HEDGE-IoT

Holistic approach towards Empowerment of the Digitalization of the Energy Ecosystem through adoption of IoT solutions

D3.2

HEDGE-IoT Interfaces and Tools for Interoperability

Co-funded by
the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

DOCUMENT CONTROL SHEET

PROJECT INFORMATION

Project Number	101136216		
Project Acronym	HEDGE-IoT		
Project Full title	Holistic Approach towards Empowerment of the Digitalization of the Energy Ecosystem through adoption of IoT solutions		
Project Start Date	01 January 2024		
Project Duration	42 months		
Funding Instrument	Horizon Europe Framework Programme	Type of action	HORIZON-IA HORIZON Innovation Actions
Call	HORIZON-CL5-2023-D3-01-15		
Topic	Supporting the green and digital transformation of the energy ecosystem and enhancing its resilience through the development and piloting of AI-IoT Edge-cloud and platform solutions		
Coordinator	European Dynamics Luxembourg SA		

DELIVERABLE INFORMATION

Deliverable No.	D3.2							
Deliverable Title	HEDGE-IoT Interfaces and Tools for Interoperability							
Work-Package No.	WP3							
Work-Package Title	Technological Enablers Specification, Design And Development							
Lead Beneficiary	TNO							
Main Author	Laura Daniele (TNO)							
Other Authors	TNO, INESC, KONC, EG, ABB, TAU, ICCS, APIO							
Due date	M19							
Deliverable Type	X	Document, Report (R)		Data management plan (DMP)		Websites, press & media action (DEC)	X	Other
Dissemination Level	X	Public (PU)		Sensitive (SEN)		Classified		
	PU: Public, fully open SEN: Sensitive, limited under the conditions of the Grant Agreement Classified R-UE/EU-R – EU RESTRICTED under the Commission Decision No2015/444 Classified C-UE/EU-C – EU CONFIDENTIAL under the Commission Decision No2015/444							

Document Revision History

Version	Date	Description of change	List of contributor(s)
0.1	15-05-2025	Early draft with Table of Contents	Laura Daniele (TNO)
0.2	22-05-2025	Extended interfaces from Dutch pilot	Barry Nouwt (TNO) Sophie Lathouwers (TNO) Laura Daniele (TNO)
0.3	23-05-2025	Extended interfaces from Slovenian pilot	Laura Daniele (TNO) Barry Nouwt (TNO) Josipa Stegić (KONC) Lenart Ribnikar (EG)
0.4	26-05-2025	Extended interfaces from Finnish pilot	Laura Daniele (TNO) Barry Nouwt (TNO) Anna Kulmala (ABB) Sami Repo (TAU) Mehdi Attar (TAU)
0.5	16-06-2025	Extended interfaces from Greek pilot	Laura Daniele (TNO) Barry Nouwt (TNO) Nikos Dimitropoulos (ICCS)
0.6	19-06-2025	Extended interfaces from Portuguese pilot	Barry Nouwt (TNO) Laura Daniele (TNO) Vasco Campos (INESC TEC) Fábio Coelho (INESC TEC) Paulo Monteiro (INESC TEC) Mateo Cardenas (NESTER)
0.7	20-06-2025	Extended interfaces from Italian pilot	Laura Daniele (TNO) Barry Nouwt (TNO) Mattia Alfieri (APIO)
0.8	14-07-2025	Stable draft for internal reviewers, including interoperability enablers, educational material and extended interfaces in the repository	Laura Daniele (TNO) Barry Nouwt (TNO) Gjalt Loots (TNO)
0.9	17-07-2025	Review by TRIALOG, INESC TEC, and Ethics Manager of D3.2 and associated online repository	Léo Cornec (TRIALOG) Vasco Campos (INESC TEC) Fábio Coelho (INESC TEC) Paulo Monteiro (INESC TEC) Tetiana Vasylieva (CSL)
0.9	18-07-2025	Processing of reviewers' comments and final version	Laura Daniele (TNO)

1.0		Final Review by Coordinator	Lenos Peratitis (ED) Nikos BIlidis (ED)

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

PARTNERS

Participant number	Participant organisation name	Short name	Country
1	EUROPEAN DYNAMICS LUXEMBOURG SA	ED	LU
2	RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN	RWTH	DE
~~3~~	~~ENGINEERING - INGEGNERIA INFORMATICA SPA~~	~~ENG~~	~~IT~~
4	EREVNITIKO PANEPISTIMIAKO INSTITOUTO SYSTIMATON EPIKOINONION KAI YPOLOGISTON	ICCS	EL
5	INESC TEC - INSTITUTO DE ENGENHARIADE SISTEMAS E COMPUTADORES, TECNOLOGIA E CIENCIA	INESC	PT
6	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	TNO	NL
7	TAMPEREEN KORKEAKOULUSAATIO SR	TAU	FI
8	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	VTT	FI
9	TRIALOG	TRIALOG	FR
~~10~~	~~CYBERETHICS LAB SRLS~~	~~CEL~~	~~IT~~
11	CENTRO DE INVESTIGACAO EM ENERGIA REN - STATE GRID SA	NESTER	PT
12	INTERNATIONAL DATA SPACES EV	IDSA	DE
13	ELIA TRANSMISSION BELGIUM	ETB	BE
14	HRVATSKI OPERATOR PRIJENOSNOG SUSTAVA D.D.	HOPS	HR
15	UNIVERSITATEA TEHNICA CLUJ-NAPOCA	TUC	RO
16	CLUSTER VIOOIKONOMIAS KAI PERIVALLONTOS DYTIKIS MAKEDONIAS	CLUBE	EL
17	F6S NETWORK IRELAND LIMITED	F6S	IE

Co-funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

18	SOCIAL OPEN AND INCLUSIVE INNOVATION ASTIKI MI KERDOSKOPIKI ETAIREIA	INCL	EL
19	ABB OY	ABB	FI
20	ENERVA OY	ENERV	FI
21	JARVI-SUOMEN ENERGIA OY	JSE	FI
22	DIMOSIA EPICHEIRISI ILEKTRISMOU ANONYMI ETAIREIA	PPC	EL
23	DIACHEIRISTIS ELLINIKOU DIKTYOU DIANOMIS ELEKTRIKIS ENERGEIAS AE	HEDNO	EL
24	INDEPENDENT POWER TRANSMISSION OPERATOR SA	IPTO	EL
25	ELLINIKO HRIMATISTIRIO ENERGEIAS	HENEX	EL
26	HARDWARE AND SOFTWARE ENGINEERING EPE	HSE	EL
27	QUE TECHNOLOGIES KEFALAIOUCHIKI ETAIREIA	QUE	EL
28	ARETI S.P.A.	ARETI	IT
29	APIO S.R.L.	APIO	IT
30	ACEA ENERGIA SPA	AE	IT
~~31~~	~~VOLKERWESSELS ICITY B.V.~~	~~VWICI~~	~~NL~~
32	ARNHEMS BUITEN BV	AB	NL
33	STICHTING VU	VU	NL
34	COOPERATIVE ELECTRICA DO VALE DESTE CRL	CEVE	PT
35	REN - REDE ELECTRICA NACIONAL SA	REN	PT
36	MC SHARED SERVICES SA	SONAE	PT
37	ELES DOO SISTEMSKI OPERATER PRENOSNEGA ELEKTROENERGETSKEGA OMREZJA	ELES	SI
38	ELEKTRO GORENJSKA PODJETJE ZA DISTRIBUCIJO ELEKTRICNE ENERGIJE DD	EG	SI
39	OPERATO DOO	OPR	SI

40	SVEUCILISTE U ZAGREBU FAKULTET ELEKTROTEHNIKE I RACUNARSTVA	UNIZG	HR
41	INSTITUT JOZEF STEFAN	JSI	SI
42	KONCAR - DIGITAL DOO ZA DIGITALNE USLUGE	KONC	HR
43	DS TECH SRL	DST	IT
44	CYBERSOCIAL LAB SRL IMPRESA SOCIALE	CSL	IT

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216.

DISCLAIMER

This deliverable is subject to final acceptance by the European Commission. The content and results of the publication herein are the sole responsibility of the publishers, it reflects only the contributors' view, and it does not necessarily represent the views expressed by the European Commission or its services, neither is the European Commission responsible for any use that may be made of the information it contains.

While the information contained in the documents is believed to be accurate, the contributor(s) or any other participant in the HEDGE-IoT Consortium make no warranty of any kind regarding this material including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose. Neither the HEDGE-IoT Consortium nor any of its members, their officers, employees, or agents, shall be responsible or liable in negligence or otherwise howsoever in respect of any inaccuracy or omission herein. Without derogating from the generality of the foregoing, neither the HEDGE-IoT Consortium nor any of its members, their officers, employees, or agents shall be liable for any direct or indirect or consequential loss or damage caused by or arising from any information advice or inaccuracy or omission herein.

COPYRIGHT NOTICE

© HEDGE-IoT, 2025

This deliverable and its content are the property of the HEDGE-IoT Consortium. This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation, or both. Reproduction is authorised provided the source is acknowledged. The content of all or parts of these documents can be used and distributed provided that the HEDGE-IoT project and the document are properly referenced.

EXECUTIVE SUMMARY

HEDGE-IoT (Holistic Energy Decentralized Grid for Enhanced Iot) is a project funded by the European Union's Horizon Europe research and innovation program. The project aims to develop an interoperable digital framework for the energy ecosystem, focusing on the deployment of Internet-of-Things (IoT) assets at different levels of the energy system, from the Transmission System Operator (TSO) level to behind-the-meter.

The main achievements of this deliverable D3.2 are summarized below.

- **Creation of a comprehensive framework for interoperability levels:**
  The project has developed a comprehensive framework of interoperability levels to ensure that different digital platforms across Europe can exchange meaningful information at the semantic level, in addition to the data formats and structures usually exchanged at the technical level. Building on established interoperability frameworks, we extended them in a framework that consists of seven distinct levels of interoperability, from traditional basic data exchange (i.e., network and syntactic interoperability) to technical interoperability via data space connectors, and moving forward to four different levels of semantic interoperability (i.e., entry-point, basic, intermediate and advanced), where the advanced semantic interoperability enables systems to unambiguously interpret and fully reason about the information they exchange.

- **Online repository and library:**
  An online, living repository has been launched to catalog and share extended digital interfaces, tools, and educational resources vital to the project. This library is accessible to both consortium partners and the broader community, providing:
    - The interoperability levels framework developed in the project,
    - Interoperability enablers, namely semantic models, tools and middleware that could support the HEDGE-IoT partners and external stakeholders to create and deploy their semantic interoperable solutions,
    - Educational materials, including tutorials and guides on key Interoperability enablers like SAREF [1] and the IEC CIM standard [3][4],
    - Concrete examples of extended interfaces for interoperability, including comprehensive metadata and, where available, open-source code.

- **Pilot collaboration and concrete results:**
  The project actively engages with pilot programs in six countries—Finland, Greece, Italy, the Netherlands, Portugal, and Slovenia. At the time of submission of this D3.2 deliverable (July 2025) partners have identified which technologies and interoperability "enablers" (such as semantic models and middleware) are most effective for integrating their diverse systems, and have implemented them in their solutions. This collaboration resulted in a portfolio of extended interfaces for interoperability tailored to different segments of the energy value chain, from grid operators to consumers. This portfolio is available in the online repository associated with D3.2.

- **Strengthening education and outreach:**
  Recognizing the complexity of semantic interoperability, the project has prioritized the creation and dissemination of clear, practical educational resources. These include newly

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

developed video tutorials and presentation slides, as well as references to official documentation and standards. All materials are accessible online through the live repository linked to deliverable D3.2. Initially designed to support HEDGE-IoT partners, these resources will also serve as a valuable onboarding tool for new partners selected through open calls. They provide essential guidance on the available HEDGE-IoT interfaces and interoperability tools, enabling new contributors to build effectively on existing work. Moreover, external stakeholders - such as energy professionals, IT developers, and other interested parties - can benefit from these materials. By helping them understand and apply interoperability concepts with confidence, the project fosters innovation and encourages practical adoption across Europe.

Significance of the Work

This deliverable marks a significant advance by not only clarifying the technical underpinnings of interoperability but also by making it more accessible to a broader segment of the industry. By structuring our repository in an open, updatable fashion, we ensure continuous relevance and alignment throughout the project. The combination of technical depth, practical examples, and educational materials positions HEDGE-IoT as a catalyst for increased integration of renewable energy, improved grid resilience, and the development of new market opportunities in the digital energy sector.

Next Steps

- **Continued development of the repository:**
  Task 3.1 concludes with the completion of this D3.2 deliverable. However, in 2026, the online resource will continue to be maintained under Task 4.3, incorporating updates and new developments related to extended interfaces, tools, and educational materials as they emerge from ongoing pilot activities.
- **Further engagement with stakeholders:**
  Open calls and outreach efforts will attract new partners, innovators, and SMEs, who will benefit from the online repository as a valuable resource, broadening the HEDGE-IoT project's impact and enriching its collective knowledge base.
- **Advancement towards interoperability:**
  The project will continue to support partners in their integration through data space connectors under Task 4.2 "Interoperability middleware - open data connector", and through semantic understanding under Task 4.3 "Semantic interoperability".

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

TABLE OF CONTENTS

Co-funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

LIST OF TABLES

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216.

LIST OF FIGURES

Co-funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

ABBREVIATIONS

Abbreviation	Full description
AI	Artificial Intelligence
AIOTI	Alliance for AI, IoT and Edge Continuum Innovation
API	Application Programming Interface
B2B	Business to Business
CIM	Common Information Model
CM	Congestion Management
CoC	Code of Conduct
DCAT	Data Catalog Vocabulary
DSO	Distribution System Operator
EC	European Commission
EDC	Eclipse Dataspace Component
EIF	European Interoperability Framework
ESA	Energy Smart Appliances
ETSI	European Telecommunication Standardization Institute
EU	European Union
GWAC	Gridwise Architecture Council
HEDGE-IoT	Holistic Energy Decentralized Grid for Enhanced Iot
HTML	Hypertext Markup Language
FSP	Flexibility Service Provider
IEC	International Electrotechnical Commission
IoT	Internet of Things
IP	Internet Protocol

IPv6	Internet Protocol version 6
JSON	JavaScript Object Notation
JSON-LD	JavaScript Object Notation for Linked Data
KE	Knowledge Engine
LFM	Local Flexibility Market
ML	Machine Learning
NEMO	Nominated Electricity Market Operator
MQTT	Message Queuing Telemetry Transport
RDF	Resource Description Framework
ODCT	Ontology-Driven Constraint Tester
OMG	Object Management Group
OWL	Web Ontology Language
RES	Renewable Energy Sources
REST	Representational State Transfer
STH	Semantic Treehouse
SHACL	Shapes Constraint Language
SME	Small and Medium-sized Enterprise
TCP	Transport Control Protocol
TSO	Transmission System Operator
SAREF	Smart Applications REFerence Ontology
SAREF4ENER	SAREF extension for the Energy domain
SIF	Semantic Interoperability Framework
SOSA	Sensor, Observation, Sample and Actuator
WP	Work Package
W3C	World Wide Web Consortium

XML	eXtensible Markup Language
XMI	XML Metadata Interchange
UDP	User Datagram Protocol
UML	Unified Modeling Language

1 INTRODUCTION

1.1 HEDGE-IOT PROJECT INTRODUCTION AND SUMMARY

The HEDGE-IoT (Holistic Energy Decentralized Grid for Enhanced IoT) project proposes a novel digital framework that aims to deploy IoT assets at multiple levels of the energy system (from behind-the-meter, up to the TSO level), to add intelligence to the edge and cloud layers through advanced AI/ML tools and to bridge the cloud/edge continuum introducing federated applications governed by advanced computational orchestration solutions. The HEDGE-IoT Framework will upgrade the RES-hosting capacity of the energy systems and unleash a previously untapped flexibility potential. It will increase the resilience of the grid, create new market opportunities and promote advances in IoT standardization, by introducing and managing a plethora of diversified, interoperable energy services over scalable and highly distributed data platforms and infrastructure. The multi-dimensional framework of HEDGE-IoT comprises the following pillars: (a) the Technology Facilitator pillar – it will exploit the computational sharing by offloading applications on the grid edge, towards providing a set of AI/ML federated learning and swarm computing applications; (b) the Interoperability pillar - leverages on leading-edge interoperable architectures, such as the data space architectures; (c) the Standardisation pillar – it will enable all involved platforms, systems, tools and actors to seamlessly communicate and exchange data in standardised formats using widely used standards, such as SAREF[1], etc.; (d) the Digital Energy Ecosystem enabling pillar – it will ensure the creation of an ecosystem facilitating the increased integration of RES and characterised by resilience. Liaisons with EU initiatives for IoT and digitalisation will be established (e.g., the AIOTI), and the engagement of stakeholders will be ensured by addressing IoT ethics and cultivating trust among end-users, thus promoting inclusivity. Scalability and replicability studies will be performed, and connections with innovators and SMEs will be established through the open call mechanism of the project.

1.2 SCOPE OF THE DOCUMENT

This document is the second and final deliverable of the Task 3.1, which aims to enable the integration of various digital interfaces, platforms and tools used in the different pilots into a digital interoperability framework across the entire project. The scope of this document is to provide a consolidated overview of the interfaces that have been extended for interoperability purposes, starting from the original platforms described in the previous D3.1 deliverable [8]. This document is

---

[1] https://saref.etsi.org/

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

accompanied by an online repository that can be accessed by clicking the "access" button at https://hedgeiot.eu/resources/repository. This repository will be updated during the project if new results become available. It has the scope to collect the extended interfaces and tools that are relevant in the project for the purpose of interoperability. Therefore, it does not aim to provide an exhaustive picture of all the interfaces and tools used in the project, but only the interoperable ones, as certain platforms, interfaces and tools that are instrumental (and vertical) for certain parts of a pilot, are not relevant in the broader scope of the horizontal common interoperability framework of the overall project.

1.3 INTENDED AUDIENCE OF THE DOCUMENT

This document and its associated online repository are intended as a means for the following audience:

- Project partners of the HEDGE-IoT consortium, to learn about the interoperability enablers of the project, share educational material, have one single common catalogue of the project's extended interfaces for interoperability (in terms of metadata/descriptions and, if available open-source, also implementations/code).
- Future project partners that will be appointed in later stage via open calls, enabling them to learn about the HEDGE-IoT interfaces and tools for interoperability, and identify opportunities to build upon in their sub-projects.
- External stakeholders that are interested in:
    - Understanding the approach used in HEDGE-IoT to enable interoperability across the energy and IoT ecosystem via a framework that is common to the project;
    - Learning about the interoperability enablers of the project and find corresponding educational material;
    - Gaining insights into the key interfaces and tools for interoperability developed in the HEDGE-IoT project (via metadata);
    - Finding a reference about these interfaces and tools for interoperability, if interested in gathering further information, and, if open source, find the source code to reuse/deploy these interfaces in their own project.

1.4 STRUCTURE OF THE DOCUMENT

This document is structured as follows:

Section 2 presents the methodology followed in this work, positioning it in relation to the other relevant tasks of the HEDGE-IoT project.

Section 3 presents the main results of this work, providing the rationale beyond the repository structure and guiding the reader through the various parts of the repository.

Section 4 proposes a discussion on our results and presents our conclusions, outlining the next steps.

Appendix A - (Section 6) provides a summary of the original platforms described in the previous D3.1 deliverable, for the reader's convenience, as most of the extended interfaces developed in this work originate from a platform or tool described in the previous D3.1 deliverable.

2 METHODOLOGY

This document is the second and final deliverable of Task 3.1, which aims to enable the integration of various digital interfaces, platforms and tools used across the project's pilots into the common digital interoperability framework that is developed in WP4.

Figure 1 illustrates the methodology adopted in Task 3.1 in relation to other relevant tasks and WPs in the project.

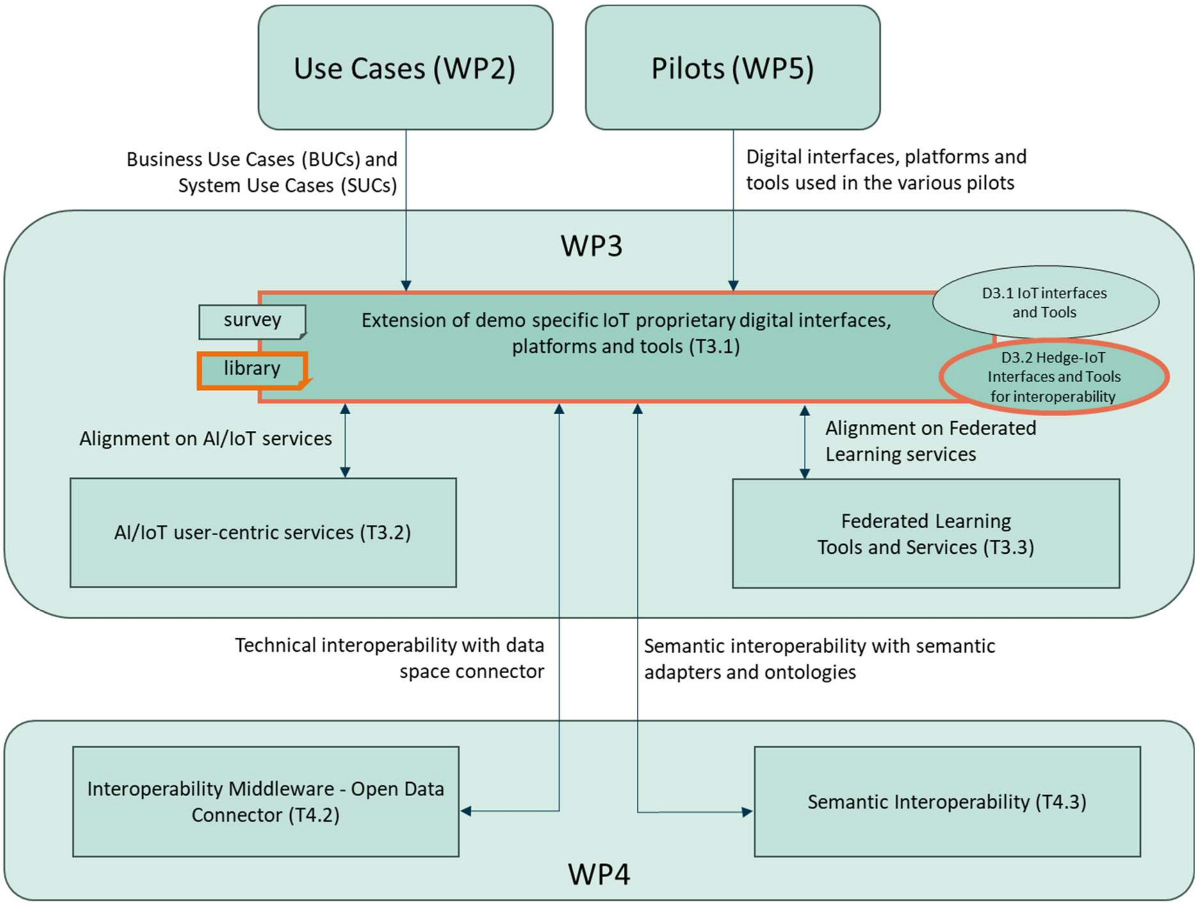


FIGURE 1. THE METHODOLOGY OF TASK 3.1 IN RELATION TO OTHER RELEVANT TASKS AND WPS OF THE PROJECT

The goal of the previous deliverable (D3.1 IoT interfaces and Tools [8]) was to make an inventory of the existing platforms, interfaces and tools considered foundational for the six project pilots in Finland, Greece, Italy, The Netherlands, Portugal and Slovenia. In this way, we provided an overview of the main technologies relevant for each pilot in the initial phase of the project. We collected this information using a survey, as shown in Figure 1. The outcome of D3.1 was used in the subsequent

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

phase of Task 3.1, in which we assessed the required level of interoperability for each pilot enabling technology, ranging from an entry point interoperability for fast integration, to an advanced interoperability option with semantics and reasoning. This resulted in a subset of interoperable enablers and extended interfaces that we published in a library, in the form of an online repository associated with this deliverable. As further shown in Figure 1, we interactively aligned with Task 4.2 "Interoperability middleware - open data connector alignment, when interoperability through data space connectors was required", and Task 4.3 "Semantic interoperability" when more advanced semantic features and formal ontologies were required. Moreover, we guaranteed alignment with the other WP3 tasks dedicated to the development of specific services, while we maintained our focus on interoperable platforms, interfaces and tools.

In the work presented in this document, we created an online repository that collects the input on extended interfaces and tools for interoperability from all the project's partners. In order to populate the repository, we first created a framework of interoperability levels and validated it with our partners. This framework builds upon the interoperability levels already established in the community (and described in D4.1 [7]), but it pays particular attention to the semantic interoperability level, refining it further. Afterwards, we conducted a series of sessions with the various pilots, starting from the initial platforms, interfaces and tools that they have submitted in D3.1. Together, we discussed and established which of those interfaces and tools were relevant for the purpose of interoperability. We assessed at which level of interoperability their work could be positioned according to our interoperability level framework, and which interoperability enablers were needed to reach their interoperability goal. A standardized template based on metadata, accompanied by example extended interfaces for interoperability, was provided to guide partners in completing their contribution to the repository. This structured approach has proven effective in collecting input from a large consortium with numerous pilots, keeping the partners engaged and motivated through focused and concise requests for contributions, while ensuring high visibility of results at any time during the process, guaranteeing a consistency of responses across different pilots and facilitating the analysis of the results.

3 REPOSITORY

The main result of this work is a an online repository that can be accessed by clicking the "access" button at https://hedgeiot.eu/resources/repository. This repository has the scope to collect the extended interfaces and tools that are relevant in the project for the purpose of interoperability. The repository is structured in the following sections:

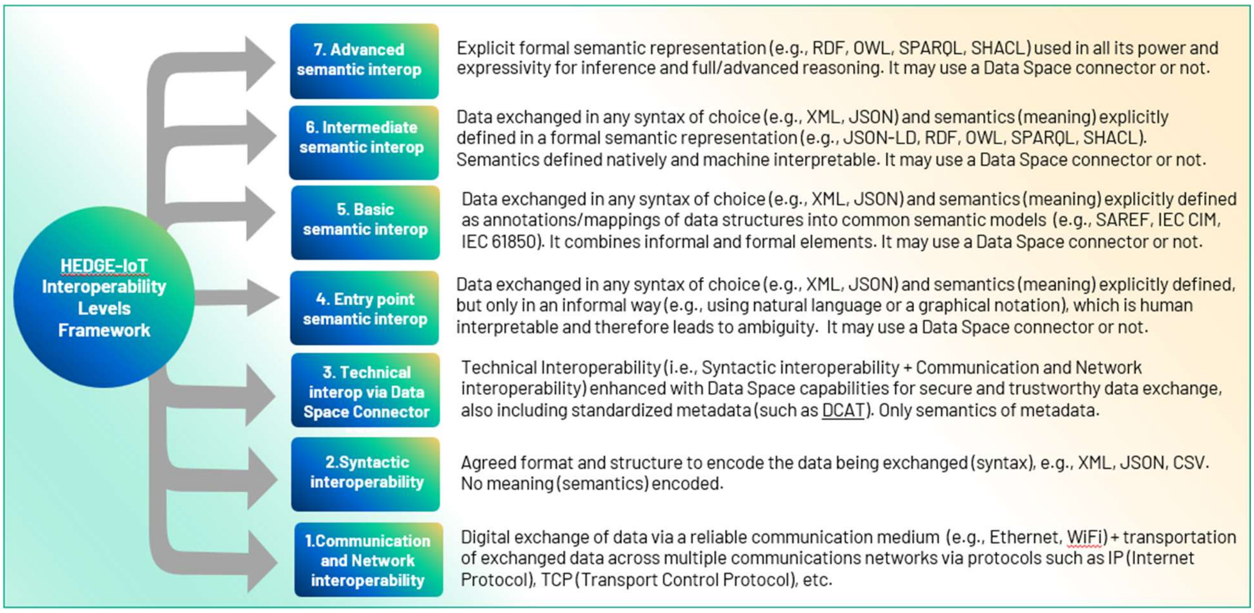
- **INTEROPERABILITY LEVELS FRAMEWORK**;
- **INTEROPERABILITY ENABLERS;**
- **EDUCATIONAL MATERIAL ON INTEROPERABILITY;**
- **EXTENDED INTERFACES FOR INTEROPERABILITY.**

The details and rationale for this structure are provided in the sub-sections hereafter.

3.1 HEDGE-IOT INTEROPERABILITY LEVELS FRAMEWORK

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216.

In D4.1 "HEDGE-IoT Interoperability Framework and Integrated Solution (First release)" [7], we have introduced interoperability as defined by established frameworks such as the European Interoperability Framework (EIF) Toolbox[2] by the EC, the Semantic Interoperability expert group by AIOTI [5], and the Interoperability Context-Setting Framework[3] by the Gridwise Architecture Council (GWAC). These efforts all agree on technical, semantic, and organizational interoperability as the main levels of interoperability. Starting from the lowest to the highest level, technical interoperability ensures that different systems can connect and communicate via networks and protocols, but also understand the data structure (syntax) contained in the messages exchanged between systems. Semantic interoperability ensures that the meaning of the exchanged data is explicitly defined, so that information exchanged by the different systems is preserved and understood correctly. Organizational interoperability ensures that businesses and organizations can work together smoothly by aligning on shared business processes, objectives and policies. As state-of-the art in the IoT/energy industry, the HEDGE-IoT project starts from the technical interoperability defined above, which is nowadays typically implemented by all systems that need to interact with other systems, but goes beyond that, focusing on the subsequent semantic interoperability level. However, semantically interoperability is represented as one single level by the existing frameworks. Therefore, we encountered the need to further refine this single semantic interoperability level, resulting in the more detailed HEDGE-IoT Interoperability Levels Framework presented in Figure 2.



7. Advanced semantic interop	Explicit formal semantic representation (e.g., RDF, OWL, SPARQL, SHACL) used in all its power and expressivity for inference and full/advanced reasoning. It may use a Data Space connector or not.
6. Intermediate semantic interop	Data exchanged in any syntax of choice (e.g., XML, JSON) and semantics (meaning) explicitly defined in a formal semantic representation (e.g., JSON-LD, RDF, OWL, SPARQL, SHACL). Semantics defined natively and machine interpretable. It may use a Data Space connector or not.
5. Basic semantic interop	Data exchanged in any syntax of choice (e.g., XML, JSON) and semantics (meaning) explicitly defined as annotations/mappings of data structures into common semantic models (e.g., SAREF, IEC CIM, IEC 61850). It combines informal and formal elements. It may use a Data Space connector or not.
4. Entry point semantic interop	Data exchanged in any syntax of choice (e.g., XML, JSON) and semantics (meaning) explicitly defined, but only in an informal way (e.g., using natural language or a graphical notation), which is human interpretable and therefore leads to ambiguity. It may use a Data Space connector or not.
3. Technical interop via Data Space Connector	Technical Interoperability (i.e., Syntactic interoperability + Communication and Network interoperability) enhanced with Data Space capabilities for secure and trustworthy data exchange, also including standardized metadata (such as DCAT). Only semantics of metadata.
2.Syntactic interoperability	Agreed format and structure to encode the data being exchanged (syntax), e.g., XML, JSON, CSV. No meaning (semantics) encoded.
1.Communication and Network interoperability	Digital exchange of data via a reliable communication medium (e.g., Ethernet, WiFi) + transportation of exchanged data across multiple communications networks via protocols such as IP (Internet Protocol), TCP (Transport Control Protocol), etc.

FIGURE 2. THE HEDGE-IOT INTEROPERABILITY LEVELS FRAMEWORK

Starting from the bottom, in Figure 2 we define the following interoperability levels:

1. **Communication & Network Interoperability** is the digital exchange of data via a reliable communication medium (e.g., Ethernet, Wi-Fi), and the transportation of these data across

---

[2] https://interoperable-europe.ec.europa.eu/collection/nifo-national-interoperability-framework-observatory/solution/european-interoperability-framework-eif-toolbox
[3] https://gridwiseac.org/pdfs/GridWise_Interoperability_Context_Setting_Framework.pdf

multiple communications networks via protocols that are independent of the data being transferred (e.g., IP/IPv6 - Internet Protocol (version 6) , TCP - Transport Control Protocol, UDP - User Datagram Protocol). In other words, if one wants to exchange a message with another can do so via the postal service, email, or messaging apps like WhatsApp or Signal.

2. **Syntactic Interoperability** is the agreement on the format and structure (syntax) to encode the data being exchanged (e.g., HTML—Hypertext Markup Language, XML—Extensible Markup Language, JSON - JavaScript Object Notation). In other words, it is the language, with its words and symbols, agreed for the data exchange. For example, two could make an agreement to send a date in the data form "YYYY-MM-DD", where YYYY indicates the year, MM indicates the month, DD indicates the day.
3. **Technical Interoperability via Data Space Connector** is the minimum level of interoperability that distinguishes the HEDGE-IoT project, i.e., we advance the state-of-the-art in IoT/energy systems going beyond the classic *"Technical Interoperability = Communication & Network + Syntactical interoperability"* (i.e., levels 1+2 in Figure 2) by adding a data space connector for secure and trustworthy data exchange, which includes metadata expressed in standardized way (such as DCAT - Data Catalog Vocabulary[4]) to explicitly and unambiguously define, for example, who are the producer and consumer of a certain dataset or data service being exchanged.
4. **Entry Point Semantic Interoperability** is the initial level that actually considers the semantics (i.e., the meaning) of the data exchanged on top of the syntax. It does so in an informal way, i.e., by specifying the semantics of the data in natural language or in graphical notation that is only human interpretable, rather than in a strict formal language with logical axioms, which, in contrast, is machine interpretable. For example, the widely-adopted UML [6] by OMG is a graphical notation for modelling object-oriented system whose semantics is informal and, as such, it depends on the personal interpretation of the developer, leading to ambiguity, especially when are machines exchanging the data (which do not possess interpretation capabilities like humans). In other words, two systems can exchange a UML model via a certain communication means (e.g., via email, or using the XML Metadata Interchange (XMI) standard[5], or via a data space connector[6]), but the final interpretation is up to the human receiving it.
5. **Basic Semantic Interoperability** is a step forward since the semantics (i.e., meaning) is not only informally defined like in level 4, but it is explicitly mapped or annotated into the syntactical data structures of level 2 (syntactic interoperability). For example, if the underlying syntactical interoperability level makes use of XML or JSON as data format exchange, certain fields of the XML or JSON messages can explicitly refer (e.g., via comments) to corresponding concepts in a semantic standard, like SAREF [1], IEC CIM [3] [4] or IEC 61850 [11]. However, it must be noted, that the machine receiving the message only processes that there is a comment for a certain field, but is not able to interpret what

---

[4] https://www.w3.org/TR/vocab-dcat/

[5] Note that in this case, what is exchanged via the XML Metadata Interchange (XMI) standard is the syntax, which is indeed machine interpretable, but not the actual meaning (semantics) of the information exchanged.

[6] Note that from level 4 up to level 7, the data space connector is not mandatory, like at level 3. Therefore, the informal semantics can be exchanged via a data space connector, or not.

Co-funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

this comment means (i.e., to which corresponding semantic concept it refers to). Therefore, the semantic interoperability is only basic.

6. **Intermediate semantic Interoperability** is the level in which the semantics is not only explicitly defined, but does so using a formal representation language that is also machine interpretable. Such formal languages include (but are not limited to) the widely adopted W3C standards like JSON-LD, RDF, OWL, SPARQL, and SHACL, which are explicitly designed to express semantics and reason about it. However, from the lessons learned in over a decade of experience with industrial partners in IoT, often, in practical applications, there is an explicit formal specification of the data exchanged in RDF/OWL, e.g., using a standardized ontology like SAREF, but the actual (powerful) reasoning capability of the language are not used.
7. **Advanced semantic Interoperability** is the highest level of interoperability, where explicit formal semantic representation (like RDF, OWL, SPARQL, SHACL) is used for inference, validation, advanced querying of the exchanged data, and full reasoning. When two systems operate at this level, they can automatically bridge the semantic descriptions of their data even when there is not an exact match and, therefore, increase their semantic interoperability. For example, if one system is interested in *Devices* (e.g., defined as *saref:Device*), while the other system provides information about *Sensors* (e.g., defined as *saref:Sensor*), they are still able to exchange data, because the reasoner infers the fact that every *saref:Sensor* is also a *saref:Device*. Additionally, this level of semantic interoperability allows automatic conversion of units of measure between systems. For example, if a first system publishes its measurements in degrees Celsius, while a second system expects the measurements in degrees Fahrenheit, they are able to overcome this semantic gap and interpret properly their measurements by automatically applying a conversion between Celsius and Fahrenheit.

In task 3.1, the HEDGE-IoT partners were advised and guided to find the most suitable interoperability levels for their solutions. The results are shown in the online repository associated to this deliverable.

3.2 INTEROPERABILITY ENABLERS

In D3.1 "IoT interfaces and tools" [8] we have investigated which platforms, interfaces and tools used in the various pilots already had or were considering support for semantic interoperability. The results showed considerable support or interest for the ETSI SAREF ontologies in the IoT domain, for data models in the utility sector, such as the IEC CIM, as defined by the IEC 61968 [3] and 61970 [4], and IEC 61850 [11]. Moreover, the following three platforms/tools examined in D3.1 (see Annex A – Section 6 for an overview) resulted to have the purpose of semantic data sharing:

- Semantic Treehouse (STH) that is used as a vocabulary hub for data spaces;
- Semantic Interoperability Framework (SIF)/ Knowledge Engine (KE) that is a middleware used to enable semantically enriched data exchange and reasoning using ontologies;
- Power CIM that is a digital platform designed for the efficient exchange and management of electrical power system information.

Co-funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Therefore, we have taken these results as input to define the so called "interoperability enablers", namely semantic models, platforms or tools that could support the HDEGE-IoT partners and external stakeholders to create and deploy their semantic interoperable solutions. Figure 3 summarizes the positioning of the HEDGE-IoT main interoperability enablers included in our online repository according to the interoperability levels in Figure 2. We have clustered our interoperability enablers in the following categories:

- **Semantic models**, such as the SAREF and SAREF4ENER ontologies, which can be positioned starting at level 5 in Figure 2, but ideally should be used at the levels 6-7 (respectively, intermediate and advanced semantic interoperability). Further, also data models that incorporate semantics in their syntax are included in the semantic models category, such as IEC CIM and IEC 61850, which can be positioned at the levels 4- 5 in Figure 2 (i.e., entry point and basic semantic interoperability, respectively).

- **Semantic tools**, such as the Power CIM and the Semantic Treehouse mentioned above, which can be used in various levels of the framework proposed in Figure 2, ranging from level 3 (technical interoperability via data space connector) up to level 6 (intermediate semantic interoperability). In addition to the tools examined in D3.1, we have added in this subsequent D3.2 deliverable also the Ontology-Driven Constraint Tester (ODC-Tester), which is a novel tool, currently under development, that focuses on ensuring technology-neutral ontology-based interoperability and behavioural testing, supporting engineers to verify, ensure and validate the interoperability compliance of data exchange between various systems with ontologies like SAREF.

- **Semantic middleware**, namely software that uses semantic technologies to facilitate the integration, management, and communication of data between different systems and applications, such as the Semantic Interoperability Framework (SIF) and its main component, the Knowledge Engine (KE) (see Annex A – Section 6). SIF and KE enable interoperability at the highest levels in Figure 2 (i.e., levels 6-7). However, we also included data space connectors, in particular the Eclipse Dataspace Components (EDC) that have been chosen in HEDGE-IoT as the common solution for implementing data spaces in the project. It must be noted that the data space connector interoperability enabler is used at level 3 (technical interoperability via data space connector), as it natively includes only semantic metadata . However, if complemented with native semantic solutions (like SAREF, SIF or KE, for example), the data space connector enabler can be used up to the highest level 7 to reach advanced semantic interoperability. This is reflected in Figure 3, where the EDC dataspace connector is visualized with a solid line at level 3, and a dashed line from level 4 to level 7.

Co-funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

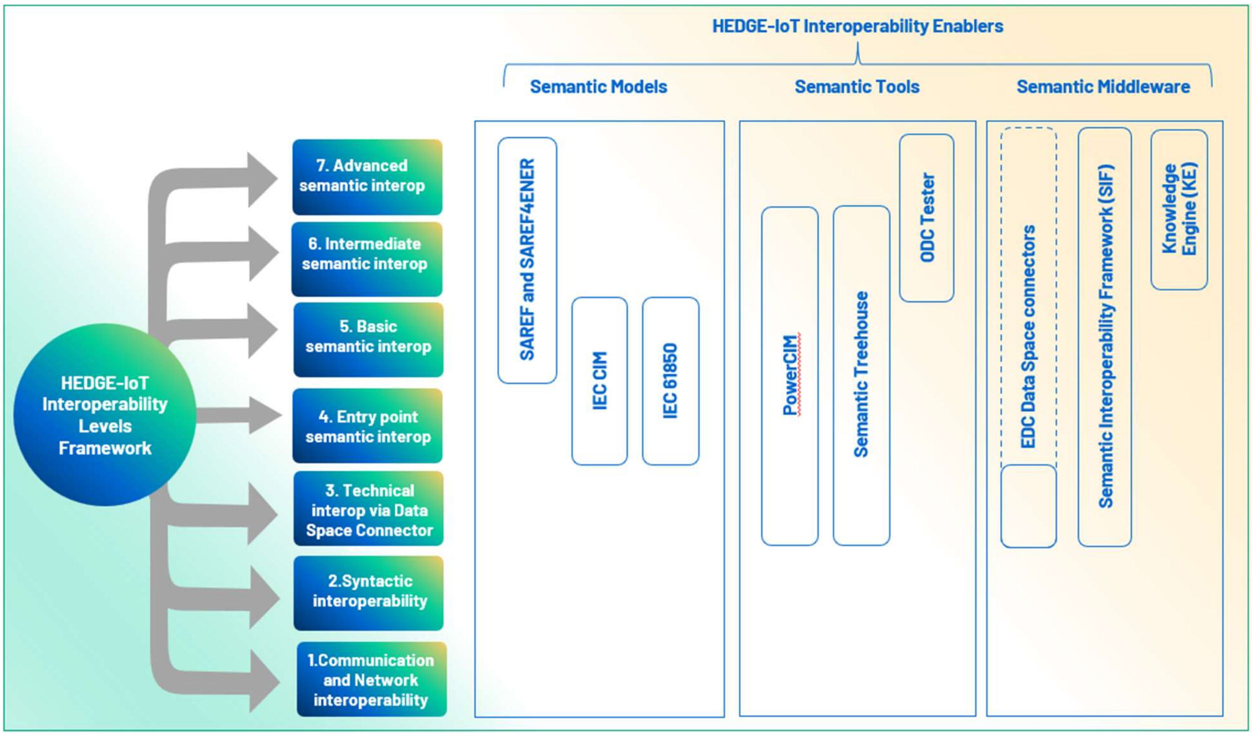


FIGURE 3. POSITIONING OF THE INTEROPERABILITY ENABLERS INTO THE HEDEGE-IOT INTEROPERABILITY LEVELS FRAMEWORK

The online repository associated with this deliverable contains a number of interoperability enablers that are categorized according to the distinction in semantic models, semantic tools and semantic middleware, as explained above. Note that the online repository is a live artefact that is updated during the project, therefore, more interoperability enablers could be added in later stages compared to the ones discussed in this deliverable and shown in Figure 3. The interoperability enablers are like building blocks that can be used to build and deploy interoperable solutions. These building blocks can be used individually or combined together. For example, a certain platform can be made interoperable, for example, by combining various interoperability enablers as follow: i) SAREF, as a Semantic Model, with ii) EDC and KE as Semantic Middleware, and iii) the Semantic Treehouse (or the ODC tester, or both) as Semantic Tools. Not all categories have to be necessarily used together in every configuration, for example, a certain platform can be made interoperable by using a single enabler, such as IEC 61850 from the Semantic Models category, like in the case of the ABB edge platform (see Annex A – Section 6) .

3.3 EDUCATIONAL MATERIAL ON INTEROPERABILITY

One significant challenge in applying and deploying semantic interoperability with industrial practitioners is the perception that the underlying semantic technology, based on ontologies and linked data, is difficult to learn. This perception is aggravated by a perceived lack of straightforward educational materials. As frequently highlighted in AIOTI and ETSI discussions with the industry, practitioners are often unaware where to find these educational resources online, despite knowing that such materials exist. This situation is overwhelming for them and further discourages the use of the technology. However, with the growing focus on improving accessibility and creating userfriendly resources, there is a promising path forward to make these technologies more approachable and widely adopted.

On one hand we encourage practitioners to actively seek out these resources and engage with the community to enhance their understanding and application of semantic technologies. On the other hand, we aim to address the issue of scattered materials on the internet by providing our HEDGE-IoT partners and external stakeholders interested in deploying semantic interoperability in their solutions with a single repository. This repository collects pointers to official documentation of our interoperability enablers (see Section 3.2) and introductory video tutorials and presentation slides. Several of these tutorials have been developed in the context of Task 4.3, where they were used as educational material internally for the HEDGE-IoT partners. Through the repository associated with this deliverable, we have extended their availability publicly to external stakeholders.

The educational material includes resources to get acquainted with SAREF, which was recently updated by ETSI to a new major release (v.4) in March 2025. This release [1] contains significant changes compared to the previous major release SAREF V3.1.1 from 2017 [9]. The repository also provides introductory resources to SAREF4ENER v2.1.1 [2], which is used as the main example of ontology in the European Code of Conduct (CoC) for Energy Smart Appliances (ESA)[7] [10]. The CoC has been signed in April 2024 by 12 manufacturers in Europe, who have agreed to introduce at least one product in the market with mappings into SAREF and SAREF4ENER for various use cases, such as the delayed start of smart appliances.

Additionally, the repository includes material on semantic models relevant for the DSO side, particularly IEC CIM [3] [4] and IEC 61850 [11]. We have also included resources related to semantic middleware, such as the SIF and KE, along with pointers and introductory tutorials for enabling tools like the Semantic Treehouse.

Please note that the online repository is a live artifact that will be updated throughout the project. Therefore, more educational material may be added in later stages beyond what is mentioned in this deliverable.

The resources in the "educational material" section of the online repository are intended to provide detailed explanations of the resources collected in the "interoperability enablers" section of the repository.

3.4 EXTENDED INTERFACES FOR INTEROPERABILITY

In the context of Task 3.1 and its related deliverables D3.1 [8] and D3.2 (the present document), we define a platform as a digital infrastructure on which some software is executed and that supports the exchange of information and data with external parties. Within the platform, services provide various types of functionalities to external parties, while interfaces describe these services, i.e.,

---

[7] https://ses.jrc.ec.europa.eu/development-of-policy-proposals-for-energy-smart-appliances

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

they are the means through which a service can be accessed and utilised. In D3.1 we surveyed the platforms expected to be used by the various pilots during the HEDGE-IoT project. A summary of these platforms is provided to the reader in Annex A – Section 6.

In this subsequent deliverable, we have collaborated with the partners to extend some of the D3.1 surveyed platforms for interoperability purposes, enabling seamless and unambiguous information exchange with other systems/ parties. Therefore, an important section of this deliverable and the associated online repository consists of a library of so called "extended interfaces". These are interfaces belonging to a specific platform that have been extended for interoperability with one or more of the interoperability enablers described in Section 3.2. This library contains source code to reuse these interfaces, if available, and relevant metadata that is structured as follows:

- Name: the name of the extended interface;
- Original platform: the initial platform that originally was not interoperable and during HEDGE-IoT has been extended for interoperability using one or more of our interoperability enablers;
- Main contributor: the organization responsible for most of the development of the extended interface using one of more of the interoperability enablers;
- Main contact: the primary point of contact for the extended interface, also available for further inquiries on commercial interfaces whose source code is not included in the repository;
- Other contributors: other organizations that contributed to the design and/or development of the extended interface;
- Pilot: the main pilot in HEDGE-IoT in which the extended interface has been developed and tested;
- Open source: indicates whether the extended interface is commercial or open source. If open source, a link to the code is provided;
- Status: indicates whether the interface and the code (if applicable) are already available or still under development. If under development, an expected release date is provided;
- Beneficiary user: refers to the party that mainly benefit from the provided interface. It can be a category/actor (e.g., DSO) or a specific organization (e.g., a specific DSO name). It can also be an end consumer. Multiple beneficiary users can be mentioned;
- Position in IoT/Electricity value chain: indicates in which part(s) of the value chain, from the TSO and DSO level to behind the meter at the home premises, the extended interface operates;
- Interoperability level: positions the extended interface according to the HEDGE-IoT interoperability levels framework described in Section 3.1;
- Interoperability enablers: indicates which interoperability enabler, from those described in Section 3.2, has been used to create the extended interface under consideration. Multiple interoperability enablers can be combined together;
- Educational material: refers the reader, possibly interested to reuse or extend the proposed interface, to related educational material from Section 3.3;
- Description: provides a short description in natural language of the extended interface and its functionality.

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

4 DISCUSSION AND CONCLUSIONS

This deliverable described the final results achieved in the context of Task 3.1 of the HEDGE-IoT project. In particular, it defined a framework for interoperability levels (see Section 3.1) where the semantic level is refined compared to existing interoperability frameworks. This does not imply that everything in HEDGE-IoT (or any context) must always reach the highest interoperability level, namely level 7 (advanced semantic interoperability), as this entails significant investments in terms of complexity, costs and time that are not always required or justified for a given interface. Instead, we advocate for a minimum interoperability level. Therefore, the extended interfaces published in our repository start at least from level 3 (technical interoperability via data space connector), which is the minimum requirement for interoperability in the HEDGE-IoT project to establish and exchange data that is secure, trustworthy, and based on standardized metadata. On the other extreme of the scale, we aim at level 6-7 (intermediate and advanced semantic interoperability, respectively) when many systems need to interoperate and use a variety of different protocols and standards, therefore when scalability is the main requirement. This advanced semantic interoperability approach has proven successful based on our experience in previous large scale pilots, such at the H2020 InterConnect project[8]. Additionally, we settle on level 5 (basic semantic interoperability) as a compromise between usability and applicability by traditional developers (who typically are not semantic experts) and performance, as adding semantics and reasoning also increases processing time and reduces system performance. Finally, we accept level 4 (entry point semantic interoperability) as an initial step towards semantic interoperability, with the expectation that it can progress to level 5 (and higher) in future stages.

In order to achieve the interoperability levels from 3 to 7 based on the requirements mentioned above, we have collected (and sometimes developed) a number of interoperability enablers to assist HEDGE-IoT partners and external stakeholders to establish first time interoperability solutions, or evolve them into higher levels of semantic interoperability according to our framework. These interoperability enablers are supported by educational material resources that have been created or selected within HEDGE-IoT.

An important step for the reproducibility of our results is a library of extended interfaces that complements the information on interoperability enablers and related educational material, with real examples of applications that can be directly reused or extended by external partners. Some of these interfaces are commercial, providing a realistic picture of a consortium that involves numerous industrial partners and grid operators. However, most of the extended interfaces are open source and, in such cases, the source code is made publicly available. The extended interfaces included in the library originate from a platform or tool described in the previous D3.1 deliverable. For the reader's convenience, we have provided a summary of these original platforms in Annex A – Section 6.

The extended interfaces for interoperability cover various areas of the IoT/electricity value chain, aligning with the HEDGE-IoT project's goal to deploy IoT assets at different levels of the energy

---

[8] https://interconnectproject.eu/

system, from the TSO level to behind-the-meter. Some extended interfaces focus on interactions within the flexibility energy market, others are dedicated to interactions at the TSO/DSO level, and several are aimed at data sharing across multiple stakeholders for energy flexibility, including building managers and prosumers. This ensures that no relevant stakeholders are neglected, demonstrating a well-distributed yet comprehensive landscape that provides solutions to all stakeholders along the value chain.

Finally, the results highlight that the pilots plan to implement data space connectors for interoperability. However, at this stage, none are yet available. Implementations of data spaces are currently under development, but we have included descriptions of their intended functionality in our repository at https://hedgeiot.eu/resources/repository. Once available, we will publish there the metadata about data space providers and consumers. Please note that the actual implementation/code of the data space connectors might contain sensitive information and may not be open source.

To benefit the broader community of stakeholders, we have collected the results of the work carried out in Task 3.1 in a public repository[9] that follows the structure and rationale presented in this document. This repository is a live resource that will be kept up to date throughout the project. The work on enabling interoperability carried out in Task 3.1 is concluded with this deliverable, and the implementation of the extended interfaces published in the repository will be finalized in the context of Task 4.2 "Interoperability middleware - open data connector" and Task 4.3 "Semantic interoperability".

---

[9] https://hedgeiot.eu/resources/repository

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

5 REFERENCES

[1] ETSI TS 103 410-1 V4.1.1 (2025-03) SmartM2M; Smart Applications; Reference Ontology and oneM2M Mapping.

[2] ETSI TS 103 410-1 V2.1.0 (2024-10) SmartM2M; Extension to SAREF; Part 1: Energy Domain.

[3] International Electrotechnical Commission (IEC) TC 57 WG14, IEC 61968 Common Information Model (CIM).

[4] International Electrotechnical Commission (IEC) TC 57 WG14, IEC 61970 Common Information Model (CIM).

[5] Martin Bauer, Laura Daniele, Antono Kung et al: Semantic IoT Solutions - A Developer Perspective, AIOTI white paper (2019) DOI 10.13140/RG.2.2.16339.53286.

[6]] OMG. Unified Modeling Language version 1.3. OMG, July 1999.

[7] HEDGE-IoT Deliverable 4.1 "HEDGE-IoT Interoperability Framework and Integrated Solution (First release)" (2025).

[8] HEDGE-IoT Deliverable 3.1 "IoT interfaces and tools" (2025)

[9] ETSI TS 103 410-1 V3.1.1 (2017-01) SmartM2M; Smart Applications; Reference Ontology and oneM2M Mapping.

[10] European Commission: Code of Conduct on energy management related interoperability of Energy Smart Appliances (V.1.0).

[11] IEC 61850 standard series "Communication networks and systems in substations"

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

6 APPENDIX A – ORIGINAL PLATFORMS DESCRIBED IN D3.1

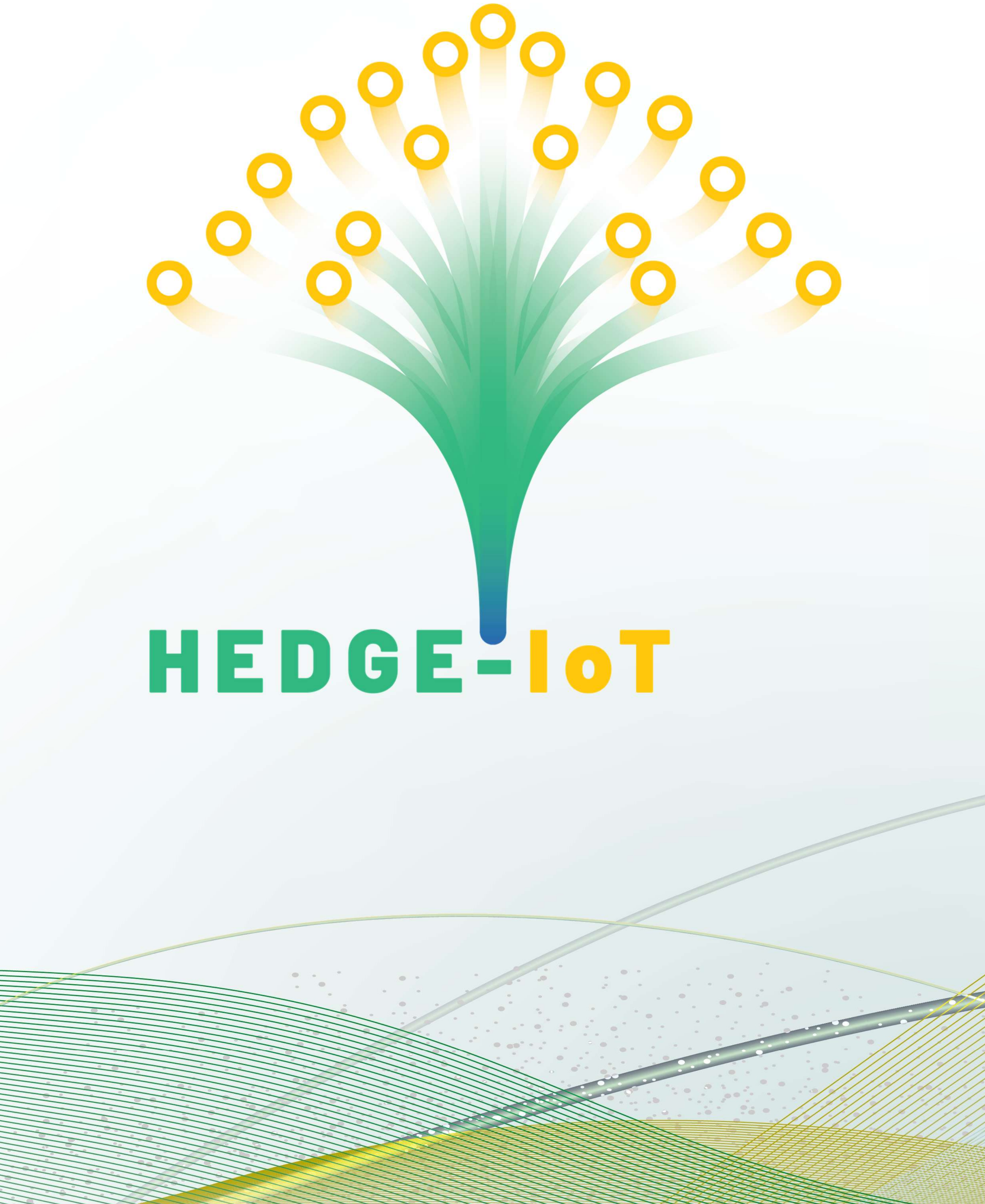
Name	Description
Hedge IoT LFM Platform	The Hedge IoT LFM Platform is designed to enable and facilitate Local Flexibility Market (LFM) trading. It provides a digital marketplace where energy producers, consumers, and prosumers (those who both produce and consume energy) can trade energy flexibility in real time. By connecting IoT devices and smart meters, the platform gathers data on energy demand, supply, and flexibility needs. This information enables participants to offer flexibility services—such as adjusting energy consumption or production levels—which grid operators can purchase to balance the local grid.
Semantic Treehouse	Semantic Treehouse is an open-source web application created by TNO. In data spaces it plays the role of the Vocabulary Hub component. It is designed to boost adoption of semantic standards by facilitating open standardization.
PowerCIM	The PowerCIM platform enables grid model data persistence and exchange using the widely deployed IEC Common Information Model standards and data formats, enabling efficient versioned model data management and semantic enrichment of telemetry time series data. The platform components are: 1. Core repository server, 2. Model viewer front end, 3. Standard IEC 61970-552 CIM/XML adapter, 4. Generic SQL and CSV adapters, 5. CIM UML metamodel management, 6. Data flow orchestrator The platform currently supports network equipment data (CIM EQ profile), network state data (CIM SSH and SV profiles), geographic layout data (CIM GL profile). In the near future we envision support for topology processing data (CIM TP profile) and schematic diagram data (CIM DL profile).
AI services for local grid resilience	This platform will actively monitor the functioning of the grid and will detect (technical) anomalies within a series of measurements provided by devices hosted at Arnhems Buiten, aiming to report possible (future) irregularities within the system.
Apio Platform	The Apio Platform is a multi-tenant data-driven IoT platform that provides energy value chain stakeholders with the ability to connect and manage assets, ingest, analyze and export data and support data driven decision making. It features well-known standards, such as MQTTS and JSON REST APIs to interact with any of its functionalities and to integrate it with any other service as well as other well-known data formats such as Parquet and Arrow for time-series data. Supporting multiple stakeholder profiles, it features several modules, such as Renewable Assets Management, Flexibility Management, Virtual Power Plant Management and more.
Real-Time Reserve Market Simulator	The Real-Time Reserve Market Simulator (MS) is an in-house developed tool that evaluates the performance of a bid submitted for a particular time frame in comparison with historical bids retrieved from ENTSO-E Transparency Platform. The platform validates the structure of the bid, applies the necessary market rules for the selected Ancillary Service and determines if the bid could be accepted in the corresponding market clearing process. In addition, it can issue activation signals/messages and perform settlement calculations.
ABB edge platform	The platform enables sharing high volume data with strict real-time requirements between different applications that are executed on an edge server in a virtualization environment.
Dynamic and automated B2B energy data and flexibility service platform	The platform will include data sharing between different stakeholders including DSO, NEMO and flexibility service provider (FSP) to realize predictive congestion management (CM). In addition, the platform provides the possibility through eclipse dataspace connector to exchange data with real-time CM algorithms running on the edge.
EdgeConnect	EdgeConnect is a digital platform that provides stakeholders (i.e., consumers, service providers, aggregators, DSOs) along the value chain of flexibility provision with an integrated ecosystem to support all main activities in this value chain, to help identify, unlock and make use of all available flexibility potential. As a multi-stakeholder platform, it comprehends several views, providing distinct value propositions for each stakeholder.
Semantic Interoperability Framework (SIF) (based on H2020 InterConnect)	SIF enables data exchange and reasoning based on semantically enriched information, providing distributed IoT EDGE/CLOUD/FOG support. The platform consists of two main components: (1) the Knowledge Engine (KE) for data exchange, and (2) the SAREF framework of ontologies as a common language. The platform's architecture supports semantic adapters for

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

	different protocols and data formats. It uses semantic adapters to map different data models to SAREF.
Home Management System (not a platform)	The solution requires installations of hardware components on the edge to track and monitor energy consumption dynamics. It can monitor the full electricity consumption and separate appliances, as well as small scale DERs (heat pumps, PVs and testing with BESS). The platform works as a unified solution, with advanced energy analytics, user interfaces and control mechanisms by users' input.
AI-library for energy applications	As part of numerous EU-funded projects, ICCS AI-based models and tools for smart building management and flexibility modelling algorithms have been developed by ICCS. Services such as demand and production forecasting, optimisation techniques in buildings, grids, energy communities, flexibility scenarios and assessment, building energy efficiency have been tested and validated both operationally and scientifically. The platform is an internal tool that is used to further test and deploy energy applications, as part of ICCS research activities.

TABLE 1. OVERVIEW OF THE ORIGINAL PLATFORMS SUBMITTED IN D3.1

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement number 101136216. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.



HEDGE-IoT