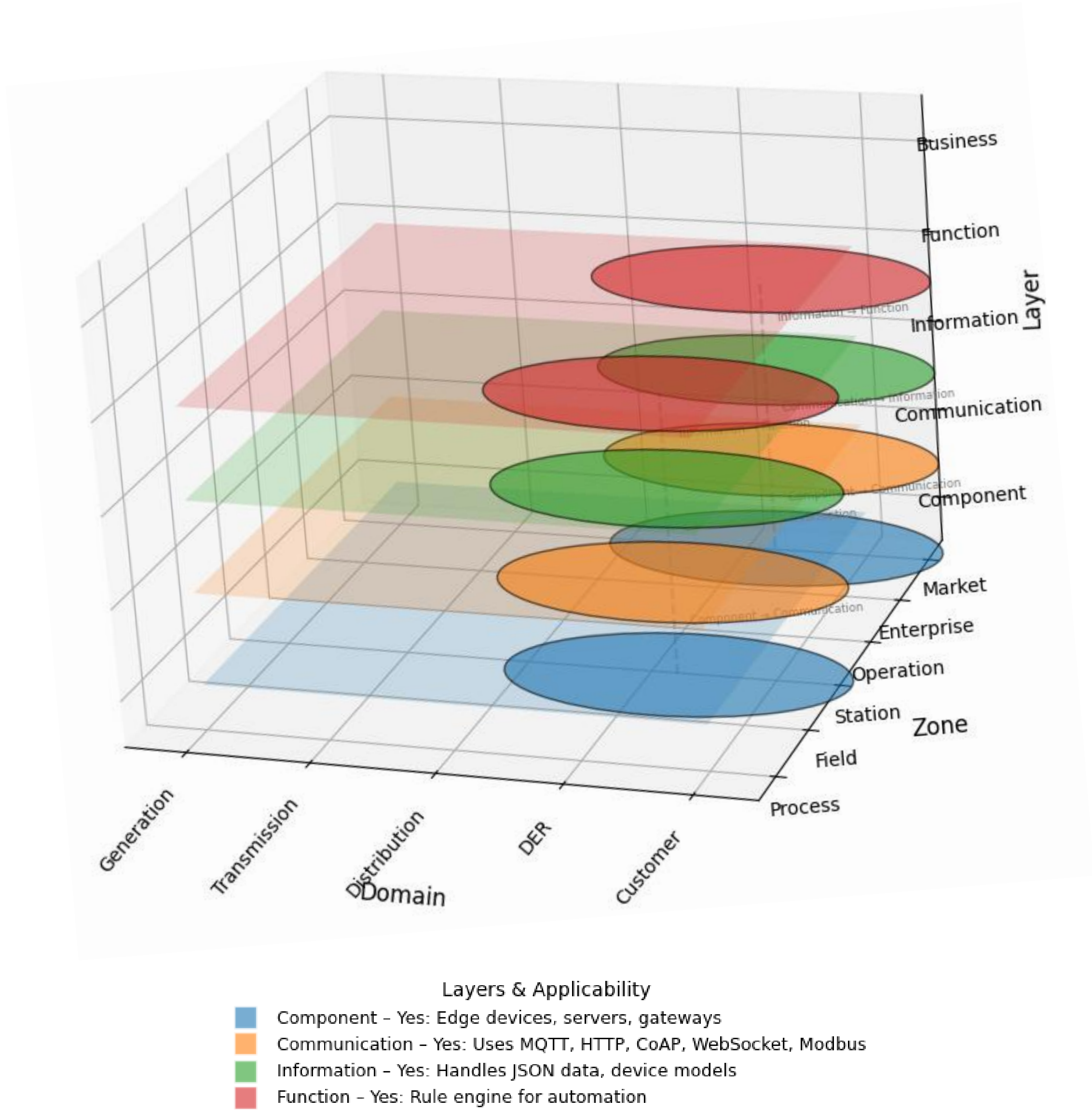

Figure 12 – Projection of Interoperability of "*Open Remote*" in SGAM

Nevertheless, several significant insights were obtained from the demonstration site that could not be addressed in the SGAM assessment. The following are the most salient of these insights:

- **Distribution/Station**: The properties of the distribution station are subject to monitoring, including, but not limited to, main and field powers, transformer temperature, transformer fault conditions, power factors, voltages and net frequency. Besides that, a new functionality is being developed that enables modelling of the distribution cables, verifying the actual load against that model, and triggers an alarm if the cable is overloaded. While "*Open Remote*" possesses the technical capability to issue commands for the deactivation of fields, this functionality is not currently implemented, nor is it a planned feature for the Dutch pilot. In the analysis, the "*Distribution Layer*" is designated as "Yes". However, in the "*Station Zone*", it is indicated as "No".

- **Market**: As of 11.07.2025, there has been interaction with GOPACS (the Dutch congestion market), where the demonstration site will be rewarded for lowering the net load for some time on request of the joint DSOs. The pilot is also engaged in the development of its own tariff model, the testing of which is scheduled to take place soon. The development and deployment of a tariff engine is therefore underway. However, as this is not yet fully incorporated at the time of writing, it is marked "*No*", but it is planned to be converted to a "*Yes*".
- **Business**: As indicated under “Market”, tariffs are generated for the billing system. However, it should be noted that there is no formal contract registration in place within “*Open Remote*”. It is evident that the billing system (*Voorstroom*) has the capability to facilitate the enrolment of cooperative users encompassing the management of contracts. However, given that the demonstration site is establishing a modest cooperative arrangement, it is anticipated that contracts will be managed manually.

In conclusion, it may be observed that “*Open Remote*” solution appears to be a strong interoperable tool. Its deployment and integration with other existing digital platforms may be achieved with some effort, and it has the capability to integrate other OSS solutions into its existing architecture.

6 Conclusions

This deliverable presented a comprehensive assessment of existing OSS solutions for active consumers in energy communities.

After an introduction in Chapter 1, the analysis started in Chapter 2 where a structured methodology for identifying and classifying OSS tools relevant to local energy communities was established. Through the definition of 10 domains, 34 categories and 144 application areas – validated by experts and informed by interviews with the demonstration sites – the specific needs and existing tools of each site were systematically captured. These inputs were then prioritised and normalised to determine the most relevant applications across the pilots. Based on this, a detailed catalogue of 204 existing OSS tools, systematically classified into applications, and characterized by 18 KPIs was developed.

The TRL assessment demonstrated that certain OSS solutions, including "*Home Assistant*" [6], "*Grafana*" [29], and "*Pytorch*" [27] demonstrated high technical maturity and real-world deployments in the context of ECs. However, some promising and technically robust tools remained underutilised or showcased lack of documented use cases in ECs.

The functionality mapping assessment demonstrated that no single tool was able to address all the high-priority application requirements of all the demonstration sites. Instead, the digital architecture would be best developed as a modular and complementary ecosystem with different tools excelling in their corresponding domains and applications. Nevertheless, there still remain certain gaps in areas of application where very few tools are available, or where the technical maturity of existing tools is insufficient. These gaps are evident in areas such as mobile applications, billing automation, and participatory governance which are critical in the modern context of ECs.

In addition, the fragmented ecosystem of OSS solutions, combined with the absence of common interoperability standards and protocols for tools with a relevant priority, poses a significant barrier to scalability. These findings are described in detail in section 6.3.

The following Table 17 presents the compiled results discussed in Chapter 3, Chapter 4, and Chapter 5. A complete mapping assessment was conducted on the 29 OSS tools classified by prioritised application, in addition to "*Open Remote*" [2] selected as the only tool in use, currently applied in the Dutch pilot.

Several OSS tools performed averagely well in all three assessments. "*OpenEMS*" [3] received the highest mean score of all the tools, proving thus to be one of the most interesting tools for dynamic pricing applications. It also scored highly for *Community Energy Management*, and *Data Visualization* functionalises (see Section 4.2).

Other interesting tools resulting from these assessments include "*Volttron*" [4] and "*Open Remote*" [2] for the application *Community Energy Management Systems*, "*Things Board*" [28] for *Energy Dashboards,* and "*EVCC*" [5] for *Smart Charging Algorithms*.

Contrarily, solutions with high TRL scores may not necessarily perform well in terms of functionality or interoperability. For example, "*Wetterdienst*" [36] has a TRL of 9, but received low interoperability points (8 out of 20) and a minimum functionality score of 2. Similarly, despite its high TRL of 9, "*Pvlib python*" [35] performed poorly in terms of functionality integration and interoperability. This is indicative of the fact that, despite their high TRL, OSS solutions are often not easily integrated in energy communities.

Table 17: Summary of results from the TRL, Functionality and Interoperability Assessments

Open Source Tools	Application	TRL	Functionality	Interoperability	SUM
Volttron	Community Energy Management Systems (CEMS)	8	22	14	44
OpenHAB	Home Energy Management Systems (HEMS)	9	13	12	34
OpenLEADR	Demand Response Systems	8	12	8	28
Smart Citizen Kit	Real-Time Energy Monitoring Platforms	7	8	6	21
pvlib python	Energy Analytics Platforms	9	5	5	19
OpenModelica	DSO level modelling	8	9	13	30
PyPSA	Community level Modelling	8	17	9	34
ResStock	Individual Unit modelling	8	13	7	28
MATPOWER	Energy System Simulation Tools	8	8	5	21
Loomio	Collaborative Decision-Making Platforms	8	3	10	21
ERPNext	Automated Billing Platforms	8	6	9	23
PowerMatcher	P2P Energy Trading Platforms	7	18	10	35
REScoopVPP	Virtual Power Plants (VPPs)	7	20	10	37
Grid Singularity (d3a.io)	Energy Trading Tool	8	18	11	37
PowSyBl	Grid Balancing Tools	8	7	7	22
OpenEMS	Dynamic Pricing Platform	8	22	15	45
Home Assistant	Mobile Apps	9	15	14	38
OpenSTEF	AI-Powered Energy Forecasting	8	19	10	37
PyTorch	Machine Learning Algorithms	9	11	10	30
MESMO	AI-Driven Energy Optimization	6	20	5	31
Anomalib	Anomaly Detection in Energy Systems	7	8	10	25
Predictive Maintenance with AI Azure	AI for Predictive Maintenance	7	18	11	36
ThingsBoard	Energy Dashboards	9	22	13	44
Grafana	Data Visualization Tools	9	7	12	28
Local Energy Sharing Simulator (LESS)	Energy Sharing Apps	4	11	9	24
Enflow	Energy Pooling Platforms	4	13	4	21
Wetterdienst	Weather Forecasting Tools	9	2	8	19
EVCC	Smart Chargin Algorithm	8	19	17	44
Reopt	Community-Based Energy Access Programs	8	18	5	31
OpenRemote	Community Energy Management Systems (CEMS)	8	22	13	43

Overall, this study formulated and presented a comprehensive mapping of OSS solutions and tools in the context of ECs. Furthermore, it also enabled the identification of strategic opportunities and gaps for future research, while supporting the development of OSS tools to be adopted by partners of the consortium for the demonstration sites of the *U2Demo* project.

In essence, strengthening the OSS ecosystem through deployment in ECs, developing a proper documentation, adhering to standards and protocols, are all crucial elements for enabling a resilient ecosystem for empowering the energy transition through ECs across Europe.

Finally, in Section 6.1 some recommendations to the demonstration sites are provided. This Section is followed by a presentation of the timeline and progress of Task 1.3, and a final examination of the primary future challenges.

6.1 Recommendations for the demonstration sites

The analysis of OSS solutions was conducted on the basis of the demonstration site representative's prioritisation according to their main objectives and requirements. Therefore, this Section provides few final key findings and recommendations, as outlined in Table 17.

The tools classified within the category *Energy Management and Monitoring Tools*, identified as Priority 1 across all demonstration sites, achieved consistently high scores. Two notable examples are "*Volttron*" [4] and "*Open Remote*" [2] for *CEMS* applications (respectively 44 and 43 total points) both with excellent interoperability and functionality capabilities. "*OpenHAB*" [34] also stood out in the *HEMS* applications for its high TRL and good interoperability scores. Additionally, "*Things Boards*" [28] for real-time data collection, processing and visualisation, and classified as *Data Analytics and Visualization Tools* (Priority 1), was assigned a TRL 9 and also performed averagely very well (44 total points).

Although *Settlement and Billing* was commonly prioritized by all pilots, the tool selected "*ERPNext*" [52] achieved a relatively low total score (23). Despite having a TRL 8, it scored particularly poorly in functionality mapping. This is because it is a tool not designed specifically for the requirements of local energy communities but for automation of billing in business enterprises. Hence it performed well for the specific requirement of automated billing platform but lagged in its functionality which are inherent to ECs.

Furthermore, *Energy Sharing Platforms* and *AI and Machine Learning Tools* categories, also being ranked as Priority 1 by the majority of pilots, were represented by tools recording comparative low TRLs thus highlighting significant gaps in maturity, at least for applications in ECs. This indicates that these tools may require further development before implementation (e.g. "*Enflow*" [54], "*Local Energy Sharing Simulator*" [55], and "*MESMO*" [49]).

The Dutch Pilot representatives expressed a particular interest in *Integration with EVs* and *Energy Distribution Tools*. In the former category, "*EVCC*" [5] achieved one of the best scores (44 points), classified in the application of *Smart Charing Algorithms and* widely adopted by many companies. This tool was assigned with the highest interoperability level among all analysed tools. In the latter category, "*OpenEMS*" [3] emerged as the best performing and interoperable tools of the current analysis. Other well-developed tools in this category are "*REScoopVPP*" [48] and "*Grid Singularity*" [38]. The former has not demonstrated any further development due to the termination of the EU Horizon funding. The latter, for energy trading applications, is a promising solution which is endorsed by the company and demonstrates active maintenance and development. Conversely, "*PowSyBl*" [39], intended for *grid balancing* applications, showed limited development and lower readiness of implementation.

Finally, insights from the Belgian Pilot representatives prioritised *Energy Access and Equity Tools* where "*Reopt*" [53] achieved good scores for TRL and functionality, though interoperability remains limited. On the other side, the Italian partners highlighted their interest in *Communication and Collaboration tools*, with "*Home Assistant*" [6] demonstrating promising levels of development in the mobile applications and HEMS.

For a targeted selection of tools aligned with specific categories, applications and use cases, the demonstration site representatives and other *U2Demo* consortium partners can directly refer to the comprehensive Excel found in the *U2Demo* Zenodo Repository [1].

6.2 Progress

This deliverable for Task 1.3 of *U2Demo*, within WP1, was developed between M4 (December) and M12 (August) 2025, in accordance with the project timeline. It is also mentioned that an additional three months were allocated for the completion of this deliverable, owing to more comprehensive study along with arrangement of interviews with the demonstrations site of *U2Demo* for Task 1.3.

In order to complete the planned work as outlined in Section 1.1,Task 1.3 was structured into three internal intermediate deliverables and seven subtasks, as summarized below:

- **Comprehensive literature review**: compilation of key domains, categories, and technologies for OSS solutions which are relevant for further research, alongside data collection from demo sites. Includes an analysis of functionalities, and limitations (subtasks 1, 2, 3).
- **Technologies maturity and Functionality Mapping**: assessment of the maturity and Technology Readiness Level (TRL) of the identified OSS solutions, ensuring compatibility between different solutions (subtasks 4,5).
- **Interoperability Assessment and SGAM**: evaluation of the relevant OSS solutions identified in both scientific research and industry, providing a comprehensive overview of their current applications (subtasks 6,7).

Figure 13 illustrates the progression and timeline of Task 1.3.

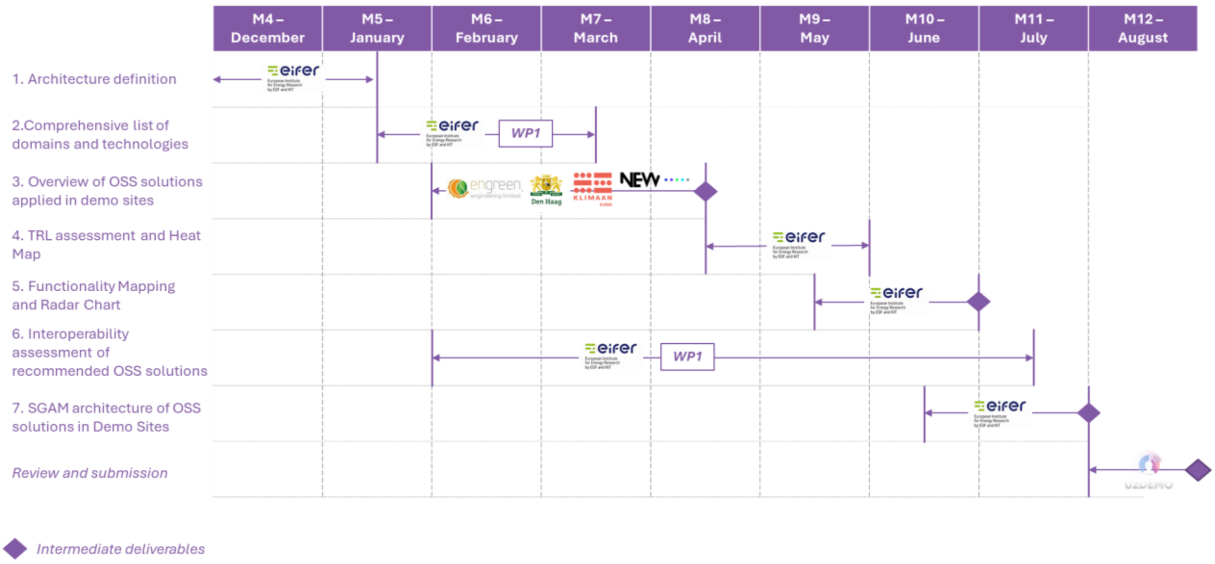

Figure 13 – Task 1.3 Timeline

6.3 Main Challenges

The evaluation of several OSS solutions and tools used for active consumers in the context of energy communities revealed certain technical, methodological and systemic challenges. These challenges impact the adoption, integration and scalability of such tools in the ECs.

The main challenges are described as follows:

- Misalignment of tools' design with respect to energy communities: Several of the evaluated tools were not explicitly designed for use in ECs, but rather targeted for academic, industrial, or utility-scale contexts, or were developed for completely other purposes but found to be suitable for use in ECs. As a result, although certain tools like "*PyPSA*" [37], "*Open Modelica*" [40], and "*MATPower*" [41] are technically robust and highly mature, they scored slightly lower than the maximum in the TRL assessment due to limited documented deployment in ECs.
- Limited use case demonstration: A significant issue that was faced during the assessment was the lack of published case studies, demonstration site data, or proper deployment documentation, particularly with regard to this study's focus on ECs. This restricted the opportunity to demonstrate real-world readiness and impacted the assessment of some promising OSS solutions.
- Fragmented tool ecosystem: Functional mapping of the prioritised OSS solutions revealed that none of the tools provided a comprehensive coverage of all the critical requirements for any medium to large-scale ECs application. This resulted in dependence on a multi-tool architecture, creating technical complexity and integration issues for ECs with limited technical expertise and capacity.
- Uneven maintenance and governance: Several promising tools suffer from limited development contributions, either due to weak community participation or the ending of grants and other finances, particularly those developed under the scheme of EU funding schemes or national projects, which were not adopted by institutions after the completion of the projects. This poses a serious challenge to the long-term sustainability and support of OSS solutions.
- Lack of interoperability standards: While all the high-priority tools chosen for the detailed assessments demonstrated API availability, some of them suffered from a lack of standardized interoperability protocols and data models. This is a serious issue that hinders the plug-and-play deployments of these OSS solutions. Many of the tools require moderate to high technical expertise or developers' support for integration into real-world ECs.

In conclusion, to leverage the full potential of OSS solutions for deployment in ECs, future efforts must take into consideration the following:

- Encouraging interoperability standardisation measures.
- Promotion of real-world deployment documentation and EC pilots.
- Proper governance and contribution support.
- Measures to encourage the adoption of tools by institutions after projects' completion (in the case of publicly funded projects).
- Integration of technical platforms with social participation which may be achieved by participation of various stakeholders of ECs to incorporate their requirements and use it as a guideline for development.

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APPENDIX A: Categorization of OSS Tools

Table I: List of Categories for the classification of OSS tools for local energy communities

N.	List of Categories	Definition
1	Energy Management and Monitoring Tools	Tools enabling monitoring, control, and optimization of local energy consumption and production.
2	Energy Distribution Tools	Systems supporting the local distribution of energy, including microgrids and grid interfaces.
3	Energy Efficiency Tools	Software and tools aimed at reducing energy waste and improving energy efficiency at multiple scales.
4	Communication and Collaboration Tools	Platforms facilitating internal and external collaboration, communication, and coordination among stakeholders.
5	Policy and Financial Tools	Tools for managing regulatory policies, incentives, subsidies, and financial modelling in energy systems.
6	Educational and Outreach Tools	Digital resources for educating community members and promoting outreach on energy-related topics.
7	Environmental Monitoring Tools	Sensors and platforms for tracking environmental variables such as air quality, emissions, and weather impacts.
8	Maintenance and Safety Tools	Systems for predictive maintenance, fault detection, and ensuring operational safety of energy infrastructure.
9	Integration with Electric Vehicles (EVs)	Tools for managing charging infrastructure, smart charging, and vehicle-to-grid (V2G) applications.
10	Renewable Energy Certificates (RECs) and Carbon Credits	Platforms for issuing, managing, and trading renewable energy certificates and carbon offsets.

11	**Artificial Intelligence and Machine Learning Tools**	AI-driven platforms for forecasting, optimization, anomaly detection, and smart control in energy systems.
12	**Decentralized Finance (DeFi) Tools**	Blockchain-based financial tools that enable tokenized energy assets, smart contracts, and peer-to-peer energy trading.
13	**Community Engagement and Participation Tools**	Tools that promote participation in decision-making, gamification, and feedback in energy communities.
14	**Resilience and Disaster Recovery Tools**	Solutions ensuring continuity of energy services during outages, natural disasters, and extreme events.
15	**Data Analytics and Visualization Tools**	Platforms for analysing and visualizing energy data to support decision-making.
16	**Regulatory and Compliance Tools**	Systems that support legal compliance, permit handling, and regulatory reporting.
17	**Innovative Financing Tools**	Non-traditional funding mechanisms like PAYS models, ESCOs, and community-based investments.
18	**Integration with IoT (Internet of Things)**	Systems that connect energy devices and enable automated, data-driven energy management.
19	**Energy Access Tools (for Off-Grid Communities)**	Solutions for decentralized, affordable energy in remote or underserved areas.
20	**Carbon Capture and Storage (CCS) Tools**	Technologies for capturing, storing, or reusing CO_2 emissions from energy processes.
21	**Energy Recovery Tools**	Technologies that reclaim energy from waste, heat, or ambient sources.
22	**Community-Based Renewable Energy Certificates (CB-RECs)**	Platforms supporting local issuance and trade of renewable energy certificates.
23	**Energy Sharing Platforms**	Tools that facilitate sharing and exchange of excess energy among community members.

24	**Energy Resilience and Adaptation Tools**	Tools that help adapt local energy systems to climate risks and enhance their resilience.
25	**Energy Access and Equity Tools**	Solutions focused on reducing energy poverty and ensuring inclusive access to clean energy.
26	**Energy Education and Training Tools**	Simulation platforms, training programs, and gamified tools to build energy literacy.
27	**Energy Policy Advocacy Tools**	Platforms enabling communities to influence policy, engage stakeholders, and assess impact.
28	**Modelling and Simulation**	Tools for simulating energy flows, scenarios, and optimization of energy systems.
29	**Hydrogen Economy Tools**	Technologies related to hydrogen production, storage, integration, and trading.
30	**Circular Economy Tools**	Platforms supporting resource recovery, waste-to-energy, and circular energy supply chains.
31	**Digitalization and Cybersecurity**	Digital twins, cybersecurity frameworks, and IT systems for secure energy operations.
32	**Social Innovation Tools**	Tools that enable co-creation, participatory design, and social impact assessments.
33	**Behavioural Energy Tools**	Analytics and nudges that influence consumer behaviour toward sustainable energy use.
34	**Settlement and Billing**	Tools for automated invoicing, dynamic pricing, and distributed ledger-based energy transactions.

Table II: List of Applications by Categories for the classification of OSS tools for local energy communities

N.	List of Applications (per Category)	Definition
1	**Energy Management and Monitoring Tools**	
1,1	Smart Meters	Provide real-time data on energy consumption and production.
1,2	Community Energy Management Systems (CEMS)	Software platforms that optimize energy use and storage.
1,3	Home Energy Management Systems (HEMS)	Allow individual households to monitor and control their energy use.
1,4	Demand Response Systems	Adjust energy consumption in response to supply conditions or price signals.
1,5	SCADA Systems (Supervisory Control and Data Acquisition)	Monitor and control energy infrastructure.
1,6	Real-Time Energy Monitoring Platforms	Provide live data on energy usage and production for informed decision-making.
1,7	Energy Analytics Platforms	Analyse energy data to identify trends, inefficiencies, and optimization opportunities.
1,8	Energy Performance Benchmarking Tools	Compare energy performance across buildings or communities to identify best practices.
2	**Energy Distribution Tools**	
2,1	Smart Grids	Advanced electrical grids that use digital communication technology to manage electricity flow efficiently.
2,2	Peer-to-Peer (P2P) Energy Trading Platforms	Enable community members to buy and sell energy directly with each other.
2,3	Virtual Power Plants (VPPs)	Aggregate distributed energy resources to act as a single power plant.
2,4	Energy Trading Tool	Enables EC managers to participate as an aggregator in the Electricity markets/Flexibility markets etc.
2,5	Distribution Network Operator (DNO) Management Tools	Manage and optimize local energy distribution networks.
2,6	Grid Balancing Tools	Ensure stable grid operations by balancing supply and demand.
2,7	Dynamic Pricing Platforms	Adjust energy prices based on real-time supply and demand conditions.
3	**Energy Efficiency Tools**	
3,1	Energy-Efficient Appliances	Appliances that consume less energy (e.g., LED lighting, Energy Star-rated devices).
3,2	Insulation and Building Envelope Improvements	Reduce heating and cooling needs.
3,3	Heat Pumps	Efficiently transfer heat for heating or cooling purposes.

3,4	CHPs	Combined Heat and Power
3,5	Energy Auditing Tools	Software and devices used to assess energy use and identify savings opportunities.
3,6	Building Energy Modelling Tools (e.g., EnergyPlus)	Simulate energy performance to optimize building design and operations.
3,7	Retrofit Planning Tools	Plan and implement energy-saving upgrades for existing buildings.
4	**Communication and Collaboration Tools**	
4,1	Community Platforms	Online platforms for community members to communicate, share information, and coordinate activities.
4,2	Blockchain Technology (or DLT)	Facilitate transparent and secure energy transactions within the community.
4,3	Mobile Apps	Provide real-time energy data, alerts, and control options to community members.
5	**Policy and Financial Tools**	
5,1	Crowdfunding Platforms	Raise funds for community energy projects.
5,2	Energy Cooperatives	Legal structures that allow community members to collectively own and manage energy assets.
5,3	Government Grants and Incentives	Financial support for renewable energy projects.
5,4	Power Purchase Agreements (PPAs)	Contracts to buy energy at a predetermined price.
5,5	Green Bonds	Finance environmentally friendly energy projects.
5,6	Energy Performance Contracts (EPCs)	Fund energy efficiency projects through savings generated.
5,7	Community Shares	Allow community members to invest in local energy projects.
6	**Educational and Outreach Tools**	
6,1	Workshops and Training Programs	Educate community members about energy efficiency and renewable energy.
6,3	Public Awareness Campaigns	Promote the benefits of community energy projects.
6,4	Online Courses and Webinars	Provide accessible education on energy topics.
6,5	Simulation Tools for Energy Education	Teach energy concepts through interactive models.
6,6	Gamification Platforms for Energy Savings	Encourage energy-saving behaviours through games and rewards.
7	**Environmental Monitoring Tools**	
7,1	Air Quality Sensors	Monitor the environmental impact of energy generation.
7,2	Carbon Footprint Calculators	Assess the carbon emissions associated with energy use.
7,3	Weather Forecasting Tools	Predict energy generation from renewable sources like solar and wind.
7,4	Environmental Impact Assessment Tools	Evaluate the ecological effects of energy projects.

7,5	Biodiversity Monitoring Tools	Track the impact of energy systems on local ecosystems.
8	**Maintenance and Safety Tools**	
8,1	Predictive Maintenance Software	Use data analytics to predict and prevent equipment failures.
8,2	Safety Equipment	Ensure safe operation of energy systems (e.g., fire extinguishers, protective gear).
8,3	Remote Monitoring Tools	Allow for real-time monitoring and troubleshooting of energy systems.
8,4	Fault Detection and Diagnostics (FDD) Tools	Identify and resolve system issues quickly.
8,5	Cybersecurity Tools for Energy Systems	Protect energy infrastructure from cyber threats.
9	**Integration with Electric Vehicles (EVs)**	
9,1	EV Charging Stations	Provide charging infrastructure for electric vehicles.
9,2	Vehicle-to-Grid (V2G) Technology	Allow EVs to feed energy back into the grid or community energy system.
9,3	EV Fleet Management Software	Optimize the use of electric vehicles within the community.
9,4	Smart Charging Algorithms	Manage EV charging to balance grid demand.
9,5	EV Integration with Renewable Energy Systems	Combine EVs with solar or wind energy for sustainable mobility.
10	**Renewable Energy Certificates (RECs) and Carbon Credits**	
10,1	REC Trading Platforms	Allow communities to buy and sell certificates representing renewable energy generation.
10,2	Carbon Credit Marketplaces	Enable communities to offset their carbon emissions by purchasing carbon credits.
10,4	Carbon Offset Platforms	Help communities and businesses offset their carbon footprint.
11	**Artificial Intelligence and Machine Learning Tools**	
11,1	AI-Powered Energy Forecasting	Predict energy demand and generation patterns.
11,2	Machine Learning Algorithms	Optimize energy distribution and storage based on historical data and real-time inputs.
11,3	AI-Driven Energy Optimization	Automate energy management for maximum efficiency.
11,4	Anomaly Detection in Energy Systems	Identify unusual patterns that may indicate issues.
11,5	AI for Predictive Maintenance	Reduce equipment failures through data-driven insights.
12	**Decentralized Finance (DeFi) Tools**	
12,1	Tokenized Energy Assets	Represent energy assets (e.g., solar panels, batteries) as digital tokens for easier trading and investment.
12,2	Smart Contracts	Automate energy transactions and agreements within the community.

12,3	Decentralized Energy Marketplaces	Enable peer-to-peer energy trading without intermediaries.
12,4	Energy Token Trading Platforms	Facilitate the exchange of energy tokens.
13	**Community Engagement and Participation Tools**	
13,1	Surveys and Polls	Gather community input on energy projects and priorities.
13,2	Participatory Budgeting Tools	Allow community members to decide how to allocate funds for energy projects.
13,3	Gamification Platforms	Encourage energy-saving behaviours through rewards and competitions.
13,4	Crowdsourcing Platforms for Energy Projects	Involve the community in funding and decision-making.
13,5	Social Network Analysis Tools	Understand community dynamics and improve engagement.
14	**Resilience and Disaster Recovery Tools**	
14,1	Microgrid Controllers	Ensure continuous energy supply during grid outages.
14,2	Backup Generators	Provide emergency power during disruptions.
14,3	Disaster Recovery Plans	Prepare for and respond to energy system failures.
14,4	Climate Resilience Planning Tools	Prepare energy systems for climate-related risks.
14,5	Energy Storage for Resilience	Store energy for use during emergencies.
15	**Data Analytics and Visualization Tools**	
15,1	Big Data Platforms	Analyse large datasets to optimize energy use and generation.
15,2	GIS (Geographic Information Systems)	Map and analyse spatial data related to energy resources and infrastructure.
15,3	Energy Dashboards	Visualize energy data for better decision-making.
15,4	Data Visualization Tools (e.g., Tableau, Grafana)	Create visual representations of energy data.
15,5	Time-Series Data Analysis Tools	Analyse trends in energy usage and production.
16	**Regulatory and Compliance Tools**	
16,1	Compliance Management Software	Ensuring that energy projects meet local, national, and international regulations.
16,2	Permitting Tools	Streamline the process of obtaining necessary permits for energy projects.
16,3	Regulatory Reporting Platforms	Simplify reporting to authorities.
17	**Innovative Financing Tools**	
17,1	Pay-As-You-Save (PAYS) Schemes	Fund energy upgrades through future savings.

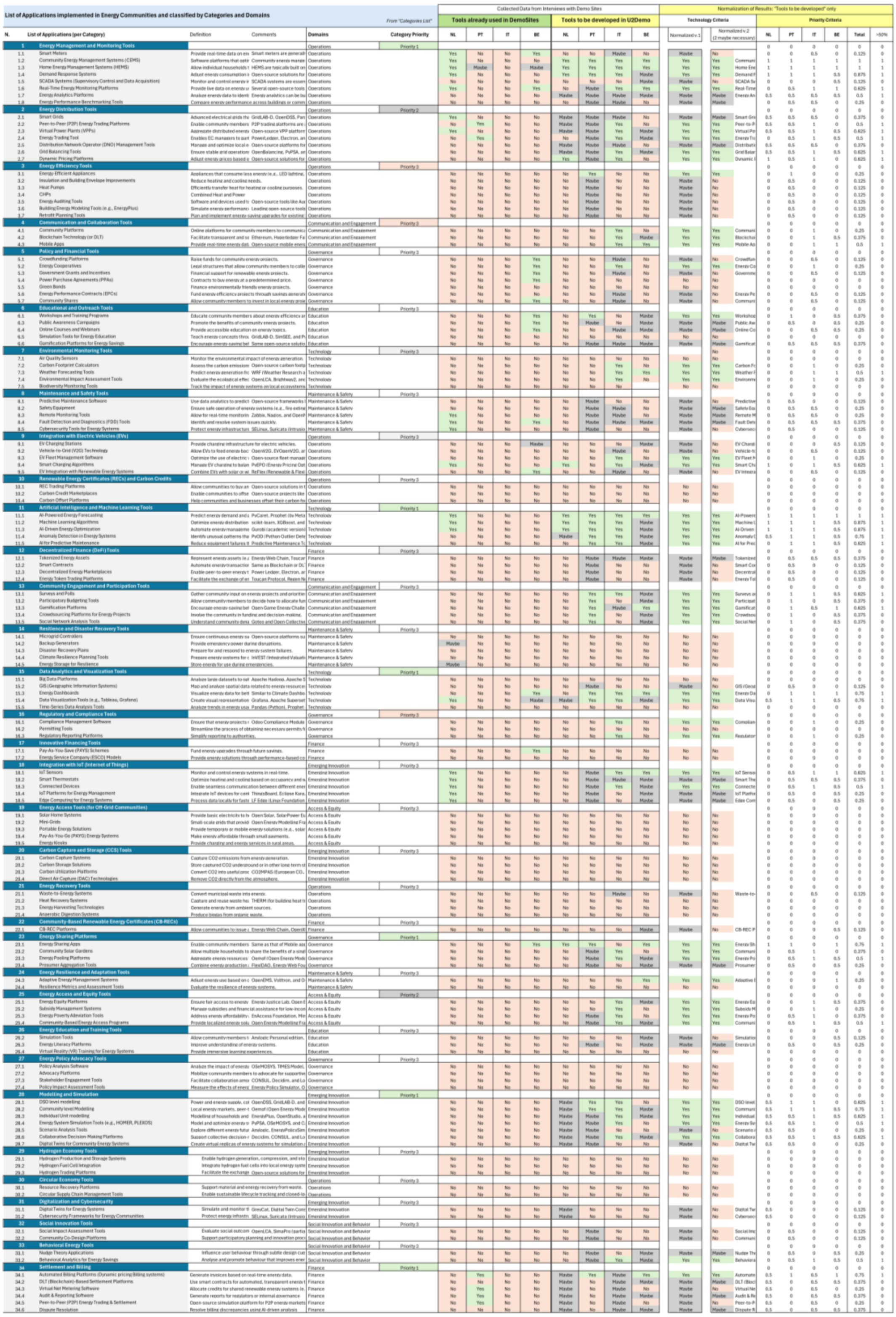
17,2	Energy Service Company (ESCO) Models	Provide energy solutions through performance-based contracts.
18	**Integration with IoT (Internet of Things)**	
18,1	IoT Sensors	Monitor and control energy systems in real-time.
18,2	Smart Thermostats	Optimize heating and cooling based on occupancy and weather conditions.
18,3	Connected Devices	Enable seamless communication between different energy systems and devices.
18,4	IoT Platforms for Energy Management	Integrate IoT devices for centralized control.
18,5	Edge Computing for Energy Systems	Process data locally for faster decision-making.
19	**Energy Access Tools (for Off-Grid Communities)**	
19,1	Solar Home Systems	Provide basic electricity to households in off-grid areas.
19,2	Mini-Grids	Small-scale grids that provide electricity to localized areas.
19,3	Portable Energy Solutions	Provide temporary or mobile energy solutions (e.g., solar lanterns, portable batteries).
19,4	Pay-As-You-Go (PAYG) Energy Systems	Make energy affordable through small payments.
19,5	Energy Kiosks	Provide charging and energy services in rural areas.
20	**Carbon Capture and Storage (CCS) Tools**	
20,1	Carbon Capture Systems	Capture CO2 emissions from energy generation.
20,2	Carbon Storage Solutions	Store captured CO2 underground or in other long-term storage solutions.
20,3	Carbon Utilization Platforms	Convert CO2 into useful products.
20,4	Direct Air Capture (DAC) Technologies	Remove CO2 directly from the atmosphere.
21	**Energy Recovery Tools**	
21,1	Waste-to-Energy Systems	Convert municipal waste into energy.
21,2	Heat Recovery Systems	Capture and reuse waste heat from industrial processes.
21,3	Energy Harvesting Technologies	Generate energy from ambient sources.
21,4	Anaerobic Digestion Systems	Produce biogas from organic waste.
22	**Community-Based Renewable Energy Certificates (CB-RECs)**	
22,1	CB-REC Platforms	Allow communities to issue and trade renewable energy certificates specific to their local projects.
23	**Energy Sharing Platforms**	

23,1	Energy Sharing Apps	Enable community members to share excess energy with neighbours.
23,2	Community Solar Gardens	Allow multiple households to share the benefits of a single solar installation.
23,3	Energy Pooling Platforms	Aggregate energy resources for shared use.
23,4	Prosumer Aggregation Tools	Combine energy production and consumption for optimization.
24	**Energy Resilience and Adaptation Tools**	
24,3	Adaptive Energy Management Systems	Adjust energy use based on changing conditions.
24,4	Resilience Metrics and Assessment Tools	Evaluate the resilience of energy systems.
25	**Energy Access and Equity Tools**	
25,1	Energy Equity Platforms	Ensure fair access to energy resources for all community members.
25,2	Subsidy Management Systems	Manage subsidies and financial assistance for low-income households.
25,3	Energy Poverty Alleviation Tools	Address energy affordability and access issues.
25,4	Community-Based Energy Access Programs	Provide localized energy solutions.
26	**Energy Education and Training Tools**	
26,2	Simulation Tools	Allow community members to simulate the impact of different energy strategies.
26,3	Energy Literacy Platforms	Improve understanding of energy systems.
26,4	Virtual Reality (VR) Training for Energy Systems	Provide immersive learning experiences.
27	**Energy Policy Advocacy Tools**	
27,1	Policy Analysis Software	Analyse the impact of energy policies on the community.
27,2	Advocacy Platforms	Mobilize community members to advocate for supportive energy policies.
27,3	Stakeholder Engagement Tools	Facilitate collaboration among policymakers, communities, and businesses.
27,4	Policy Impact Assessment Tools	Measure the effects of energy policies.
28	**Modelling and Simulation**	
28,1	DSO level modelling	Power and energy supply, collective flexibility, self-consumption, energy sharing and participation in Electricity Markets
28,2	Community level Modelling	Local energy markets, peer-to-peer trading, sector coupling, local demand response, flexibility
28,3	Individual Unit modelling	Modelling of households and equipment, energy management systems, self-consumption
28,4	Energy System Simulation Tools (e.g., HOMER, PyPSA)	Model and optimize energy systems.

28,5	Scenario Analysis Tools	Explore different energy futures and their impacts.
28,6	Collaborative Decision-Making Platforms	Support collective decision-making for community energy projects.
28,7	Digital Twins for Community Energy Systems	Create virtual replicas of energy systems for simulation and optimization.
29	**Hydrogen Economy Tools**	
29,1	Hydrogen Production and Storage Systems	Enable hydrogen generation, compression, and storage.
29,2	Hydrogen Fuel Cell Integration	Integrate hydrogen fuel cells into local energy systems.
29,3	Hydrogen Trading Platforms	Facilitate the exchange of hydrogen as an energy carrier.
30	**Circular Economy Tools**	
30,1	Resource Recovery Platforms	Support material and energy recovery from waste.
30,2	Circular Supply Chain Management Tools	Enable sustainable lifecycle tracking and closed-loop processes.
31	**Digitalization and Cybersecurity**	
31,1	Digital Twins for Energy Systems	Simulate and monitor the operation of energy systems in real-time.
31,2	Cybersecurity Frameworks for Energy Communities	Protect energy infrastructure against cyber threats and attacks
32	**Social Innovation Tools**	
32,1	Social Impact Assessment Tools	Evaluate social outcomes and benefits of energy projects.
32,2	Community Co-Design Platforms	Support participatory planning and innovation processes.
33	**Behavioural Energy Tools**	
33,1	Nudge Theory Applications	Influence user behaviour through subtle design cues.
33,2	Behavioural Analytics for Energy Savings	Analyse and promote behaviour that improves energy efficiency.
34	**Settlement and Billing**	
34,1	Automated Billing Platforms (Dynamic pricing Billing systems)	Generate invoices based on real-time energy data.
34,2	DLT (Blockchain)-Based Settlement Platforms	Use smart contracts for automated, transparent energy transactions.
34,3	Virtual Net Metering Software	Allocate credits for shared renewable energy systems (e.g., community solar
34,4	Audit & Reporting Software	Generate reports for regulators or internal governance
34,5	Peer-to-Peer (P2P) Energy Trading & Settlement	OSS simulation platform for P2P energy markets (useful for testing trading algorithms)
34,6	Dispute Resolution	Resolve billing discrepancies using AI-driven analysis

APPENDIX B: Interviews with the Pilots

Table III: Overview of the interview results from the four demonstration sites, extract from Sheet N.3 "Applications List" available in the *U2Demo* Zenodo repository [1]

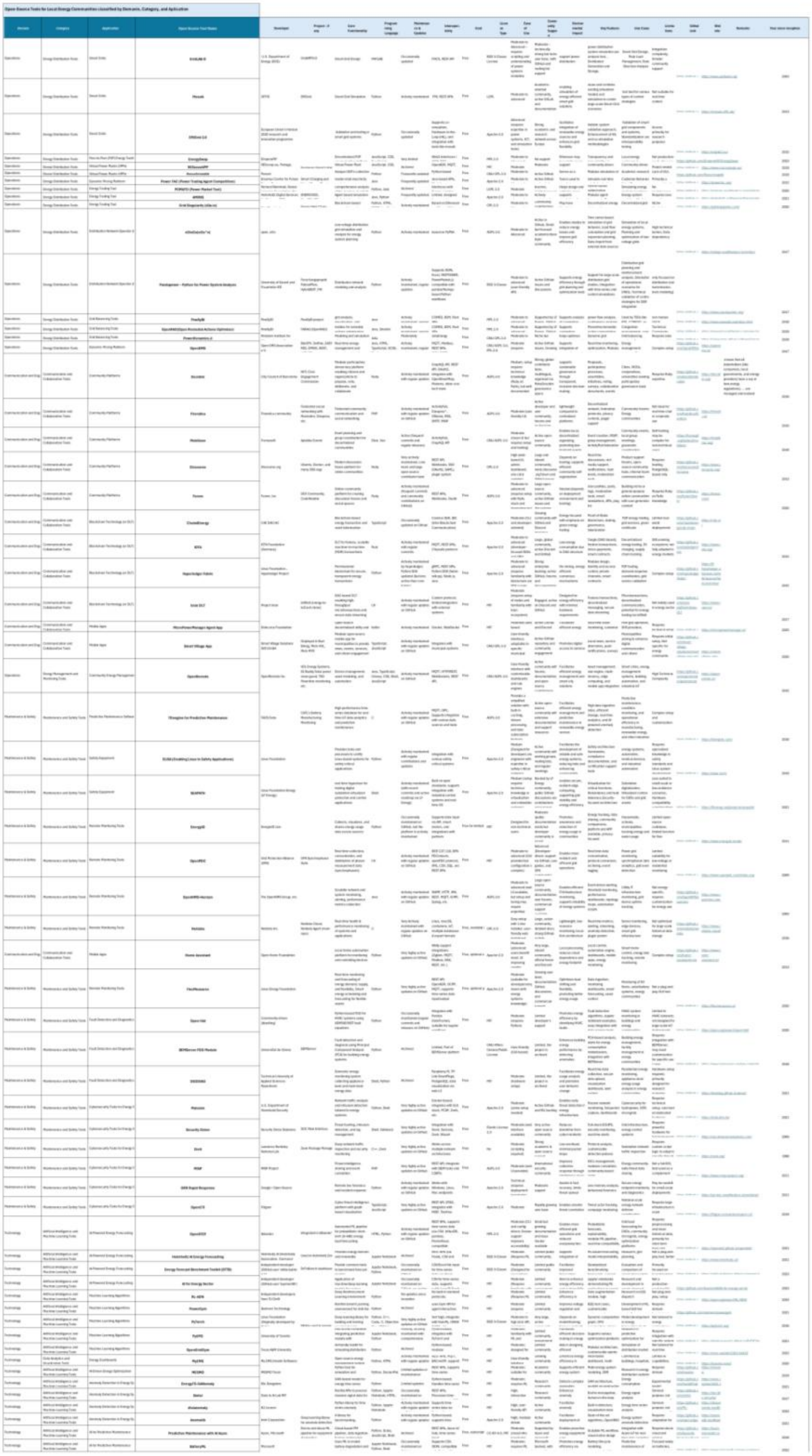


List of Applications implemented in Energy Communities and classified by Categories and Domains

N.	List of Applications (per Category)
1	**Energy Management and Monitoring Tools**
1.1	Smart Meters
1.2	Community Energy Management Systems (CEMS)
1.3	Home Energy Management Systems (HEMS)
1.4	Demand Response Systems
1.5	SCADA Systems (Supervisory Control and Data Acquisition)
1.6	Real-Time Energy Monitoring Platforms
1.7	Energy Analytics Platforms
1.8	Energy Performance Benchmarking Tools
2	**Energy Distribution Tools**
2.1	Smart Grids
2.2	Peer-to-Peer (P2P) Energy Trading Platforms
2.3	Virtual Power Plants (VPPs)
2.4	Energy Trading Tool
2.5	Distribution Network Operator (DNO) Management Tools
2.6	Grid Balancing Tools
2.7	Dynamic Pricing Platforms
3	**Energy Efficiency Tools**
3.1	Energy-Efficient Appliances
3.2	Insulation and Building Envelope Improvements
3.3	Heat Pumps
3.4	CHPs
3.5	Energy Auditing Tools
3.6	Building Energy Modeling Tools (e.g., EnergyPlus)
3.7	Retrofit Planning Tools
4	**Communication and Collaboration Tools**
4.1	Community Platforms
4.2	Blockchain Technology (or DLT)
4.3	Mobile Apps
5	**Policy and Financial Tools**
5.1	Crowdfunding Platforms
5.2	Energy Cooperatives
5.3	Government Grants and Incentives
5.4	Power Purchase Agreements (PPAs)
5.5	Green Bonds
5.6	Energy Performance Contracts (EPCs)
5.7	Community Shares
6	**Educational and Outreach Tools**
6.1	Workshops and Training Programs
6.3	Public Awareness Campaigns
6.4	Online Courses and Webinars
6.5	Simulation Tools for Energy Education
6.6	Gamification Platforms for Energy Savings
7	**Environmental Monitoring Tools**
7.1	Air Quality Sensors
7.2	Carbon Footprint Calculators
7.3	Weather Forecasting Tools
7.4	Environmental Impact Assessment Tools
7.5	Biodiversity Monitoring Tools
8	**Maintenance and Safety Tools**
8.1	Predictive Maintenance Software
8.2	Safety Equipment
8.3	Remote Monitoring Tools
8.4	Fault Detection and Diagnostics (FDD) Tools
8.5	Cybersecurity Tools for Energy Systems
9	**Integration with Electric Vehicles (EVs)**
9.1	EV Charging Stations
9.2	Vehicle-to-Grid (V2G) Technology
9.3	EV Fleet Management Software
9.4	Smart Charging Algorithms
9.5	EV Integration with Renewable Energy Systems
10	**Renewable Energy Certificates (RECs) and Carbon Credits**
10.1	REC Trading Platforms
10.2	Carbon Credit Marketplaces
10.4	Carbon Offset Platforms
11	**Artificial Intelligence and Machine Learning Tools**
11.1	AI-Powered Energy Forecasting
11.2	Machine Learning Algorithms
11.3	AI-Driven Energy Optimization
11.4	Anomaly Detection in Energy Systems
11.5	AI for Predictive Maintenance
12	**Decentralized Finance (DeFi) Tools**
12.1	Tokenized Energy Assets
12.2	Smart Contracts
12.3	Decentralized Energy Marketplaces
12.4	Energy Token Trading Platforms
13	**Community Engagement and Participation Tools**
13.1	Surveys and Polls
13.2	Participatory Budgeting Tools
13.3	Gamification Platforms
13.4	Crowdsourcing Platforms for Energy Projects
13.5	Social Network Analysis Tools
14	**Resilience and Disaster Recovery Tools**
14.1	Microgrid Controllers
14.2	Backup Generators
14.3	Disaster Recovery Plans
14.4	Climate Resilience Planning Tools
14.5	Energy Storage for Resilience
15	**Data Analytics and Visualization Tools**
15.1	Big Data Platforms
15.2	GIS (Geographic Information Systems)
15.3	Energy Dashboards
15.4	Data Visualization Tools (e.g., Tableau, Grafana)
15.5	Time-Series Data Analysis Tools
16	**Regulatory and Compliance Tools**
16.1	Compliance Management Software
16.2	Permitting Tools
16.3	Regulatory Reporting Platforms
17	**Innovative Financing Tools**
17.1	Pay-As-You-Save (PAYS) Schemes
17.2	Energy Service Company (ESCO) Models
18	**Integration with IoT (Internet of Things)**
18.1	IoT Sensors
18.2	Smart Thermostats
18.3	Connected Devices
18.4	IoT Platforms for Energy Management
18.5	Edge Computing for Energy Systems
19	**Energy Access Tools (for Off-Grid Communities)**
19.1	Solar Home Systems
19.2	Mini-Grids
19.3	Portable Energy Solutions
19.4	Pay-As-You-Go (PAYG) Energy Systems
19.5	Energy Kiosks
20	**Carbon Capture and Storage (CCS) Tools**
20.1	Carbon Capture Systems
20.2	Carbon Storage Solutions
20.3	Carbon Utilization Platforms
20.4	Direct Air Capture (DAC) Technologies
21	**Energy Recovery Tools**
21.1	Waste-to-Energy Systems
21.2	Heat Recovery Systems
21.3	Energy Harvesting Technologies
21.4	Anaerobic Digestion Systems
22	**Community-Based Renewable Energy Certificates (CB-RECs)**
22.1	CB-REC Platforms
23	**Energy Sharing Platforms**
23.1	Energy Sharing Apps
23.2	Community Solar Gardens
23.3	Energy Pooling Platforms
23.4	Prosumer Aggregation Tools
24	**Energy Resilience and Adaptation Tools**
24.3	Adaptive Energy Management Systems
24.4	Resilience Metrics and Assessment Tools
25	**Energy Access and Equity Tools**
25.1	Energy Equity Platforms
25.2	Subsidy Management Systems
25.3	Energy Poverty Alleviation Tools
25.4	Community-Based Energy Access Programs
26	**Energy Education and Training Tools**
26.2	Simulation Tools
26.3	Energy Literacy Platforms
26.4	Virtual Reality (VR) Training for Energy Systems
27	**Energy Policy Advocacy Tools**
27.1	Policy Analysis Software
27.2	Advocacy Platforms
27.3	Stakeholder Engagement Tools
27.4	Policy Impact Assessment Tools
28	**Modelling and Simulation**
28.1	DSO level modelling
28.2	Community level Modelling
28.3	Individual Unit modelling
28.4	Energy System Simulation Tools (e.g., HOMER, PLEXOS)
28.5	Scenario Analysis Tools
28.6	Collaborative Decision-Making Platforms
28.7	Digital Twins for Community Energy Systems
29	**Hydrogen Economy Tools**
29.1	Hydrogen Production and Storage Systems
29.2	Hydrogen Fuel Cell Integration
29.3	Hydrogen Trading Platforms
30	**Circular Economy Tools**
30.1	Resource Recovery Platforms
30.2	Circular Supply Chain Management Tools
31	**Digitalization and Cybersecurity**
31.1	Digital Twins for Energy Systems
31.2	Cybersecurity Frameworks for Energy Communities
32	**Social Innovation Tools**
32.1	Social Impact Assessment Tools
32.2	Community Co-Design Platforms
33	**Behavioral Energy Tools**
33.1	Nudge Theory Applications
33.2	Behavioral Analytics for Energy Savings
34	**Settlement and Billing**
34.1	Automated Billing Platforms (Dynamic pricing Billing systems)
34.2	DLT (Blockchain)-Based Settlement Platforms
34.3	Virtual Net Metering Software
34.4	Audit & Reporting Software
34.5	Peer-to-Peer (P2P) Energy Trading & Settlement
34.6	Dispute Resolution

APPENDIX C: OSS Tools Complete List

Table IV: List of OSS Tools for local energy communities, extract from Sheet N.5 "Open-Source Tools" available in the *U2Demo* Zenodo repository [1]



[illegible]

APPENDIX D: Functionality Mapping

Table V: Functionality Mapping of all 30 selected OSS solutions, extract from Sheet N.9 "Functionality Mapping" available in the *U2Demo* Zenodo repository [1]

	1	2	3	4	5	6	7	8	9	10	11	12	
Open-Source Tools	CEMS	HEMS	DR Systems	Community level Modelling	AI-powered Forecasting	ML algorithms	AI-Driven Energy Optimization	Anomaly Detection	Energy Dashboards	Data visualization	Energy sharing Apps	Automated Billing Platforms	SUM
Volttron	3	2	3	2	1	2	2	2	1	1	2	1	22
OpenHAB	1	3	1	0	0	1	1	0	2	3	1	0	13
OpenLEADR	2	1	3	0	0	1	1	1	1	1	1	0	12
Smart Citizen Kit	1	1	0	0	1	1	0	1	1	2	0	0	8
pvlib python	0	0	0	0	2	2	0	0	0	1	0	0	5
OpenModelica	1	1	0	3	1	1	0	0	0	2	0	0	9
PyPSA	1	0	2	3	2	2	2	1	1	2	1	0	17
ResStock	3	1	1	2	2	2	0	0	0	2	0	0	13
MATPOWER	3	0	2	0	1	1	0	0	0	1	0	0	8
Loomio	0	0	0	0	0	0	0	0	0	3	0	0	3
ERPNext	1	0	0	0	0	0	0	0	0	2	0	3	6
OpenSTEF	2	1	2	2	3	3	1	1	1	2	1	0	19
PyTorch	0	0	0	0	3	3	3	1	0	1	0	0	11
MESMO	2	1	2	3	2	2	2	2	1	2	1	0	20
Anomalib	0	0	0	0	0	3	1	3	0	1	0	0	8
Predictive Maintenance with AI Azure	1	1	2	1	3	3	3	3	0	1	0	0	18
ThingsBoard	2	2	2	1	2	2	1	2	3	3	1	1	22
Grafana	0	0	0	0	0	0	0	1	3	3	0	0	7
Local Energy Sharing Simulator (LESS)	1	0	0	2	0	0	1	0	1	1	3	2	11
Enflow	2	1	1	2	1	1	2	0	0	0	2	1	13
PowerMatcher	2	2	3	1	1	1	1	1	1	2	2	1	18
REScoopVPP	3	0	2	2	1	1	1	1	2	2	3	2	20
Grid Singularity (d3a.io)	3	0	2	2	1	1	1	1	1	1	3	2	18
PowSyBl	1	0	1	1	1	1	0	0	1	1	0	0	7
OpenEMS	3	2	2	1	1	1	2	2	2	3	2	1	22
Reopt	2	2	2	3	2	2	1	1	1	1	1	0	18
Home Assistant	2	3	2	0	1	1	0	0	2	3	1	0	15
EVCC	3	2	1	3	0	0	0	3	3	3	0	1	19
Wetterdienst	0	0	0	0	1	1	0	0	0	0	0	0	2
OpenRemote	3	2	1	1	1	1	2	2	3	3	2	1	22