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D3.3

Report on the integrated Pan-European community of testing facilities

int:net
Interoperability Network for the Energy Transition

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ABSTRACT

This report describes the activities carried out to establish a Pan-European community of interoperability testing facilities within the int:net project. It outlines the creation of collaborative structures, knowledge-sharing events, and links to European and international initiatives that support harmonised testing practices. The report also introduces tools developed to enable interoperability testing and capacity building, including a secure data-sharing environment, a semantic compliance checker, a dedicated interoperability lab for data spaces, and an online guide for newcomers. These efforts aim to strengthen cooperation and improve reproducibility across Europe. The report concludes with an outlook on sustaining and expanding the community and using dedicated platforms for future collaboration.

KEYWORD LIST

Energy Domain, Interoperability, Pan-European, Community, Testing Facilities

DISCLAIMER

EXECUTIVE SUMMARY

This report provides an overview of the activities carried out to establish and strengthen a Pan-European community of interoperability testing facilities within the int:net project. The work builds on previous efforts to harmonise testing concepts and map existing infrastructures and focuses on creating a collaborative environment that promotes knowledge exchange and alignment of testing practices across Europe.

The report describes the development of the int:net Community Platform, especially the focus group related to interoperability testing, which serves as a central hub for sharing resources, best practices, and event information. These structures have enabled active engagement among stakeholders, including research organisations, universities, industry representatives, and networks. The community now comprises around sixty members from across Europe, ensuring a diverse and balanced representation.

Several outreach and capacity-building activities have supported this effort. These include online sessions such as Lunch Talks, interoperability testing events organised in cooperation with ENTSO-E, and the Vienna Summer School, which provided training and fostered cross-sector dialogue. The report also highlights collaborations with European projects such as ENERSHARE and OMEGA-X, as well as international initiatives including DERlab, NFDI4Energy, and the International Energy Agency programs. These interactions have strengthened alignment with emerging frameworks and opened opportunities for future joint testing campaigns.

In addition to community-building measures, the report presents tools developed to support interoperability testing and knowledge sharing. These include a secure data-sharing environment for laboratories, a semantic compliance verification tool, a dedicated interoperability lab for validating data exchange across energy platforms, and an online guide designed to help newcomers understand interoperability concepts and testing approaches. Together, these tools aim to harmonise testing practices, improve reproducibility, and provide practical resources for validating interoperability in real-world use cases.

The report concludes by emphasising the importance of sustaining and expanding the community beyond the project's lifetime. Future work should focus on refining the developed tools, strengthening links with European data space initiatives and international standardisation efforts, and leveraging platforms to support ongoing collaboration and knowledge exchange.

CONTENTS

1 Introduction

1.1 Objectives of the work reported

The objective of this report is to present the activities undertaken to establish and strengthen a Pan-European community of Interoperability (IOP) Testing Facilities. It focuses on community-building measures such as the creation of collaborative platforms, the organisation of knowledge-sharing events, and engagement with European and international initiatives. In addition, the report documents the development of tools that support IOP testing and knowledge exchange, including the Lab Data Space, Ontology Checker, Energy Data Spaces Interoperability Lab, and the IOP Compass. These contributions aim to harmonise testing practices, foster collaboration among stakeholders, and provide practical resources for validating IOP in int:net use cases.

1.2 How to read this document

This report can be read independently, but builds on previous work in int:net, particularly Deliverables D3.1 [1] and D3.2 [2]. D3.1 introduced concepts and procedures for harmonising IOP testing, while D3.2 provided an inventory of European testing facilities and a blueprint for new infrastructures. This report extends these efforts by consolidating the community and introducing tools that enable collaborative testing and capacity building. Readers familiar with D3.1 and D3.2 will find continuity in the approach, while newcomers can use this document as a standalone reference for understanding the community-building activities and technical contributions developed in this phase.

1.3 Structure of the document

The document is organised into four main sections. Section 1 introduces the purpose and objectives of the work and explains its relation to previous deliverables. Section 2 describes the activities undertaken to build the Pan-European community of testing facilities, including collaboration structures, events, and links to European and international initiatives. Section 3 presents the tools developed to support IOP testing and knowledge sharing, such as the Lab Data Space, Ontology Checker, Energy Data Spaces Interoperability Lab, and the IOP Compass. Finally, Section 4 summarises the main conclusions and provides an outlook on future activities.

2 Community Building

This section presents the activities and strategies implemented to establish and strengthen the Pan-European community of IOP testing facilities. The emphasis is on creating a collaborative environment that promotes knowledge exchange, harmonisation of testing procedures, and integration of diverse infrastructures. This section outlines the mechanisms employed to engage stakeholders, including the development of dedicated platforms, participation in European initiatives, and alignment with international networks. By consolidating efforts across projects and organisations, the community aims to address IOP challenges in smart energy systems and accelerate the transition towards a more integrated and resilient energy ecosystem.

2.1 Community Platform – Focus Group on Testing Facilities

The Interoperability Focus Group (IFG) 4[1] (see Figure 1) is a key element of the int:net community platform initiative, designed to address IOP testing approaches, test cases, and the integration of testing facilities. Its mission is to overcome existing gaps in smart grid and smart energy system testing by harmonising procedures and supporting the evolution of a Pan-European network of testing infrastructures. IFG4 provides a collaborative environment for stakeholders to exchange knowledge, share best practices, and jointly develop solutions to IOP challenges.

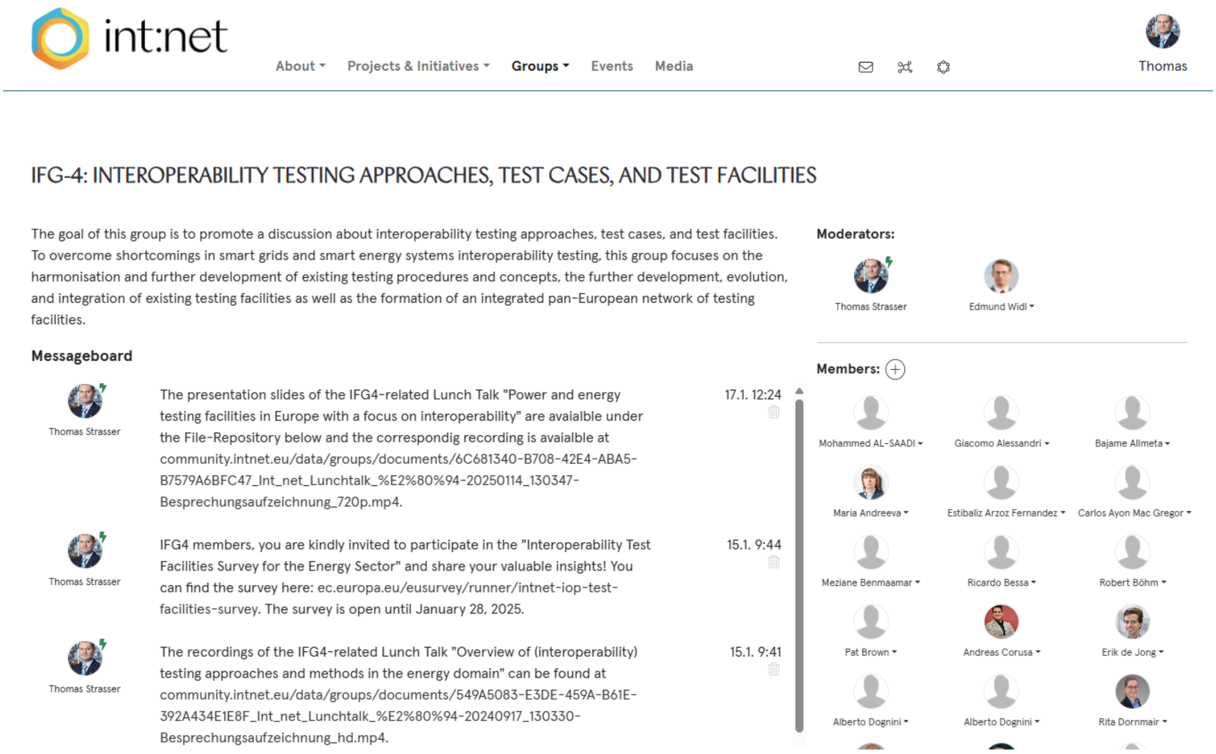

Figure 1: Screenshot from the IFG4 page

[1] https://community.intnet.eu/Groups/IFG-4-Interoperability-Testing-Approaches-Test-Cases-and-Test-Facilities

Shared Information and Resources

The IFG4 platform serves as a repository of knowledge and practical tools. Key resources include:

- *Presentation Slides and Recordings:* Lunch Talk sessions such as “Power and energy testing facilities in Europe with a focus on interoperability” and “Overview of interoperability testing approaches and methods in the energy domain”.
- *Deliverable References:* Summaries and links to D3.1 and D3.2, which underpin discussions on harmonisation and facility integration.
- *Surveys and Reports:* For example, the IOP Test Facilities Survey for the Energy Sector, aimed at mapping existing infrastructures and identifying future needs.
- *Event Announcements:* Information on Connectathon Energy and other IOP testing campaigns supported by IFG4.

These materials ensure that IFG4 functions not only as a discussion forum but also as a practical knowledge base for harmonised testing approaches.

Group Membership Overview

The IFG4 community comprises approximately 60 members, representing a broad spectrum of organisations:

- *Research and Technology Organisations (RTOs):* The largest share, including leading European applied research institutes.
- *Universities:* Contributing academic expertise and methodological development.
- *Industry and Solution Providers:* Offering practical insights from implementation and deployment.
- *Networks and Associations:* Facilitating cross-sector collaboration and standardisation efforts.
- *Geographical Spread:* Members are drawn from across Europe, with strong representation from Central and Western Europe (Austria, Germany, France, Spain), complemented by participants from Northern and Southern regions. This diversity ensures a balanced perspective on regulatory frameworks, technical requirements, and market conditions.

Key Takeaways

IFG4 acts as a cornerstone for building a sustainable IOP testing ecosystem. By hosting essential resources, engaging a diverse membership, and promoting harmonisation, the group strengthens Europe’s capacity to validate interoperable solutions for smart energy systems. Its activities lay the groundwork for long-term collaboration and the integration of testing facilities into a coherent Pan-European network.

2.2 ENTSO-E Interoperability Testing Events

IOP testing is a cornerstone for ensuring that European electricity networks can operate securely and efficiently under increasingly complex conditions. ENTSO-E, as the association of European Transmission System Operators (TSOs), plays a pivotal role in developing and validating standards that enable seamless data exchange across borders. These standards, such as the Common Grid Model Exchange Standard (CGMES) and Network Code (NC) Profiles, are essential for operational planning, coordinated security analysis, and remedial action optimisation.

To accelerate adoption and improve implementation quality, ENTSO-E organises dedicated IOP testing events. These events provide a collaborative environment for TSOs, Distribution System Operators (DSOs), Regional Coordination Centres (RCCs), software vendors, and research projects to validate specifications, identify gaps, and share best practices. They also serve as a platform for addressing technical challenges such as version management, data quality, and conformity assessment. The following subsections summarise two major events held in 2023 and 2024.

CGMES Interoperability Test – Brussels, May 2023

The CGMES Interoperability Test focused on validating CGMES version 3.0, an International Electrotechnical Commission (IEC) standard designed to support reliable data exchange for operational planning and system development. The event gathered around 50 participants from 35 organisations across Europe (see Figure 2). Discussions and tests covered TSO-DSO data exchange, boundary and reference data handling, JavaScript Object Notation (JSON) for Linked Data (JSON-LD) serialisation, and conformity assessment processes.

Figure 2: Impressions from the CGMES Interoperability Test event in Brussels

While CGMES v3.0 provides a stable baseline for future developments, the IOP revealed limited readiness among stakeholders. Key challenges included the absence of clear transition roadmaps, insufficient test coverage, and the need for automated conformity assessment. Vendors demonstrated partial support for CGMES v3.0, but further development is required to achieve full compliance. The event underscored the importance of structured planning and proactive engagement to ensure timely adoption. Further details of this IOP test are provided in the related testing report[2].

Standard Vetting Interoperability Test – Brussels, July 2024

The Standard Vetting Interoperability (SV-IOP) Test targeted the vetting of NC Profiles for Regional Coordination Processes (RCP) and their interaction with the CGMES specification. These profiles underpin critical processes such as Coordinated Security Analysis and remedial action optimisation. The event validated NC Profiles version 2.3 and explored IOP challenges in multi-version environments where CGMES 2.4 and 3.0 coexist alongside NC Profiles 2.2 and 2.3.

Tests confirmed that combining different versions of CGMES and NC Profiles is technically feasible but requires dedicated conversion tools and clear governance. Vendors successfully imported and exported structural and scheduled data in most cases, although issues with namespaces, missing references, and SHACL validation were observed. The event also highlighted the need for improved data quality and clearer guidance on mandatory attributes and profile usage. Further details of this IOP test are provided in the related testing report[3].

Key Takeaways

The two ENTSO-E events demonstrated the importance of structured and collaborative approaches to IOP testing. Both highlighted the need for:

- *Clear transition roadmaps and deadlines* to accelerate adoption of CGMES v3.0 and NC Profiles.
- *Automated and structured conformity assessment processes* to reduce complexity and resource requirements.
- *Common validation and conversion tools*, along with improved source data quality, to ensure successful implementation.
- *Enhanced collaboration and training*, supported by concrete use cases, to foster alignment between TSOs, RCCs, and vendors.
- *Periodic IOP events* as a mechanism for knowledge sharing, standard refinement, and readiness for future regulatory and operational requirements.

2.3 Linked European Data Space Projects

On March 5, 2025, TECNALIA organised in Derio, Bizkaia, Spain, the Interoperability Assessment Workshop: ENERSHARE[4] and OMEGA-X[5] Data Models. The workshop aimed to demonstrate semantic IOP between two major European energy data space initiatives, with a specific focus on the exchange of smart meter data. The demo was a joint effort by int:net's Energy Data Spaces Cluster Projects (EDSCP), which brings together the ENERSHARE, EDDIE, SYNERGIES, and DATACELLAR projects,

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3 https://intnet.eu/images/SV%20IOP%20Report%202024_v1-0-0.pdf

4 https://enershare.eu/

5 https://omega-x.eu/

along with OMEGA-X. Its goal was to address one of the main shortcomings of current data space initiatives: although several sectoral data spaces already exist (like in manufacturing, energy, and mobility), they remain isolated and lack full IOP. To overcome this limitation, the adoption of a common semantic layer was proposed, based on the EUMED (EUropean My Energy Data) Metering Ontology[6], derived from IEC 61968-9:2022 and adopted by the European Union (EU). This profile provides a standardised representation of energy data, enabling consistent transformation and exchange between heterogeneous systems (see Figure 3).

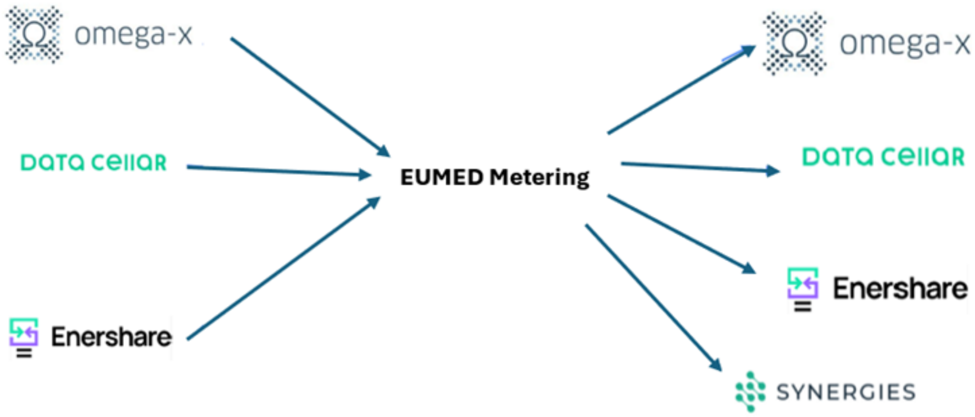

Figure 3: Energy Platform interoperability enabled by EUMED Metering

During the workshop, two data exchange scenarios between ENERSHARE and OMEGA-X were presented, with TECNALIA providing data transformation and retrieval services, while ENGIE and EDF contributed semantic mappings to ensure alignment with the EUMED profile.

This exercise demonstrated the feasibility of semantic IOP across energy data spaces but also had a broader significance within int:net's IOP testing activities (see also Section 3.3). By setting up a concrete test case and validating it through a reproducible methodology, the workshop contributed to the harmonisation of testing procedures for semantic IOP.

In terms of outcomes, the event successfully proved the role of the EUMED Metering Ontology as a robust common data model to bridge heterogeneous systems, and it delivered reusable services that can support future testing exercises. More importantly, it fostered collaboration between key European stakeholders (i.e., TECNALIA, ENGIE, EDF, and others), laying the foundations for a network of institutions jointly addressing IOP challenges. In this sense, the workshop not only demonstrated technical feasibility but also served as a practical step towards building the integrated Pan-European community of testing facilities that int:net aims to consolidate.

2.4 Summer School (Vienna Week)

The int:net Summer School on Governance in Energy Interoperability[7], held from June 23 to June 27, 2025, at the AIT Austrian Institute of Technology in Vienna, with around 30 participants (see Figure 4),

[6] https://fz-hannou.github.io/Omega-X/EumedMetering.html
[7] https://intnet.eu/events/81-int-net-summer-school-on-interoperability-in-governance

has focused on the crucial role of IOP in the energy sector. It has gathered professionals, researchers, and policymakers to discuss how energy systems, particularly in Europe, can evolve through seamless integration and coordination on different levels (technical, organisational, etc.).

The event consisted of a series of expert sessions, each designed to address different facets of IOP in the energy sector. Notable sessions related to IOP testing included:

- Session on *“Community of Interoperability Testing Facilities”*: This session delved into the challenges of ensuring IOP in Smart Grids and the importance of rigorous testing. It presented a European-wide overview of existing testing facilities, highlighted gaps, and called for harmonised testing approaches.
- *Cross-Sector Symposium on Interoperability*: A day was devoted to understanding how IOP in energy systems can be enhanced by lessons learnt from testing in other sectors (especially in healthcare).

Figure 4: Impressions from the int:net Summer School in Vienna

By presenting a European-wide overview of testing infrastructures, the summer school highlighted current capabilities and identified key gaps that need to be addressed to ensure the successful deployment of interoperable technologies. The session on IOP testing facilities provided an in-depth look at how harmonised testing across various facilities can ensure that new technologies meet the required standards and work together effectively within the larger energy ecosystem. As such, this initiative helped forge collaboration across borders and disciplines, fostering a shared understanding of IOP and creating networks of professionals dedicated to advancing testing facilities. By building these connections, the event helped to set the stage for further coordinated efforts to improve IOP across Europe, contributing to the creation of a community dedicated to IOP testing in the energy sector (and possibly beyond).

2.5 Other European Projects, Networks, and Initiatives

This section outlines collaborations that complement int:net's core activities. These initiatives strengthen IOP, foster knowledge exchange, and align testing practices across sectors. By engaging with projects, networks, and thematic clusters, int:net promotes harmonised methodologies and sustainable ecosystems for IOP in Europe.

2.5.1 Projects

This subsection highlights European research projects that support int:net's objectives by addressing IOP challenges in areas such as energy management, consumer flexibility, and cross-sector integration. These projects contribute semantic frameworks, testing methods, and digital tools, and actively participate in IOP testing, including int:net's IOP activities, ensuring alignment with harmonised procedures.

Plug&plAy eneRgy ManagEmeNt for hybrID Energy Storage (PARMENIDES)

The Horizon Europe PARMENIDES project[8] (Grant Agreement ID: 101096453) introduces an innovative Energy Management System for Hybrid Energy Storage Systems (EMS4HESS). This next-generation Energy Management System (EMS) is designed to optimise the operation of diverse energy assets within Renewable Energy Communities (RECs), with a particular focus on Hybrid Energy Storage Systems (HESSs). HESS refers to the coordinated use of multiple storage technologies – such as batteries, thermal storage, and electric vehicle charging infrastructure – managed as a unified flexibility resource. The EMS4HESS platform leverages semantic knowledge to dynamically manage these assets, ensuring grid compliance, maximising self-consumption, and supporting user-defined optimisation goals.

At the core of the EMS4HESS architecture lies the PARMENIDES Energy Community Ontology (PECO), which provides a formal and extensible vocabulary for describing energy community structures, asset properties, optimisation strategies, and flexibility signals. PECO enables semantic IOP across data models and information layers, allowing EMS4HESS to integrate heterogeneous devices and systems in a scalable and replicable manner.

The project demonstrates its solutions in two pilot countries – Austria and Sweden – which represent contrasting regulatory and technical environments. The Austrian pilots focus on regional energy communities with automated asset optimisation and grid-friendly operation, while the Swedish pilot explores

[8] https://parmenides-project.eu/

short-term flexibility, seasonal storage, and user interaction in a multi-apartment building context. These pilots serve as testbeds for the ontology-driven EMS architecture, providing valuable insights into the practical implementation of RECs under different national frameworks.

By combining semantic modelling, advanced optimisation, and real-world validation, PARMENIDES contributes to the broader goals of the clean energy transition. It enables scalable and replicable solutions for energy communities, supports the integration of renewable energy, and fosters citizen participation in the transformation of the energy system. A collaboration between int:net and PARMENIDES has been established to enhance and utilise the AIT Virtual Verification Laboratory (VLab) virtual environment for applying the IOP-by-design principle, as well as for integration and IOP testing [1].

As part of this collaboration, a new specification compliance testing tool was developed, applicable to both client/consumer and server/producer components. The AIT VLab validator tool is positioned between the client and the implementation (which can be either a mock or a functional module) and intercepts all communication between them. It verifies whether the exchanged messages comply with the agreed module specification and identifies any deviations in requests or responses from either side.

Initially, the validator supported a synchronous communication model based on RESTful APIs for virtual environments created in AIT VLab. Ongoing work extends this functionality to also support an asynchronous communication model. This is being implemented using a publisher/subscriber mechanism supported by middleware. The current middleware of choice is a Message Queuing Telemetry Transport (MQTT)-compatible broker, but the implementation can be easily adapted to support Kafka as well. This extension facilitates the implementation of event-driven use cases, such as those demonstrated in the Austrian pilot of the PARMENIDES project.

Finally, a module for automated code generation was implemented. Based on the given specification, this module generates code snippets in various programming languages, providing developers with a foundational skeleton. It includes source code for module mock-ups and complete code for specification-compliant communication.

Sustainable Consumer Engagement and Demand Response (SENDER)

The Horizon 2020 SENDER project[9] (Grant Agreement ID: 957755) started in October 2020 and was completed in March 2025. It introduced three pilots in Austria, Finland, and Spain with ~400 household participants and >1,200 Demand-Response (DR) events covering varied climates, building stock, and market setups.

SENDER put household consumers and prosumers at the centre of demand response by co-creating convenient, privacy-preserving services that also help the grid. Pilots in Austria, Finland, and Spain captured diverse climates, building types, and market rules. A consortium of DSOs, Small and Medium-sized Enterprises (SMEs), and research partners combined social innovation with a modular technical stack to move DR from a purely technical exercise to human-centred, day-to-day value for families.

Technically, SENDER combined cloud services for forecasting, flexibility profiling, and orchestration with controllable assets (heating, ventilating, air conditioning, electric vehicle charging, and water heating)

[9] https://www.sender-h2020.eu/

via a Smart Box and device adapters. In line with General Data Protection Regulation (GDPR)-aligned procedures (clear consent, joint-controller arrangements), which established trust and guaranteed compliance with data use, household-level models and digital twins estimated flexibility and facilitated replication without depending on rigid baselines. About 399 families participated in the three trials, 241 installations were done, and 234 households completed the pilot phase.

Operationally, the project executed 1,212 upward and downward DR events. Indicative flexibility ranged around 1.8 kW for HVAC, 3 kW for boilers, and 11 kW for EV chargers; on average, about 29% of controllable load could be flexed under tested conditions. Analytics identified over a hundred consumer usage patterns to refine forecasts and tailor engagement, while a set of exploitable results emerged: the Smart Box and adapters, smart EV-charging and water-heating control, a flexibility management toolkit, consumer apps for transparency and participation, forecasting algorithms, digital twins, a virtual lab, and an integration platform, each with exploitation plans to support post-project uptake.

As part of the collaboration between SENDER and int:net, the AIT VLab environment was used to validate IOP aspects of the flexibility management toolkit and integration platform. This cooperation ensured that SENDER's technical components were tested against harmonised procedures and aligned with interoperability-by-design principles. VLab provided a controlled environment for simulating data exchange and verifying compliance with agreed specifications, thereby strengthening the replicability and scalability of SENDER solutions within the broader European IOP framework.

Beyond technical outcomes, SENDER identified key replication lessons that can guide similar projects and activities:

- *Prioritise compatibility* by using standards-based interfaces, maintaining a certified hardware list, and verifying control paths early.
- *Align market roles and settlement procedures* with aggregators and DSOs from the outset.
- *Leverage digital-twin evaluation* to reduce risk in emerging markets.
- *Emphasise co-creation* to build trust and engagement, and use baseline-free Key Performance Indicators (KPIs) for easier comparisons.

Combined with regulatory inputs on privacy and standardisation, these efforts deliver a workable, scalable residential flexibility model that benefits consumers (comfort, savings, sustainability), system operators (reliable flexibility services), and SMEs (new products and business models).

2.5.2 Networks and Initiatives

This subsection summarises exchanges with key European networks that complement int:net's objectives by promoting harmonised IOP testing practices, knowledge sharing, and alignment with emerging frameworks.

European Distributed Energy Resources Laboratories (DERlab)

The collaboration with DERlab[10] was multifaceted and focused on strengthening IOP testing practices. Information was exchanged on best practices, use and test cases, testing and validation procedures,

[10] http://www.der-lab.net/

guidelines, and rules. Discussions also covered approaches for lab dataspaces (see also Section 3.1) and their role in enabling secure and efficient data sharing between facilities. Furthermore, several DERlab members actively contributed to the Interoperability Test Facility Inventory compiled in Deliverable D3.2 [1], providing insights into existing infrastructures and supporting the mapping of capabilities across Europe. This engagement ensured that DERlab's experience in distributed energy resources testing informed int:net's efforts to build a coherent Pan-European testing ecosystem.

National Research Data Infrastructure for Energy (NFDI4Energy)

The interaction with NFDI4Energy[11] centred on sharing best practices, test cases, and validation procedures, as well as guidelines and rules relevant to IOP testing. Initial discussions explored how the Interoperability Test Facility Inventory (i.e., Deliverable D3.2) could be represented in a machine-readable format to improve accessibility and integration with reproducibility tools. NFDI4Energy is developing solutions for experiment and result reproducibility, which align with int:net's objectives. However, as the initiative started later than int:net, practical implementation was not feasible within the project timeline. Usable outputs from NFDI4Energy are expected after the conclusion of int:net, offering opportunities for future collaboration and alignment.

2.6 International Networks and Initiatives

This subsection summarises interactions with international collaborations, especially with Technical Cooperation Programs (TCPs) of the International Energy Agency (IEA), that complement int:net's objectives by promoting global alignment on IOP testing and fostering knowledge exchange across sectors.

IEA TCP ISGAN – Smart Grid International Research Facility Network (SIRFN)

The collaboration with the IEA TCP International Smart Grid Action Network (ISGAN)[12] focused primarily on the Lab Data Space concept (see Section 3.1), which aims to enable secure and efficient data sharing between research infrastructures. Through ISGAN's SIRFN working group, int:net contributed to discussions on joint research activities for IOP testing, including approaches for experiment reproducibility and harmonised data exchange. The exchange covered best practices for testing procedures, guidelines, and validation methods, ensuring alignment with international efforts to standardise IOP frameworks. This interaction strengthens the link between European and global initiatives, paving the way for future joint testing campaigns and shared infrastructures.

IEA TCP DHC – District Heating and Cooling

The IEA's TCP on District Heating and Cooling (DHC)[13] hosts the so-called Annex TS8, a collaborative research project focusing on experimental investigations of DHC systems. This project aims to advance and demonstrate experimental research for DHC network expansion by identifying appropriate experimental methods and digital technologies, as well as linking testing facilities.

On September 3, 2025, a joint workshop of the IEA DHC Annex TS8 and int:net was held (online event). The workshop consisted of a presentation on the topic of IOP testing and the related work done within

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[11] https://nfdi4energy.uol.de/
[12] https://iea-isgan.org/
[13] https://www.iea-dhc.org/

int:net. This was followed by a discussion on the role of IOP and IOP testing within the IEA DHC Annex TS8 and the heat sector in general. The discussion centred around the following 2 subjects:

1. *Role of IOP in the heat sector*: In contrast to the power sector, IOP has had a less prominent role in the heat sector in the past. Historically, this is mostly owed to the fact that DHC networks are typically only local (or in a few cases regional) systems, without the need for operational coordination on a larger scale (e.g., in contrast to the interconnected European power transmission system). This is also reflected in the fragmented regulatory landscape in Europe, which provides very different legal conditions for the operation of DHC networks throughout Europe. However, digitalisation has become a driver for IOP in the heat sector. For instance, system operators are increasingly aware of the benefits of open standards, as they help them avoid vendor lock-in. Nevertheless, as this is a new topic, IOP testing is a relatively new subject in the heat sector.
2. *Need for a community of testing facilities*: There is currently no permanent community established (in Europe or elsewhere) that serves as a dedicated platform for testing facilities in the heat sector. However, the work in Annex TS8 clearly shows the benefits of establishing a permanent dialogue between testing facilities. This helps to exchange new ideas, establish common research activities, and align on common interests. There are efforts ongoing as part of the Annex TS8 to initiate such a community, probably in association with IEA TPC DHC or other international associations. An alignment with a European community of testing facilities beyond the heat sector would be welcome.

Please be aware that the above statements reflect the opinions of the experts in the workshop. Anyhow, these discussions underline the growing importance of IOP beyond electricity and the potential for cross-sector collaboration in future testing frameworks.

In addition to Annex TS8, int:net also reached out to Annex TS9 related to DHC digitalisation, focusing on IOP in general for energy systems, definitions, but also IOP testing approaches and exploring opportunities for future collaboration.

3 Developed Tools

This section presents the tools and frameworks developed within int:net to support IOP testing and validation. These solutions address key challenges such as semantic compliance, reproducibility, and secure data exchange between testing facilities. By providing practical environments and automated verification mechanisms, the tools enable harmonised testing procedures and foster collaboration across European and international networks. Each subsection describes the purpose, technical approach, and role of these tools in building a sustainable IOP testing ecosystem.

3.1 Lab Data Space

Collaboration in science and research is essential for advancing knowledge, tackling complex problems, and fostering innovation. By working together, research organisations can achieve results that would be difficult or impossible to accomplish individually. However, such collaboration faces technical and organisational challenges, including data privacy and security concerns, the need for robust data management plans, risk of data misuse, and the lack of trusted, user-friendly tools for data sharing. Overcoming these barriers is critical to enable the secure and efficient exchange of research data.

To address these challenges, int:net and ISGAN's SIRFN jointly developed a Joint Research Activity (JRA) focused on creating a Lab Data Space. This initiative aims to strengthen inter-laboratory interaction by providing a secure, standards-based environment for sharing research data across facilities. The Lab Data Space (see Figure 5) concept builds on principles of digital sovereignty, ensuring that data exchange respects ownership, privacy, and compliance requirements.

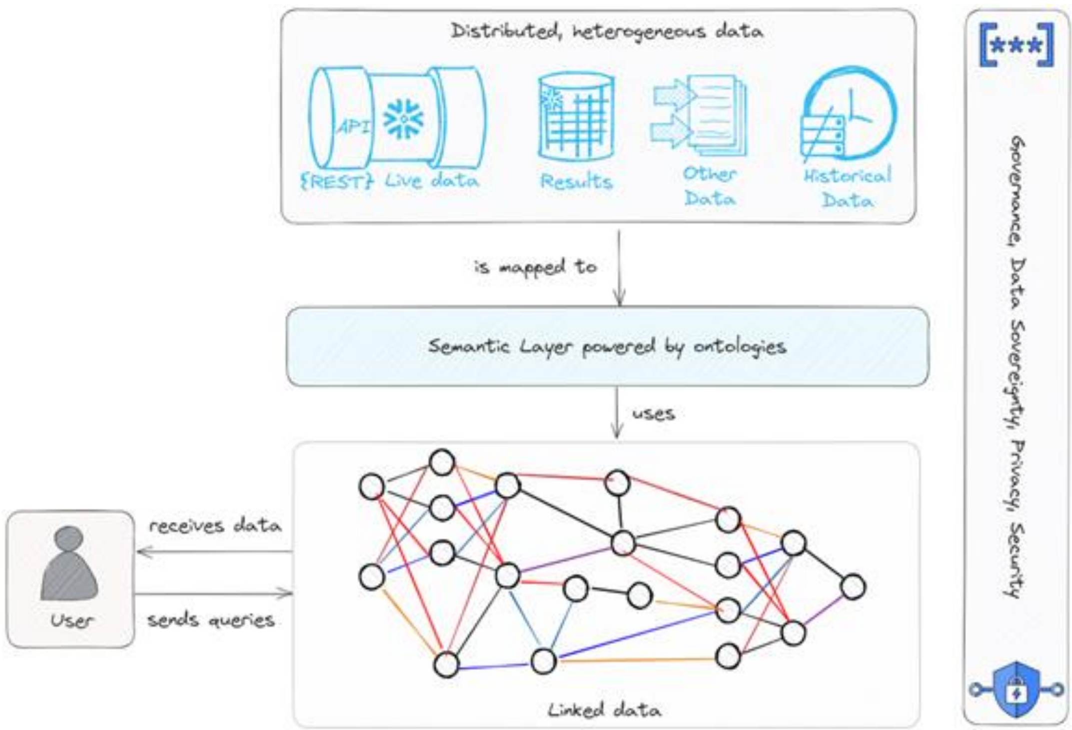

Figure 5: Overview of the Lab Data Space idea

The objectives of the JRA include:

- Identification of common use cases for IOP testing and data sharing.
- Definition and development of a common Research and Technology Infrastructure (RTI) ontology to enable semantic IOP.
- Design and implementation of infrastructure and support services for secure data exchange.
- Development of a working prototype of the Lab Data Space platform.
- Demonstration of selected use cases to validate functionality and reproducibility.

This collaborative effort provides a foundation for future global IOP testing frameworks and supports reproducibility of experiments across geographically distributed facilities. The JRA is led by AIT in co-operation with the following research infrastructures:

- Technical University of Denmark (DTU), Denmark
- ZHAW Zurich University of Applied Sciences, Switzerland
- Salzburg Research (SRFG), Austria
- National Institute of Advanced Industrial Science and Technology (AIST), Japan

The work is still ongoing, and while significant progress has been made in defining the architecture and developing core components, a fully functional prototype of the Lab Data Space is expected after the end of int:net. This ensures continuity of efforts and alignment with international initiatives under ISGAN SIRFN.

3.2 Ontology Checker

The Ontology-Driven Constraint (ODC)-Tester is designed to ensure technology-neutral, ontology-based IOP among heterogeneous systems. By leveraging standardised ontologies, such as SAREF (Smart Applications REFerence ontology), engineers can verify, validate, and certify the semantic compliance – and therefore IOP compliance – of data exchanges. The testing methodology builds upon the European Commission's Joint Research Centre's (JRC) Code of Conduct (CoC) for Energy Smart Appliance (ESA) IOP test framework.

ODC-Tester in int:net

The first proof-of-concept for ODC-Tester was launched within the int:net project, initially conceived as a SAREF-based tester, as detailed in Deliverable D3.1 [1] and later extended to be able to test the compliance with any kind of ontologies. Its main objectives were to:

- Support the JRC CoC for ESA IOP by providing a reusable, ontology-driven test tool.
- Assess a variety of test cases, both internal to int:net and external, to determine where ontology-based testing adds value.

Key functionalities of the int:net prototype include (see Figure 6):

1. *Ontology Compliance:* Validates that simulated or real datasets conform to SAREF-based Shapes Constraint Language (SHACL) shape constraints.
2. *IOP Support:* Generates execution logs to help engineers pinpoint and diagnose semantic mismatches between systems.
3. *Report Generation:* Produces comprehensive reports summarising conformance results and recommending remediation steps.

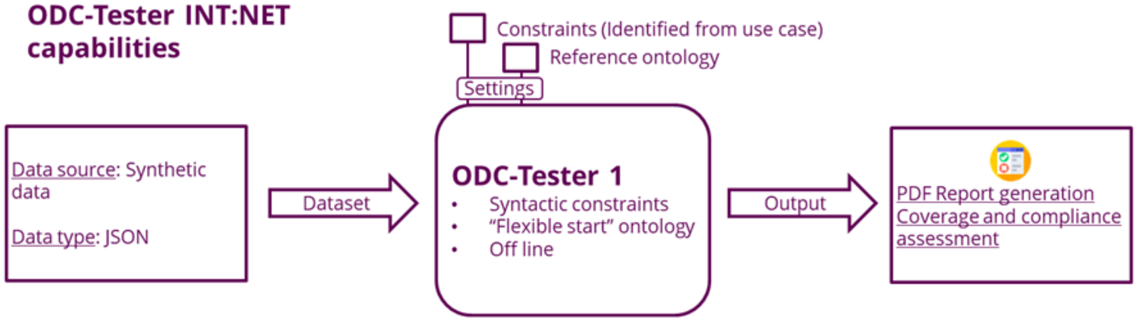

Figure 6: int:net version of ODC-Tester capabilities

Under the hood, the ODC-Tester web application employs a SHACL engine to enforce semantic constraints. A detailed technical presentation is available in the related research article [3].

To date, ODC-Tester development has followed the JRC CoC timeline (Phase 1 – 2024).

- Delivered Version 1.0 of the Code of Conduct for Energy Smart Appliances[14].
- Eleven manufacturers signed the written CoC, committing to market SAREF-compliant devices within an agreed timeframe.
- Participation in the JRC-DG ENER workshop on Energy Management Interoperability of Energy Smart Appliances in 2024[15].

Version 1.0 remained a non-binding, document-only CoC, which means that the use of testing tools was optional, and no specific testing tool was formally mandated. The manufacturer's engagement is only to respect the code and to put in the market SAREF-compliant smart devices. Thus, for now, it is not mandatory or agreed in the CoC to use the ODC-Tester, which is now positioned as a supportive tool to verify IOP and compatibility with SAREF and whose use is optional. At this point, no manufacturer has yet adopted the ODC-Tester, but TRIALOG is in contact with manufacturers who are interested in knowing more about this tool and are willing to share some datasets from their products to contribute to the tests of the current version and the extension of its functionalities.

Continuous Development Beyond int:net

In parallel to the Second Phase of the CoC, ODC-Tester development continues in interaction with the JRC's Process and Technical Working Groups, to prepare for real-world appliances testing. However, as int:net funding is now concluded, the upcoming evolutions of this tool are now supported by the European project HEDGE-IoT[16].

Within HEDGE-IoT, TRIALOG contributes to the activities "supporting the SAREFisation Process" with the exploration and development of a new testing flow for the ODC-Tester. Extending ODC-Tester testing flow with behavioural testing capabilities, enhanced visualisation functionalities, and real datasets testing. To pave the way to complete use cases validation (static/syntactic and dynamic/behavioural)

[14] https://ses.jrc.ec.europa.eu/development-of-policy-proposals-for-energy-smart-appliances#section-1796
[15] https://ses.jrc.ec.europa.eu/sites/default/files/2024-10/4.1_trialog_iop_standards_coc_ontology_tester_antonio_kung.pdf
[16] https://hedgeiot.eu/

(e.g., JRC CoC ESA use cases). A contribution to standardisation activities on behavioural testing is expected.

Currently, HEDGE-IoT is in the pilot-definition phase, collecting real-world datasets and scoping long-term tasks. Concurrently, ODC-Tester is engaging with the EEBUS[17] Spine IoT task group to foster community building and broaden data acquisition channels, even though the tool will remain technology-neutral in the future.

Conclusion: Future of ODC-Tester

int:net successfully established the ODC-Tester concept and sparked active collaboration within the JRC CoC community, evidenced by TRIALOG's participation in numerous workshops and working group meetings. To transition from prototype to production-ready tool, ODC-Tester development will proceed under JRC CoC Phase 2[18], supported by European projects such as HEDGE-IoT and later O-CEI. A primary goal for Version 2 is to introduce Behavioural Compliance Verification[19], enabling comprehensive "behavioural testing" of smart appliances in addition to semantic conformance checks Indeed, in any of the use cases of the CoC, further to the semantic conformity, the order in which the data exchanges between the Customer Energy Manager and the smart appliances take place is also extremely relevant to verify since it is critical for the success of the use case.

3.3 Energy Data Spaces Interoperability Lab

The achievement of semantic IOP between heterogeneous data spaces requires not only conceptual approaches but also robust and reproducible testing environments. To this end, TECNALIA has developed the Semantic Interoperability Lab, which provides a dedicated infrastructure to validate IOP across smart grid components and energy data platforms. To validate the infrastructure, one of the objectives was to migrate what had been developed for the workshop, originally on a local computer, to this new infrastructure. From an int:net perspective, this lab represents a tangible contribution to the establishment of a Pan-European community of testing facilities by offering both methodological insights and practical tools that can be replicated in other contexts.

From a technical perspective, the lab relies on an infrastructure designed for efficiency, robustness, and scalability (see Figure 7). At its core, a Kubernetes node orchestrates the deployment of pods and Docker containers, ensuring scalability and reliable management of services. All container images are stored in TECNALIA's Artifactory repository, which acts as a centralised hub. Before acceptance, images undergo a series of tests, including functionality, security, and performance, that ensure compliance and readiness for deployment.

[17] https://www.eebus.org/
[18] https://ses.jrc.ec.europa.eu/development-of-policy-proposals-for-energy-smart-appliances#section-2717
[19] https://ses.jrc.ec.europa.eu/sites/default/files/2025-10/5.2.-ontology-driven-constraint-tester-%28trialog%29.pdf

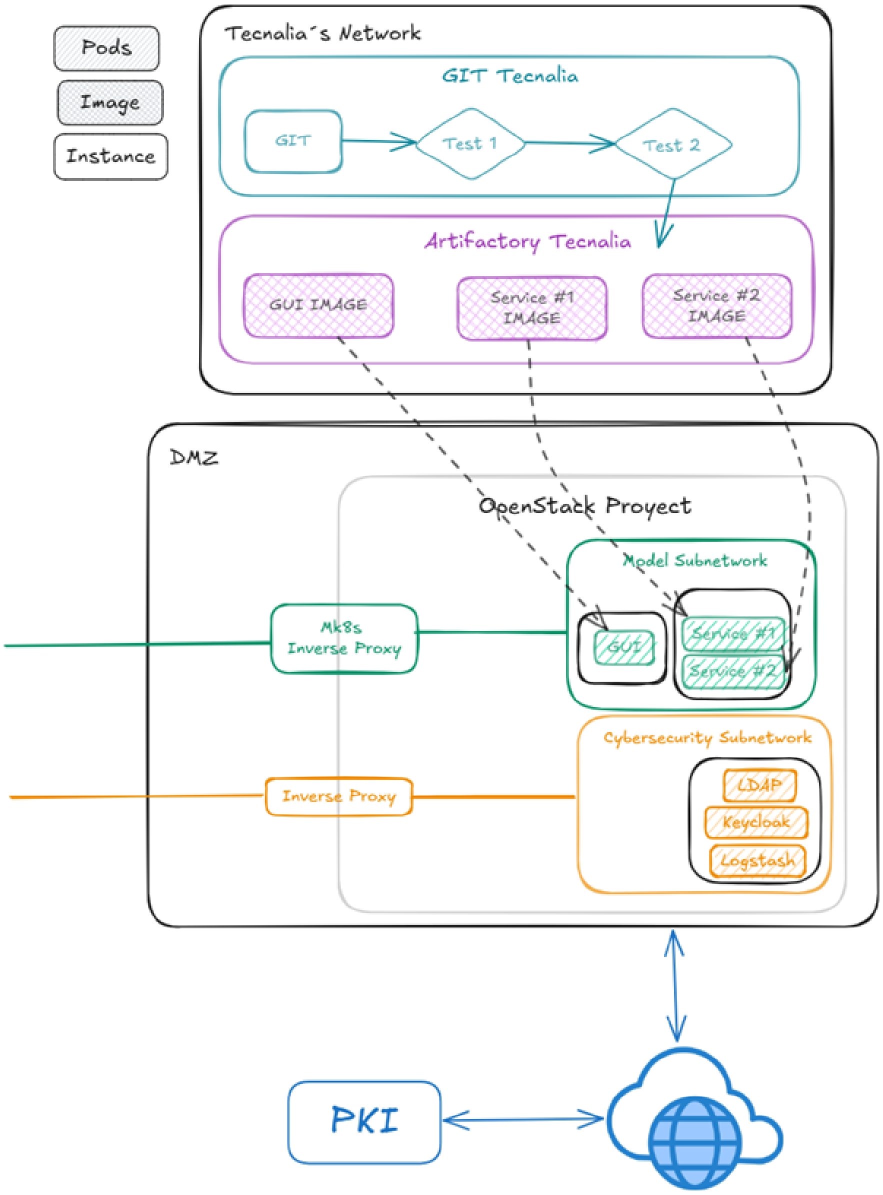

Figure 7: Figure 2: Semantic Interoperability Lab Infrastructure

Security is embedded by design into the infrastructure. The lab integrates Let's Encrypt as a Public Key Infrastructure (PKI) to guarantee the authentication and confidentiality of communications. Lightweight Directory Access Protocol (LDAP) supports centralised user and credential management, while Keycloak enforces authentication and authorisation policies, ensuring only trusted access to services and data. In parallel, Logstash is used to aggregate and process infrastructure logs, facilitating both monitoring and incident detection. This combination of open-source security components underpins the reliability and trustworthiness of the lab, which is essential when considering the future role of testing infrastructures in IOP certification.

Additionally, to be able to migrate the workshop to the infrastructure, the following elements were required:

- A dedicated Docker container for compliance verification ensures that the data and services meet the specific standards and requirements of the project.
- A Docker container responsible for data transformation. This service transforms the source data into the EUMED Metering format, ensuring compatibility with the target systems.
- A third Docker container that provides a Graphical User Interface (GUI). This interface handles internal calls for information retrieval and facilitates user interaction with the system, allowing intuitive visualisation and management of the data.

The motivation behind the Interoperability Assessment Workshop: ENERSHARE and OMEGA-X Data Models lies in the broader challenge identified in recent years: while multiple initiatives, such as the International Data Spaces Association (IDSA)[20] and GAIA-X[21] have promoted the development of sectoral data spaces with reference architectures and building blocks, these spaces remain disconnected from one another. To enable a genuine single market for data and services, IOP across data spaces must be achieved. A workshop, an intermediate step has been proposed: converting the source ontology of each platform into a common representation, the EUMED Metering Ontology, which is based on IEC 61968-9:2022 and adopted at the EU level. This intermediate format (see Section 2.3) simplifies the process of ontology transformation and ensures consistency and integrity of data during exchange. Each project defines specific mappings to EUMED, thus facilitating uniform interpretation and enabling adaptation to diverse target ontologies.

After the demo (see Section 2.3), where the OMEGA-X and ENERSHARE demonstrations were implemented on a local computer, these demos were later deployed as examples to test the versatility of the newly established laboratory infrastructure. In the workshop, TECNALIA, ENGIE, and EDF collaborated to demonstrate two scenarios of semantic IOP: the exchange of smart meter data from ENERSHARE to OMEGA-X, and vice versa. These demonstrations illustrated how the lab can validate real IOP use cases, providing insights not only for OMEGA-X but also for the harmonisation of procedures and the definition of certification pathways.

Scenario 1: Data from ENERSHARE to OMEGA-X

This scenario is characterised by as shown in Figure 8:

- *Transformation and Compliance Service:* TECNALIA, within the ENERSHARE project, developed a service that converts ENERSHARE data into a format compatible with OMEGA-X, ensuring full compliance with its structures and requirements.
- *Information Retrieval Service:* An additional service implemented in the OMEGA-X project, enabling efficient access and management of the transformed data.
- *Semantic Mappings:* ENGIE defined the mappings required to semantise ENERSHARE data into the EUMED format, ensuring consistent interpretation and seamless IOP between both platforms.

[20] https://internationaldataspaces.org/
[21] https://gaia-x.eu/

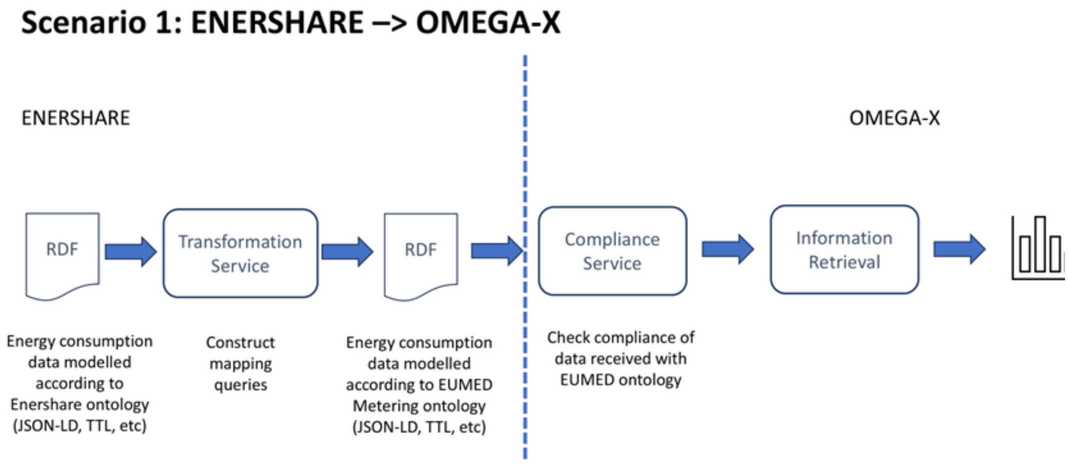

Figure 8: Scenario 1 Schema – data from ENERSHRE to OMEGA-X

Scenario 2: Data from OMEGA-X to ENERSHARE

This scenario is characterised by as shown in Figure 9:

- *Transformation and Compliance Service:* TECNALIA developed a service to transform OMEGA-X data into a format compatible with ENERSHARE, facilitating integration without data loss.
- *Semantic Mappings:* EDF defined the semantic mappings required to translate the OMEGA-X pilot (MAIA municipality) into the EUMED format, ensuring uniform interpretation and reliable IOP.

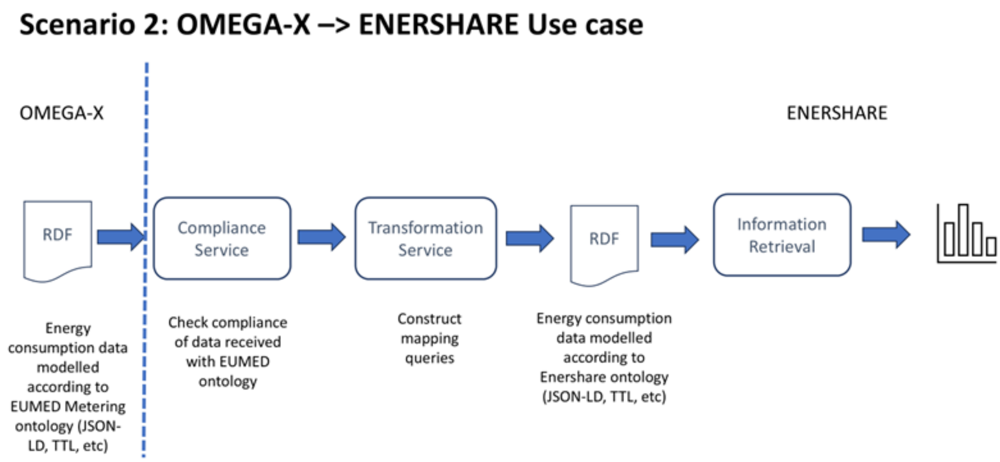

Figure 9: Scenario 2 Schema – data from OMEGA-X to ENERSHARE

Beyond the technical deployment, the lab contributes to the identification of requirements and challenges that are directly relevant to WP3. Among the requirements are full compliance with the EUMED Metering profile, robust semantic mappings, scalable orchestration through Kubernetes, and the availability of GUI-based services for data retrieval and visualisation. Security aspects were also highlighted, including authentication, authorisation, and logging mechanisms to guarantee trustworthy testing environments. The challenges observed include the inherent complexity of semantic transformations, the difficulty of ensuring uniform interpretation of heterogeneous data, the integration of diverse virtualised components, and the scalability needed to handle large data volumes and network traffic. Additional challenges relate to automating testing and deployment processes, as well as the rigorous validation of results to ensure reproducibility and trust.

In summary, the Semantic Interoperability Lab developed by TECNALIA goes far beyond the scope of a project-specific demonstrator. It provides a reusable and secure environment for testing semantic IOP across energy data spaces, producing valuable insights on transformation services, compliance checks, orchestration strategies, and security mechanisms.

3.4 IOP Compass

The int:net IOP Compass[22] has been launched as an online capacity-building tool designed to support novices in understanding IOP concepts and testing approaches. Within int:net, its contribution is twofold: first, it provides a structured entry point for stakeholders who are new to IOP, offering clear explanations of key principles, standards, and processes; second, it serves as a practical guide for planning and executing IOP testing activities across diverse energy system use cases.

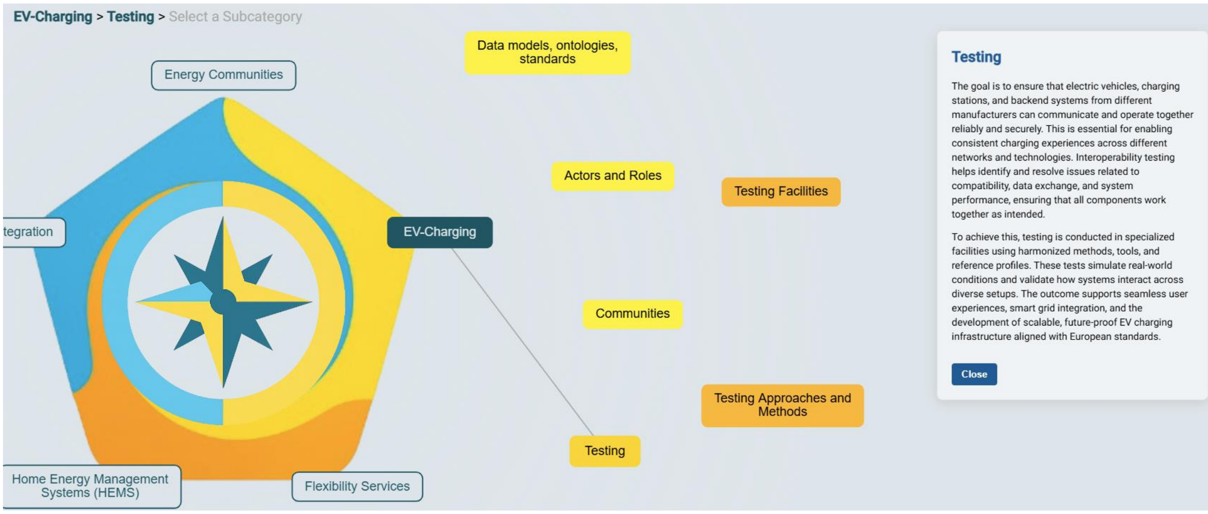

Figure 10: Interoperability Test Facility aspect of the IOP Compass

The IOP Compass simplifies complex topics by organising them into intuitive layers: technical, semantic, organisational, and legal, and linking these to real-world examples. This enables users to quickly grasp how IOP challenges manifest in practice and what testing strategies can address them. For int:net IOP testing, the Compass complements other tools such as the Ontology Checker and Lab Data Space by providing a conceptual foundation that aligns testing objectives with IOP maturity levels. It also supports the harmonisation of testing practices across facilities by promoting a common language and methodology.

By offering interactive resources, structured guidance, and references to standards and best practices, the IOP Compass strengthens the Pan-European community of testing facilities. It not only facilitates knowledge transfer but also builds capacity for future IOP initiatives, ensuring that testing activities are

[22] https://sgaaire.offis.de/iop-compass/

scalable, reproducible, and aligned with emerging certification frameworks. In this way, the IOP Compass plays a pivotal role in bridging the gap between theory and practice, empowering stakeholders to contribute effectively to interoperable and resilient energy systems.

4 Conclusions and Outlook

This report has outlined the activities undertaken to establish and strengthen a Pan-European community of IOP Testing Facilities. Key achievements include the creation of collaborative structures through the int:net Community Platform, especially IFG4, which serves as a central hub for sharing resources, best practices, and event information. The community has grown to include around 60 members from research organisations, universities, industry, and networks across Europe, ensuring a diverse and balanced representation. Knowledge-sharing activities such as Lunch Talks, ENTSO-E IOP testing events, and the Vienna Summer School have further supported capacity building and harmonisation of testing approaches.

The report also highlighted links with European projects and international initiatives, including collaborations with ENERSHARE, OMEGA-X, DERlab, NFDI4Energy, and IEA TCP programs. These interactions have strengthened alignment with emerging frameworks and fostered cross-sector knowledge exchange. Such collaborations underline the importance of IOP beyond electricity and open opportunities for future joint testing campaigns.

In addition to community-building efforts, several tools have been developed to support IOP testing and knowledge exchange: the Lab Data Space for secure data sharing between laboratories, the Ontology Checker for semantic compliance verification, the Energy Data Spaces Interoperability Lab for validating data exchange across platforms, and the IOP Compass as a capacity-building resource for newcomers. These tools provide practical support for harmonising testing practices and improving reproducibility across diverse use cases.

The established community and developed tools offer a strong foundation for continued collaboration beyond the int:net project. Future work should focus on expanding the network, refining the tools for broader adoption, and strengthening links with European data space initiatives and international standardisation efforts. In this context, the Interoperability People and Projects Connector (IntPPC)[23] could serve as an effective platform for sustaining and extending these activities, enabling structured engagement between stakeholders and supporting the evolution of IOP testing ecosystems in Europe.

[23] https://intppc.eu/

LIST OF FIGURES

LIST OF ABBREVIATIONS

CGMES	Common Grid Model Exchange Standard
CoC	Code of Conduct
DERlab	European Distributed Energy Resources Laboratories
DHC	District Heating and Cooling
DR	Demand-Response
DSO	Distribution System Operator
EDSCP	Energy Data Spaces Cluster Projects
EMS	Energy Management System
EMS4HESS	Energy Management System for Hybrid Energy Storage Systems
ESA	Energy Smart Appliance
EU	European Union
EUMED	EUropean My Energy Data
GDPR	General Data Protection Regulation
HESS	Hybrid Energy Storage System
IDSA	International Data Spaces Association
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IFG	Interoperability Focus Group
IntPPC	Interoperability People and Projects Connector
IOP	Interoperability
ISGAN	International Smart Grid Action Network
JRA	Joint Research Activity
JRC	Joint Research Centre
JSON	JavaScript Object Notation
JSON-LD	JSON for Linked Data
KPI	Key Performance Indicator
LDAP	Lightweight Directory Access Protocol
MQTT	Message Queuing Telemetry Transport
NC	Network Code
NFDI4Energy	National Research Data Infrastructure for Energy
ODC	Ontology-Driven Constraint
PECO	PARMENIDES Energy Community Ontology
PKI	Public Key Infrastructure
RCC	Regional Coordination Centre
RCP	Regional Coordination Processes

REC	Renewable Energy Community
RTI	Research and Technology Infrastructure
RTO	Research and Technology Organisation
SAREF	Smart Applications REFerence Ontology
SHACL	Shapes Constraint Language
SIRFN	Smart Grid International Research Facility Network
SME	Small and Medium-sized Enterprise
SV-IOP	Standard Vetting Interoperability
TCP	Technical Cooperation Program
TSO	Transmission System Operator
VLab	Virtual Verification Laboratory

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