Semantic Interoperability for DR Schemes Employing the SGAM Framework

Andrea Cimmino*, Nikoleta Andreadou†, Alba Fernández-Izquierdo*, Christos Patsonakis‡, Apostolos C. Tsolakis‡,
Alexandre Lucas†, Dimosthenis Ioannidis‡, Evangelos Kotsakis†, Dimitrios Tzovaras‡, and Raúl García-Castro*

*Ontology Engeneering Group, Universidad Politécnica de Madrid, Madrid, Spain
{albafernandez, cimmino, rgarcia}@fi.upm.es
†Energy Security, Distribution and Markets Unit, Joint Research Centre, 21027 Ispra, Italy
{nikoleta.andreadou, alexandre.lucas, evangelos.kotsakis}@ec.europa.eu
‡Centre for Research and Technology Hellas, Information Technologies Institute, 57001 Thessaloniki, Greece
{cpatsonakis, tsolakis, djoannid, dimitrios.tzovaras}@iti.gr

Abstract—Demand Response (DR) systems are gaining momentum in the EU energy markets albeit based on fragmented standards that, as a result, hinder interoperability. These discrepancies necessitate the introduction of a semantically enriched umbrella framework that will allow DR systems to exchange and consume data transparently, an issue that is currently unaddressed. Furthermore, to support semantically interoperable DR architectures, a multi-layer compliance testing framework is required that will examine and quantify the technical, syntactic and semantic properties of individual DR systems. In this work, the aforementioned gaps in the literature are addressed by, first, introducing an OpenADR-based semantic enrichment component. According to the guidelines of the Smart Grid Architecture Model (SGAM) framework, a concrete evaluation procedure of this component is presented, which allows for a step-by-step syntactic and semantic testing. Following the identification of the instruments composing the testbed and the equipment/links under test at SGAM's communication and information layers, the Basic Application Interoperability Profiles (BAIOPs) are defined and their involved steps are described. Experiments demonstrate the validity of the presented methodology, while also evaluating the introduced component.

Keywords—Semantic Interoperability, Demand Response, Smart Grids, W3C, SGAM

I. INTRODUCTION

Electricity grids are undergoing radical transformations driven by policies that mandate the smooth, yet constantly increased integration of Renewable Energy Sources (RES) and the full-blown inclusion of end-customers in energy markets. These policies impose a new mode of operation for smart grids that revolves around decentralised electricity generation where consumers will also act as producers (prosumers). In this modern operational paradigm, Demand Response (DR) is recognised at a global level [1], [2] as a key enabler of decentralised demand-side flexibility management.

The fragmentation of standards endowed for building appliances, building and/or energy management systems, as well as, marketplaces, has imposed severe roadblocks in the large-scale deployment of DR services, especially with the exponential growth of Internet of Things (IoT) solutions that are available in the markets. Relying on energy-related standards, e.g., USEF [3] or SAREF [4], different frameworks have been proposed to deliver semantic interoperable architectures, which allow the transparent exchange and consumption of information amongst multiple smart grid layers.

Nevertheless, the focus of those frameworks has been allocated only at the infrastructure level and not on the information exchange level. In addition, since numerous standards lack semantics, as defined by the W3C (e.g., OpenADR [5]), such endeavours become even more cumbersome. The significance of the matter at hand is highlighted by the fact that a dedicated working group has been formed in the respective IEC Technical Committee towards delivering the next generation of semantically-enabled standards [6].

A wide number of testing suites and methodologies for measuring the interoperability degree achieved by a framework have been proposed in an attempt to evaluate and validate, not only their applicability, but also their overall performance. One of the most well-known and established methodologies for interoperability is the Smart Grid Architecture Model (SGAM) [7], which originated from the Reference Architecture working Group mandated by the EU's 490 mandate [8]. SGAM consists of 5 layers of interoperability, namely: i) component layer, for physical systems connection; ii) communication layer, for the communication technology and protocols for data transmission; iii) information layer, for common understanding of exchanged data; iv) functional layer, for functions and services specification and, v) business layer, for business models and market structures.

In this paper, an OpenADR-based semantic enrichment component is introduced to provide the necessary interoperability umbrella among currently available fragmented DR standards. The SGAM framework is employed to introduce how semantic interoperability can be evaluated and quantified in the context of DR schemes. To this end, a set of test cases are detailed by defining the steps they require and their expected outputs in order to evaluate the interoperability at the communication and the information layers of SGAM. These test cases are a result of the work developed in the on-going

research project DELTA H2020[1]. The test cases provide the environment for an in depth evaluation and quantification demonstrating the level of technical, syntactic and semantic interoperability achieved.

II. RELATED WORK

Throughout the years, several evaluation models and methodologies have been introduced, thus, presenting multiple layers for testing interoperability. Examples include NIST's Testing Environments [9], ETSI's Generic Approach to Interoperability Testing [10], the Smart Grid Architecture Model (SGAM) [7] and the VDE Test Suite 2.0 [11]. A more extensive literature review on such standards has been presented in the author's previous work in [12].

Out of all of the standards identified though, only a few (e.g., NIST, SGAM, VDE) account for syntactic and semantic interoperability. Semantic interoperability has been gaining a lot of attention since 2013 [13] due to emerging technologies, such as Internet of Things and Distributed Systems. An interesting gap in the review presented in [13] is the absence of a methodology analysis regarding the evaluation of semantic interoperability (Research Question 4). Nevertheless, there are interesting approaches for interoperability testing for IoT systems, such as the testing tool proposed by the F-INTEROP research project [14]. Yet again, a new testing methodology is proposed, without building upon a previously existing one.

Focusing on the energy domain, some standards already provide in their specification interoperability (IOP) testing procedures, even if they are incomplete, such as the IEC 61850 (Part 6 - Configuration Testing, part 10 - Conformity Testing of Servers, etc.). Bleiker et al. [15] have presented an extensive methodology for testing interoperability building upon these guidelines, while also providing additional measures for both IEC 61850 and IEC 61968/70 (CIM). Nevertheless, specifically for DR-related aspects, there are still limitations concerning end-to-end data exchange that have not been identified in any interoperability testing procedure, which is mainly attributed to the ongoing evolution of such schemes in the smart grid context. Even in cases where dedicated standards have been described, such as the OpenADR standard [5], while the respective compliance test tool has been implemented, it is still inaccessible either due to cost, or even obfuscation of the involved testing methodology. Finally, this is also highlighted by the ongoing current research endeavours that attempt to address semantic interoperability limitations through different approaches and frameworks [16], [17].

Contrary to all of the aforementioned findings, this work presents in detail test cases for evaluating syntactic and semantic interoperability in DR schemes. The presented approach is built on top of SGAM, a mature, EU standardized and open framework for testing interoperability in smart grids, building on top of OpenADR, which covers more and more ground in DR applications throughout the globe.

[1]https://www.delta-h2020.eu/

III. SEMANTIC INTEROPERABILITY

Semantic interoperability is a property that allows systems to exchange data and, more importantly, consume such data transparently [18]. This is essential for DR scenarios where important decisions, such as control actions on third-party systems/assets, depend on data exchanges among components that comply to different standards.

Semantic interoperability is built upon two other layers [19], i.e., technical and syntactic interoperability. Technical interoperability refers to heterogeneous protocols and mechanisms that can be used to exchange data. Syntactic interoperability refers to the heterogeneity of formats that data may adopt. Finally, semantic interoperability refers to how data is modelled and its incurred meaning.

Implementing a semantically interoperable architecture consists on homogenising the data that flows across different systems and providing common means of accessing, formatting and modeling them. There is a wide number of semantic interoperability approaches depending on how and when such homogenisation is performed [20]. One of the approaches relies on a centralised service to which queries can be issued. This service responds to queries by homogenising on the fly data originating from arbitrary sources, a process which is facilitated by appropriate metadata that are available to the service [21]. Other approaches require practitioners to adapt their systems by design [22], i.e., developing a system that already meets the established format, model and mechanisms to provide data. The most recent approach for implementing semantically interoperable systems relies on semantic web technologies [19], namely: RDF, SPARQL and, especially, standard ontologies.

A. Semantic interoperability for Demand Response in DELTA

Within the ongoing H2020 DELTA project, a semantically interoperable architecture has been delivered. The current approach is built upon two main pillars: an ontology and a software component, which is referred to as the DELTA Common Information Model (DCIM).

The employed approach consists of establishing a common data model, format and mechanism to exchange data, i.e., homogenising data in the three interoperability layers that comprise the semantic one. To achieve such goal, this approach relies on semantic web technologies. As a result, the syntactic layer is achieved by requiring systems to use any serialisation of RDF, e.g., Turtle, JSON-LD, or N3.

The semantic layer is achieved by establishing an ontology to be used by the involved systems, which must cover DR concepts. However, up to the authors knowledge, there is no ontology for DR. An ontology has been developed based on OpenADR to address this issue in DELTA, which provides a semantically enriched version of the standard [23]. The DELTA OpenADR ontology is publicly available at http://delta.iot.linkeddata.es/.

The OpenADR standard already establishes the mechanisms that can be employed to exchange data [24], e.g., REST APIs, which can be invoked by agents participating in a P2P network

with specific features. In order to meet these requirements the DCIM has been developed.
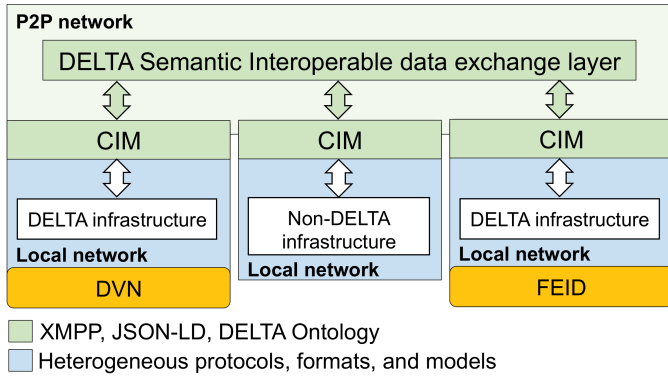

Fig. 1. DELTA semantic interoperability implementation.

The DCIM is the DELTA component that interconnects different systems of the DELTA platform and allows them to transparently exchange data, as depicted in Figure 1. In addition, the DCIM empowers systems that do not meet the interoperability requirements of DELTA, either in a technical, syntactic, or semantic context, a mechanism to be DELTA compliant. As a result, the DCIM can interconnect a DELTA system with a non-DELTA compliant system.

Figure 1 depicts how the DCIM is deployed as a sub-component of both the DELTA Virtual Node (DVN) and the Fog-Enabled Intelligent Device (FEID). These are two distinct systems of the DELTA architecture that employ the DCIM to communicate DR signals by employing the DELTA (OpenADR-compliant) ontology among the different system layers of DELTA (i.e., aggregator, DNVs, customers).

IV. THE SGAM FRAMEWORK

The SGAM framework aims at supporting the design of smart grid use cases with an architectural approach allowing for a representation of interoperability viewpoints in a technology neutral manner, both for current and future implementations. It is a three dimensional model that is merging the dimension of five interoperability layers (Business, Function, Information, Communication and Component) with the two dimensions of the Smart Grid Plane, i.e., zones, which represent the hierarchical levels of power system management: Process, Field, Station, Operation, Enterprise and Market, and domains, which cover the complete electrical energy conversion chain: Bulk Generation, Transmission, Distribution, DER and Customers Premises [7]. Fig. 2 provides a graphical representation of SGAM where the 5 layers of interoperability are illustrated, along with zones and domains.

SGAM serves as guidance for interoperability testing, indicating that such tests can take place in one of the 5 defined layers. It should be noted that the SGAM representation (domains, zones and layers) follows the CEN/CENELEC representation. The Joint Research Centre (JRC) of the European Commission has created a methodology for interoperability testing taking into account the specifications of SGAM's layers [25]. As has
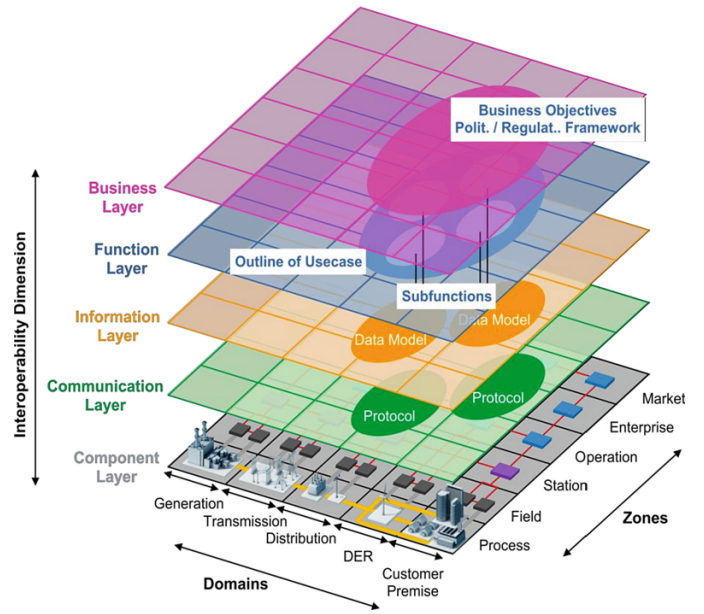

Fig. 2. Illustration of SGAM's interoperability layers and smart grid plane dimensions [7].

been recently shown [26], SGAM has been used extensively over the last couple years presenting promising evaluation use cases on multiple smart grid layers.

According to SGAM's methodology, the first step is to define the use case to be examined and map it on the SGAM layers. The testbed is defined along with the equipment under test. For each test case, only one equipment under test should be defined. Further on, the possible Basic Application Profiles (BAPs) are defined, meaning that for each link of interaction, the possible standards or options of standards are determined. One BAP should contain only one standard or one option of a standard for each link of interaction. As a next step, the Basic Application Interoperability Profiles (BAIOPs) are defined, meaning that for the links of interaction referring to the testbed, only one standard is set (one standard per link). Considering that the mode of operation of the testbed is fixed and known, whereas for the link of interaction referring to the equipment under test it is not, one standard or option of a standard is considered as the one to be tested referring to the link of interaction (one standard or option to be tested for each test case). Finally, it should be noted that the BAIOP contains the steps to be followed to conduct the tests.

In the use case described in this paper, it is presented how the DCIM can be tested in order to ensure interoperability between DELTA's FEID and DVN components. Building upon SGAM, to provide for technical, syntactic and semantic interoperability [27], the two specific layers that need to be considered are the communication and information layers. Regarding interoperability across these layers, the following holds: 1) communication interoperability is related with the correct transmission and receipt of data and, 2) information interoperability is related with the correct interpretation of

data, i.e., whether the receiver can "understand" the data. There are many standards that can be used for both of these layers and for each of the bilateral links under examination. In the methodology for interoperability testing developed by the Energy Security, Distribution and Markets Unit of JRC [25], it is highlighted that the testbed is fixed, as well as, the standards used for each link. The focus of the tests are on the equipment under test, along with its respective link.

V. EVALUATION & TESTING METHODOLOGY FOR DR

A. Use Case Description and Mapping on SGAM Layers

In this work, a first detailed use case is presented in order to test the interoperability of the DCIM architecture. The use case is analysed, mapped to the SGAM framework and the steps to be performed in terms of interoperability testing are described. Focus is given on the information layer, since semantic interoperability is of vital importance here.
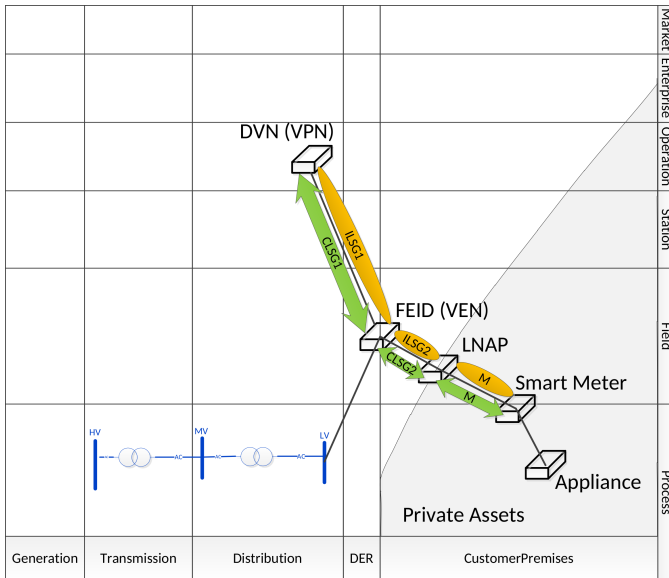

Fig. 3. Mapping of use case on SGAM; interactions with green and orange colors correspond to the communication and information layers, respectively.

The DELTA components, e.g., the Aggregator and the DELTA virtual node (DVN) and the DVN with the Fog Enabled Intelligent Device (FEID) are linked through the DCIM component, which is integrated as a sub-component within the Aggregator, the DVN and the FEID.

In the use case described in this paper, it is presented how interoperability can be tested and ensured between the FEID and the DVN components. The use case is mapped on the SGAM framework according to CEN/CENELEC guidelines (Fig. 3). In the two ends (FEID – DVN), different specifications are used in order to achieve communication. The Local Network Access Point (LNAP) is usually integrated within the smart meter and is an interface that enables communication with the smart meter. It should be also noted here that the FEID can be both at customer premises and at the DER level, i.e., a photovoltaic panel. All components lie at the distribution level.

In [25], it is indicated that the Basic Application Profiles (BAPs) and the Basic Application Interoperability Profiles (BAIOPs) need to be specified for the test cases to be defined. Each BAP contains only one standard or an option of a standard. The BAIOP(s) contain the steps of the test case related to the combination of one BAP that corresponds to each of the available equipment links connecting the equipment under test. There are several standards that can be used for each link of interaction. To provide for a more comprehensive presentation, in Fig. 3, the links corresponding to the "Information Layer Standards Group" (ILSG) and the "Communication Layer Standards Group" (CLSG) are enumerated, respectively. In Fig. 3, the straight lines illustrate the representation on the component layer; the green arrows show the representation on the communication layer; and the orange ellipses show the representation on the information layer. For more information on the representation of the interoperability layers, the reader is directed to [12]. Table I provides a comprehensive list of standards that can be used for each link depicted in Fig. 3.

TABLE I
LIST OF STANDARDS FOR EACH LINK OF INTERACTION.

ILSG1	ILSG2	M
DELTA Ontology, OpenADR, USEF, EMIX, EFI	Modbus, KNX, BACnet, TCP/IP	Standards for M interface
CLSG1	**CLSG2**	**M**
XMPP, HTTP, HTTPS, MQTT	XMPP, HTTP, HTTPS, MQTT	Standards for M interface

For the ILSG5 and CLSG5 standard groups, the rules for the link between the smart meter and the LNAP are applied. The standards applied are the ones referring to interface M, as this is defined in [28]. A summary of the standards used for this link can also be found in [12].

B. Definition of the Testbed, EUT and Standards Selected

This work aims at testing the interoperability of the system giving focus on semantic interoperability. According to the methodology for testing procedures, only one equipment under test (EUT) and only one link can be considered each time for defining the test cases. For this reason, the DVN is considered to be the equipment under test and the link to be tested is the one between the FEID and the DVN. Table II enlists the instruments that compose the testbed and the equipment under test. Table III details the links related to the instruments of the testbed plus the equipment under test and the standards used.

TABLE II
INSTRUMENTS COMPOSING THE TESTBED AND THE EQUIPMENT UNDER TEST.

	Testing Scenario
Testbed	DVN LNAP Smart meter Appliances
Equipment Under Test	DVN
Link Under Test	DVN - FEID

For the creation of the BAIOP(s) and the equivalent test cases no other BAPs will be analysed, apart from the ones corresponding to the standards/options defined in Table III. For the link under test, one option/standard is considered, which is the basis to form the BAIOP(s) and the test case description. Overall, the interaction and the interoperability between the FEID and DVN is shown. The interoperability methodology for testing is followed and each interoperability layer is described with focus on the information layer.

TABLE III
LINKS AND STANDARDS USED RELATED TO THE INSTRUMENTS
COMPOSING THE TESTBED AND EQUIPMENT UNDER TEST.

Link	CL-Standard	IL-Standard
LNAP – Smart Meter	ITU-T G. 9904 (PRIME protocol)	EN 62056
LNAP – FEID	RS-232 or RS-485	Modbus RTU
FEID - DVN	TCP/IP (HTTP - XMPP - HTTP)	DELTA Ontology (JSON-LD - XML - JSON-LD)

C. BAIOP Description and Results

Two test cases are described step by step, one for the communication layer (Table IV) and one for the information layer (Table V), respectively, following the SGAM templates. For the first layer, a very basic communication testing procedure is presented to ensure both connectivity and reliability regarding data flow. A total amount of 100 messages is considered as a good starting point for evaluating such attributes. Nevertheless, more experiments are required towards establishing the silver lining of testing. Accordingly, for the second layer and for every message that has passed the communication test, the payloads are evaluated in terms of syntactic and semantic interoperability. Since the test case described is based on the DELTA ontology, the test includes a step that validates the JSON-LD format that is used for the payload structure. The next step validates the data model used by means of the DELTA SHACL shapes [29]. As a final verdict, regarding semantic interoperability, all of these steps are needed to succeed in order for the test case to conclude with a PASS.

TABLE IV
BAIOPs FOR THE COMMUNICATION LAYER.

Test Case ID	ComTest
BAIOP ID/UC ID	CU/FDC
Interoperability Layer	Communication
Test Case Summary	Test network connectivity and message exchange
Test Purpose	Test the correct interaction between the FEID and the DVN.
Test Description - Steps	Step 1: All other links are considered fully operational. Step 2: Send 100 messages. Step 3: Evaluate receipt of 100 messages. Step 4: Validate integrity of received messages. Step 5: Output test verdict. PASS: Communication was established and 100% of the messages were successfully transmitted and reliably received. FAIL: Communication was not established, or less than 100% of the messages were successfully transmitted, or received messages were corrupt.

Table VI presents the results related to the test cases that were presented in Tables IV and V, which explore different

TABLE V
BAIOPs FOR THE INFORMATION LAYER

Test Case ID	InfoTest
BAIOP ID/UC ID	IU/FDI
Interoperability Layer	Information
Test Case Summary	Test that the messages transmitted have the proper format (JSON-LD) and comply to the DELTA Ontology.
Test Purpose	Test the correct information exchange between the FEID and the DVN.
Test Description - Steps	Step 1: A PASS in the communication layer is verified. Step 2: Validate that the data received have the proper format (Syntactic Interoperability). Step 3: Validate that the data received have the proper model by means of the DELTA SHACL Shapes (Semantic Interoperability). Step 4: Output test verdict. PASS: Data received have the proper format and follow the proper data model. FAIL: Data received do not have the proper format, or do not follow the proper data model.

scenarios related to the information layer. Three different formats, JSON-LD, XML and Turtle were tested using five different data models, namely SAREF, SAREF4ENER, OpenADR standard, OpenADR ontology and DELTA Ontology. For each one of these options of data models, the BAIOP test steps are performed, as these are described above. The final result of the BAIOP test, either in the communication or the information layer is shown in the following table. As anticipated, any data model (e.g., SAREF and OpenADR) that is part of the DELTA ontology is a PASS in these tests, while others that are not included in DELTA ontology FAIL. For instance, SAREF4ENER fails due to data model misalignment (although format is the same, i.e., RDF), while the OpenADR standard fails due to data format misalignment.

Generally, systems based on standards that rely on different formats can be semantically interoperable by using RDF translation techniques [21]. These consists of translating data, expressed in heterogeneous formats (CSV, JSON, XML, ...) and models, into RDF data modelled with a specific ontology. Systems that rely on RDF data, which nevertheless use different ontologies, can be semantically interoperable by using OWL properties identifying relations between classes. This latter approach is the one followed in DELTA in order to be semantic interoperable with SAREF and OpenADR ontology.

TABLE VI
COMMUNICATION AND INFORMATION TEST CASES RESULTS.

Test #	Test Case ID	Test Case Description	Test Case Verdict
1	ComTest	SAREF (JSON-LD)	PASS
2	InfoTest	SAREF (JSON-LD)	PASS
3	ComTest	SAREF4ENER (JSOND-LD)	PASS
4	InfoTest	SAREF4ENER (JSOND-LD)	FAIL
5	ComTest	OpenADR Standard (XML)	PASS
6	InfoTest	OpenADR Standard (XML)	FAIL
7	ComTest	OpenADR Ontology (JSON-LD)	PASS
8	InfoTest	OpenADR Ontology (JSON-LD)	PASS
9	ComTest	DELTA Ontology (JSOND-LD)	PASS
10	InfoTest	DELTA Ontology (JSOND-LD)	PASS
11	ComTest	DELTA Ontology (Turtle)	PASS
12	InfoTest	DELTA Ontology (Turtle)	PASS

VI. CONCLUSION & FUTURE WORK

To conclude, this manuscript leverages the SGAM framework to present a clear methodology for testing semantic interoperability for DR-related systems. By deploying a dedicated software component that enables semantic interoperability within two different technical components of a DR-oriented architecture, the necessary testbed was created to evaluate the presented framework. Both the information and communication layers of the SGAM framework were tested, evaluating in depth the technical, syntactic and semantic interoperability between the DVN and FEID components. Various tests using different formats and data models verified the methodology presented. Future work includes the integration of other formats and data models, such as the OpenADR standard and SAREF4ENER, so as to expand the versatility of the DCIM component, not only in terms of data models (i.e., ontologies and standards) but also in terms of data formats (JSON, XML, etc.). In parallel, building upon SGAM, a more thorough testing methodology with more cases will be elaborated.

VII. ACKNOWLEDGEMENT

VIII. NOMENCLATURE

DR Demand Response
SGAM Smart Grid Architecture Model
RDF Resource Description Framework
W3C World Wide Web Consortium
RES Renewable Energy Sources
IoT Internet of Things
DCIM DELTA Common Infomation Model
FEID Fog-Enabled Intelligent Device
DVN DELTA Virtual Node

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