SAREF-Compliant Knowledge Discovery for Semantic Energy and Grid Interoperability

Amelie Gyrard, Antonio Kung, Olivier Genest, Alain Moreau

SAREF-Compliant Knowledge Discovery for Semantic Energy and Grid Interoperability

Amelie Gyrard*, Antonio Kung*, Olivier Genest*, Alain Moreau*
* Trialog, Paris, France {amelie.gyrard, antonio.kung, olivier.genest, alain.moreau}@trialog.com

***Abstract*—Modern cities are becoming "green and sustainable" once effective and optimized energy management of resources, gathering, and integration of data from smart energy and building are executed. The integration of heterogeneous technologies, and devices, require an interoperable solution to describe devices and data exchanged.**

SAREF is an ontology supported by the ETSI SmartM2M standard to achieve interoperability among IoT projects, architectures, etc. that can be extended to any IoT vertical domains such as smart buildings or energy. SAREF can be used to describe data sent through communication protocols or once that data must be processed (e.g., on the cloud, gateways, devices). ETSI does not provide tools yet that support the SAREF ontology to avoid engineers from developing from scratch. We design a SAREF-compliant sensor dictionary which also overcomes SAREF limitations. The sensor dictionary, applied to energy scenarios, is employed by a reasoner to infer meaningful knowledge from sensor data. Online demonstrators are available. The scenarios are also relevant for the Interconnect European-funded project that comprises 50 partners to design interoperable smart buildings and grids.

Keywords*—Internet of Things, Artificial Intelligence, Ontology, Semantic Reasoning, Semantic Web Technologies, Reusable Knowledge Engineering, Semantic Web of Things (SWoT), Knowledge Directory Service, Body of Knowledge, Smart Home, Building, Energy, Grid.

I. Introduction

Modern cities are becoming "green and sustainable" once effective and optimized energy management of resources, gathering, and integration of data from smart building, and energy are executed. The integration of heterogeneous technologies, and devices, require an interoperable solution to describe devices and data exchanged.

Several devices are designed to monitor energy consumption: the Linky meter is deployed in more than 30M French houses and building, and there are other solutions such as Hager, Schneider Electric, Legrand, Google PowerMeter, and Apple Reveals Smart-Home Energy Management. PowerMeter[1] was designed in 2009 to record the user's electricity usage in near real-time but abandoned two years later. Apple Reveals Smart-Home Energy Management Dashboard System[2] in 2010. If the companies do not develop the full-stack compatible with 1) sensors, 2) the final application for consumers, 3) and other products; the designed product can fail to succeed. It illustrates the need for interoperability between devices, applications, and sensor data. In this paper, **we focused on semantic interoperability on data to infer meaningful information.**

SAREF is an ontology supported by the ETSI SmartM2M standard (M2M stands for Machine-to-Machine) to achieve interoperability among IoT projects, architectures, etc. that can be extended to any IoT vertical domains such as smart building, and energy [1]. SAREF can be used to describe data sent through communication protocols or once that data must be processed (e.g., on the cloud, gateways, devices). ETSI does not provide tools yet that support the SAREF ontology to avoid engineers to develop from scratch. **There is a need to design a SAREF-compliant sensor dictionary applied to energy scenarios. The dictionary is employed with a reasoner, to infer meaningful knowledge from sensor energy data**. The scenarios, accessible via online demonstrators (see Table II), are also designed for the Interconnect European-funded project[3].

We address the following **research questions (RQ)**:

- RQ1: What are the sensors relevant to the energy domains? Are there standardized sensor dictionaries for the energy domain? Are there ontology standards for the energy domain?
- RQ2: What are the limitations of the existing ontology-based energy projects? Can we reuse the domain expertise designed in past projects?
- RQ3: What are the rules and reasoning mechanisms to interpret energy sensor data to help developers design faster their IoT energy applications?

The main **contributions** of this paper are:

- C1: Alignment of the sensor dictionary with the SAREF ontology and its extensions (SAREF4ENER, SAREF4BLDG) and the IEC 61360 - Common Data Dictionary standard[4]; it addresses RQ1 in Section II.
- C2: A deep investigation of the ontology-based energy projects shared though the LOV4IoT-Energy ontology catalog; it addresses RQ2 in Section III.
- C3: The reasoner retrieves knowledge to design energy use cases; it addresses RQ4 in Section III.
- C4: Results promoted within the ISO/IEC 21823-3 IoT semantic interoperability [2], and the AIOTI WG03 Standardisation[5] Semantic Interoperability Expert Group [3] [4] where the reasoner is taken as a baseline [5]. SAREF designers are also involved within AIOTI WG03.

[1]https://en.wikipedia.org/wiki/Google_PowerMeter
[2]https://www.patentlyapple.com/patently-apple/2010/01/apple-reveals-smart-home-energy-management-dashboard-system-1.html
[3]https://interconnectproject.eu/
[4]https://cdd.iec.ch/cdd/iec61360/iec61360.nsf/TreeFrameset?OpenFrameSet
[5]https://aioti.eu/aioti-wg03-reports-on-iot-standards/

978-1-4673-9944-9/18/$31.00

Structure of the paper: The sensor dictionary for energy is described in Section II. SAREF-compliant energy scenarios are introduced in Section III; the classification of the source of the knowledge to prove the veracity of our scenarios is included. The SAREF limitations are summarized in Section IV. The paper concludes and envisions future work in Section V.

II. SAREF-Compliant Semantic Sensor Energy Dictionary

We built a sensor dictionary for energy compliant with standards such as ETSI SAREF and IEC 61360 Common data Dictionary.

Sensor Dictionary for Energy: We designed a pattern to classify sensors for the energy domain: for each sensor, we provide the produced measurements and the associated unit; we also deal with synonyms. Furthermore, we referenced for each sensor the source of knowledge using it (e.g., past projects referenced within the ontology-based IoT project catalog (see Section III), and reasoning mechanisms to interpret energy sensor data (see the rule discovery project in Section III).

Sensor Dictionary Compliant with IEC 61360 - Common Data Dictionary: The sensor dictionary is extended to be compliant with the IEC 61360 - Common Data Dictionary standard[6] (see Table I, the last column). The sensor dictionary highlights the limitations of the IEC 61360 standard which references less than ten types of sensors.

SAREF-Compliant Semantic Annotation: The sensor dictionary is compliant with the terms employed by SAREF when possible, as illustrated in Table I. The limitations of SAREF are summarized in Section IV. Sensor energy datasets (e.g., JSON, XML) follow the SenML format[7] to represent sensor measurement, its value, its unit, and its timestamp. Available demonstrators are providing code examples (see Section III). A simple rule repository for the semantic annotation is already available such as if "t" or "temp" or "temperature" and located in the room probably it is a room temperature and will be annotated following the dictionary mentioned above which is implemented as an ontology.

III. SAREF-Compliant Energy Scenarios

We designed scenario demonstrators (collected in Table II) to answer the following competency questions by executing the reasoning and query engines:

- Retrieving the sensors relevant for the energy domain.
- Discovering knowledge (e.g., rules) for each sensor (e.g., power meter sensor).
- Executing the reasoning engine to perform the full scenario (e.g., interpreting power meter data).
- The dataset must be compliant with at least one of those ontologies (e.g., SAREF and its extensions, M3[8], W3C SSN/SOSA[9], iot.schema.org[10], etc.).

[6]https://cdd.iec.ch/cdd/iec61360/iec61360.nsf/TreeFrameset?OpenFrameSet
[7]https://tools.ietf.org/html/rfc8428
[8]http://sensormeasurement.appspot.com/?p=m3
[9]https://www.w3.org/TR/vocab-ssn/
[10]https://iot.schema.org/

The sequence diagram (illustrated in Figure 1) explains the interactions of the sensor dataset and its annotation, storage and execution of reasoning and query engines: 1) Semantically annotating the energy dataset to be compliant with ontologies, 2) Storing triples (semantic sensor data) to the triplestore, 3) Loading semantic datasets, 4) Loading ontologies, 5) Loading rules, 6) Executing the reasoning engine with the set of rules compliant with the ontologies which will update the triplestore, and 7) Loading and executing the SPARQL query to retrieve the semantic datasets and ontologies by selecting a subset of the triplestore content.

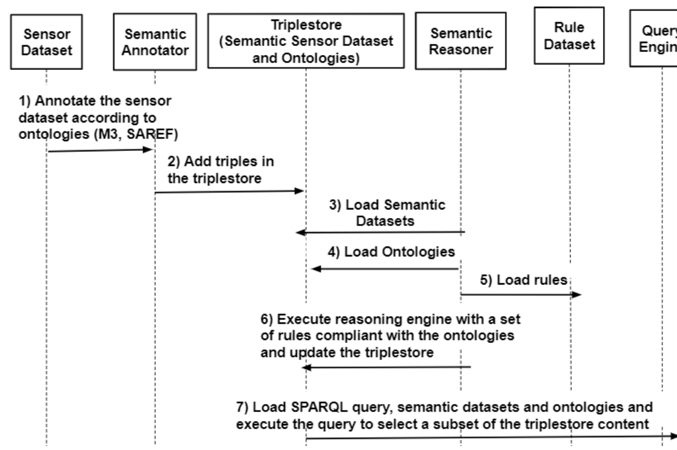

Fig. 1: Semantic annotation, reasoning and query sequence diagram

Ontology-Based IoT Project Catalog For Energy Management (LOV4IoT-Energy): We collected and analysed the state of the art to enrich our ontology-based IoT energy project knowledge base (LOV4IoT-Energy is summarized in Table III). Our survey is the result of a continuous enrichment of the LOV4IoT ontology catalog [6] since 2012 dealing with more and more expertise and synonyms (e.g., smart grid, renewable energy, power plant, micro-grid, etc.). We provide tools to support the reuse of the survey outcome (e.g., dump of ontology code, web services, and web-based ontology catalog) and release them for the AI4EU Knowledge Extraction for the Web of Things Challenge[11]. Meanwhile, we are aware of Systematic Literature Review (SLR) guidelines such as [7]. The survey on energy ontologies is also reused within the reasoning discovery explained hereafter; both are frequently updated (see Table II for URLs). Manual extraction and semi-automatic analysis [8] [9] have been done to extract knowledge.

Knowledge Discovery and Reasoning for Energy (S-LOR Energy): The sensor energy dictionary depicted in Table I described in Section II is employed within the energy rule discovery [34] (see Table II for URL). Each sensor for the energy domain can be automatically retrieved using SPARQL queries; the sensor dictionary is displayed in Figure 2, the content shown on the GUI is from Table I and Table III.

End-to-End Energy Scenarios: The knowledge acquired to infer meaningful information is implemented as rules. We simulated sensor data (e.g., power consumption data using the SenML format). We annotated the data to be compliant

[11]https://www.ai4eu.eu/ke4wot

Sensor, Measurement Name and Unit	M3 Scenarios	SAREF-Core, SAREF4ENER, SAREF4BLDG	Other Names and Standards E.g., IEC 61360 Common Data Dictionary
m3:Sensor	✓M3-Generic	✓saref-core:Sensor	Device? IEC 61360 AAA103 - sensor
m3:LightSensor (Sensor) m3:Illuminance m3:Lux	✓M3-Home	✓saref-core:LightSwitch saref-core:illuminanceunit	IEC 61360 AAA105 - light sensor Light switch, Luminosity Sensor, Lamp Illuminance Sensor, Lighting
m3:Lamp (Actuator)	✓M3-Home	✓saref4bldg:Lamp	IEC 61360 AAA075 - lamp
m3:OccupancyDetector m3:Presence xsd:boolean	✓M3-Home	✓saref-core:Motion, saref-core:Occupancy,	IEC 61360 AAA109 - proximity sensor Pyroelectric IR (PIR) Occupancy Detector, Intrusion Detector, Trespassing, presence detector, motion sensor
m3:SoundSensor m3:Sound, m3:Decibel	✓M3-Home	✓saref4bldg:audiovolume	IEC 61360 AAA159 - microphone Microphone, Noise level, Volume
m3:HumiditySensor m3:Humidity m3:Percent	✓M3-Weather	✓saref-core Humidity (property) no HumiditySensor, no HumidityUnit no percent	IEC 61360 AAA104 - humidity sensor Hygrometer, Humidifier
m3:Thermometer m3:Temperature m3:DegreeCelsius	✓M3-Energy	✓saref-core:TemperatureSensor saref-core:Temperature saref-core:TemperatureUnit	IEC 61360 AAA110 - temperature sensor Thermostat
m3:LuminousEfficacySensor m3:LuminousEfficacy m3:LumenPerWatt	✓M3-Energy	Not found	- - -
m3:Ventilation (Actuator)	✓M3-Energy	✓saref-core:HVAC	HVAC, Fan -
m3:Heating (Actuator)	✓M3-Energy	✓saref-core:HVAC	HVAC
m3:AirConditioner (Actuator)	✓M3-Energy	✓saref-core:HVAC	HVAC, Cooling, AC
m3:ElectricalCurrentSensor m3:ElectricCurrent m3:Ampere	✓M3-Energy	Not found saref4bldg:primaryCurrent (owl:objectProperty) CurrentUnit not found, Ampere not found	Intensity
m3:ElectricalPotentialSensor m3:ElectricalPotential, m3:Volt	✓M3-Energy	Not found saref4bldg:primaryVoltage (owl:ObjectProperty)	Electric potential difference (Voltage)
m3:ElectricalResistanceSensor m3:ElectricalResistance, m3:Ohm	✓M3-Energy	Not found saref4bldg:initialResistance (owl:ObjectProperty)	-
m3:FrequencySensor m3:Frequency m3:Hertz	✓M3-Energy	Not found saref4bldg:nominalFrequency (owl:ObjectProperty) saref4bldg:primaryFrequency (owl:ObjectProperty)	-
m3:ThermalConductivitySensor m3:ThermalConductivity m3:WattPerMeterKelvin	✓M3-Energy	Not found saref4bldg;thermalConductivity (owl:ObjectProperty)	-
m3:PowerMeter m3:Power, m3:Watt	✓M3-Energy	✓saref-core:Power, saref-core:PowerUnit but no PowerMeter	-

TABLE I: Subset of the SAREF-compliant sensor dictionary, applied to energy (similar sensor tables for building, weather, and air quality can be provided). We focused on sensors employed within the Interconnect project.

Tool Name	Tool URL
LOV4IoT-Energy Ontology -based IoT Project Catalog	http://lov4iot.appspot.com/?p=lov4iot-energy
LOV4IoT-Weather Ontology -based IoT Project Catalog	http://lov4iot.appspot.com/?p=lov4iot-weather
LOV4IoT-Home Ontology -based IoT Project Catalog	http://lov4iot.appspot.com/?p=lov4iot-home
S-LOR Energy Rule Discovery	http://linkedopenreasoning.appspot.com/?p=slor-energy
S-LOR Weather Rule Discovery	http://linkedopenreasoning.appspot.com/?p=slor-weather
S-LOR Home Rule Discovery	http://linkedopenreasoning.appspot.com/?p=slor-home
M3-Energy Full Scenarios	http://sensormeasurement.appspot.com/?p=energy
M3-Weather Full Scenarios	http://sensormeasurement.appspot.com/?p=weather
M3-Home Full Scenarios	http://sensormeasurement.appspot.com/?p=home

TABLE II: Available demonstrators: ontology catalog, rule discovery, and full scenarios for energy, building, and weather

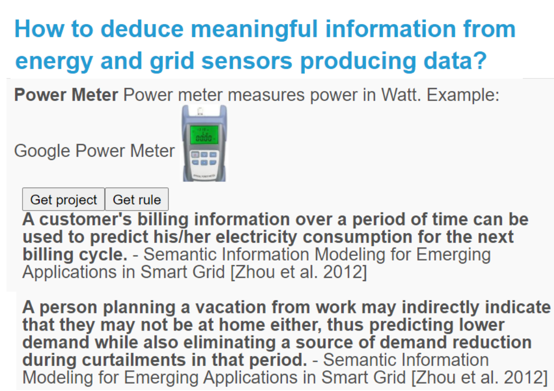

Fig. 2: Demonstrator: the sensor dictionary queried and used via web services and displayed on the GUI

with ontologies (the file can be access though the demos referenced in Table II). The semantic reasoner (e.g., Jena inference engine) is executed on the semantic sensor dataset and the set of rules all compliant with each other. For instance, after executing the reasoning engine, a rule has been executed that deduces that a mobile phone uses 5 Watt, as illustrated in Figure 3. We have more and more scenarios (Table II) including various sensors (introduced in Table I), as an example:

- *Energy Data*: power, frequency, luminous efficiency, electric current, electrical potential, resistance, thermal conductivity, etc.
- *Weather Data*: solar radiation data with 5 rules for various thresholds (see Table IV or the S-LOR Energy online demo for a more exhaustive sensor dictionary (URL in Table II).
- *Home Data*: thermometer, light sensor, occupancy detector, etc. are used in a cross-domain home scenario.
- *Air Quality Data*: NO2, PM10, O3, PM2.5, SO2, CO.
- More and more scenarios are being added within the same

Authors	Year	Project	OA	Reasoning	Sensors
Esnaola-Gonzalez et al. [10] Tekniker/Spain	2020 2018	Energy Efficiency Prediction Semantic Assistant Cross-domain: Energy and Building	✓	✓HermiT	Use sensors from M3
SAREF4ENER [1] ETSI EU Standard	2017	SAREF4ENER supported by the ETSI standard	✓	Not found	Numerous sensors
Bonino, Brizzi et al. [11] Italy/Germany/Sweden	2016 2008	DogOnt - Cross-domain: Energy and Home	✓	✓[12]	Numerous sensors
Lefrancois et al. [13] EMSE/France, ITEA3	2017 2016	Smart Energy Aware System (SEAS) ontologies	✓	Not found	Numerous sensors
Burel et al. [14] KMi/UK	2016	EnergyUse ontology, extracting knowledge from post	✓	Not found	Smart plug, energy
Kofler, Reinish et al. [15] Vienna/Austria	2012 2008	ThinkHome ontology (based on DogOnt) and Energy	✓	✓DL reasoner	Numerous sensors
Poveda Villalon et al. [16] UPM/Spain	2015	Linked data for building energy consumption	✓	✓Pellet	Energy consumption
Kolchin et al. [17] Saint-Petersburg, Russia	2014	Monitoring of Smart Meters using CQELS	✓	✓CONSTRUCT SPARQL queries	EnergyMeter, ElectricityMeter ElectricalPotentialSensor,
Dey, Dasgupta et al. [18] Kolkata/India	2015 2013	EnergyMeter ontology based on SSN and other ontologies	✓*	✓[19] Fact++, Hermit	Electric current, Power, Voltage EnergyMeter, Electromagnetic
Nguyen, Raspitzu et al. [20] The Netherlands	2014 2012	Activity Recognition, Energy Savings	✓*	✓OWL DL, Hermit	Sound Sensor(Acoustic), PIR (Passive Infrared), Pressure
Groza et al. [21] Romania	2015	Wind energy Semi-Automatic Construction from Wikipedia	✓	✓DL, Racer (code ✓)	wind location, wind turbine
Kott et al. [22] Wroclaw/Poland	2019	Energy Consumption Households	Not found	Not found	electricity Consumption, CO2
Lork et al. [23] Singapore	2019	Building Energy Management System (BEMS)	Not found	✓SWRL inference rules	Numerous sensors
Kucuk et al. [24]	2018- 2010	Electrical Power Quality Ontology (PQONT) Turkish Electricity Transmission Company	Not found	✓Pellet for consistency	power, frequency, voltage
Santodomingo et al. [25] Germany	2015 2011	Rule converter SWRL and Jena Rules between 2 IEC standards (**CIM** and SCL)	Not found	✓Rule-based (SWRL, Jena Rule Language)	EnergyMeter, PowerMeter, ElectricityMeter
Wicaksono et al. [26] Karlsruhe/Germany	2013 2012	Energy Management System in Building	Not found	✓SWRL, SWRLJessBridge, classification rule, Naive Bayes	-
Zhou et al. [27] USA	2012	Semantic Smart Grid Information Model Demand-Response (DR)	Not found	✓Semantic Complex Event Processing (SCEP) engine	Thermometer, CarbonDioxideSensor OccupancyDetector
Tomic, Fensel et al. [28] FTW/Vienna/Austria	2013 2010	SESAME-S project (SEmantic SmArt Metering - Services for Energy Efficient Houses), reduce energy bill	Not found	✓SQWRL, SWRL, JESS	smart meter, washing machine weather data etc.
Linnenberg et al. [29] Germany	2013	Energy-Efficiency	Not found	✓Ontobroker inference engine	Energy meter
Han, Jeong, Lee et al. [30] Daejeon/Korea	2011	Efficient Building Energy Management System	Not found	✓inference rules	temperature, humidifer, light, air quality, occupancy, illuminance boiler, ventilation, HVAC, chiller
Cheong et al. [31] South Korea	2011	Energy-Aware Smart Homes	Not found	✓11 SWRL rules Pellet with Jena	humidity, solar radiation, CO2, Thermometer, Accelerometer, occupancy, light, power
Crapo et al. [32] [33] USA	2010 2009	Semantic Information Model for Smart Grid - **CIM**	Not found	✓Jena Rules	Meter

TABLE III: **Ontology-based energy and grid projects (total=22)**, more are referenced by the LOV4IoT-energy ontology catalog, including reasoning mechanisms and sensors employed. Some works are not referenced here due to space issues.
Legend: Ontology Availability (OA), when the code is available, the ontologies are classified on the top. Then, the ontology-based projects are classified by year of publications.
* means that the ontology has been sent to us but it is not publicly accessible online. Even if the ontology is not accessible, we are referencing the projects since reasoning mechanisms and sensors relevant to the energy domain are mentioned.

demos with different kind of sensor data (as referenced within Table I) and more and more rules to deduce high level information.

Technologies employed in the implementation: Our demonstrators (Table II) are implemented with the Jena Semantic Web framework that can deal with RDF, RDFS, OWL languages to implement the sensor dictionary. This dictionary is implemented within the M3 ontology which is refined for the energy domain; Java to develop REST web services with the JAX-RS library to hide the complexity of using semantic web technologies, and the Graphical User Interface with Ajax, JQuery, JavaScript, HTML, and CSS.

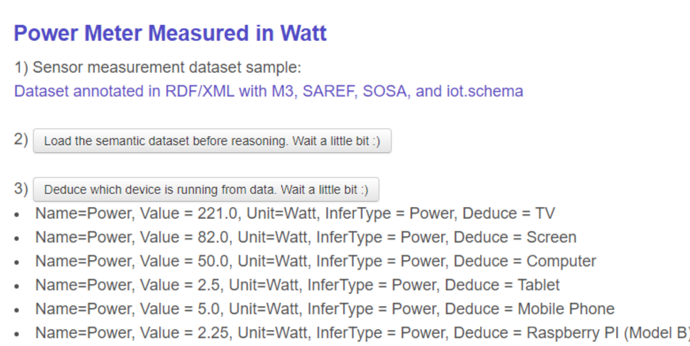

Fig. 3: Power meter scenario: a mobile phone uses 5 watts

Sensor, Measurement Name and Unit	M3 Scenarios	SAREF-Core, SAREF4ENER, SAREF4BLDG	Other Names and Standards E.g., IEC 61360 Common Data Dictionary
m3:Thermometer m3:Temperature m3:DegreeCelsius	✓M3-Energy	✓saref-core:TemperatureSensor saref-core:Temperature, saref-core:TemperatureUnit	IEC 61360 AAA110 - temperature sensor Thermostat saref4watr:ExternalTemperature (owl:NamedIndividual)
m3:LightSensor (Sensor) m3:Illuminance m3:Lux	✓M3-Weather	✓saref-core:LightSwitch	IEC 61360 AAA105 - light sensor Light switch, Luminosity Sensor, Lamp Illuminance Sensor, Lighting
m3:HumiditySensor m3:Humidity m3:Percent	✓M3-Weather	✓saref-core:Humidity (property) no HumiditySensor, no HumidityUnit no percent	IEC 61360 AAA104 - humidity sensor Hygrometer, Humidifier saref4watr:Humidity (owl:NamedIndividual)
m3:PrecipitationSensor, m3:Precipitation m3:Meter, m3:Inch, m3:MilimeterPerHour	✓M3-Weather	Not found	Rain, Pluviometer saref4watr:Precipitation (owl:NamedIndividual)
m3:AtmosphericPressureSensor m3:AtmosphericPressure m3:Pascal	✓M3-Weather	✓saref-core:Pressure (property) saref4watr:AtmosphericPressure (owl:NamedIndividual) saref4bldg:workingPressure?,)	IEC 61360 AAA108 - pressure sensor Atmospheric Pressure Sensor, Barometer, Barometric Pressure Sensor
m3:SolarRadiationSensor m3:SolarRadiation m3:WattPerMeterSquare	✓M3-Weather	✓saref4bldg:SolarDevice, saref4bldg:solarReflectance, saref4bldg:solarTransmittance	- PAR (Photosynthetically Active Radiation) Sun Light, Solar Panel, Photovoltaic, solar irradiance
m3:WindSpeedSensor m3:WindSpeed, m3:KiloMeterPerHour	✓M3-Weather	Not found	-
m3:WindDirectionSensor m3:WindDirection, m3:DegreeAngle	✓M3-Weather	Not found	-
m3:CloudCoverSensor, m3:CloudCover, m3:Okta	✓M3-Weather	Not found	-
m3:SunPositionElevationSensor m3:SunPosition, m3:DegreeAngle	✓M3-Weather	Not found	-
m3:SunPositionDirectionSensor m3:SunPositionDirection, m3:DegreeAngle	✓M3-Weather	Not found	-

TABLE IV: Subset of the SAREF-compliant sensor dictionary applied to the weather domain.

IV. Key Contributions and Lessons Learnt

We designed a sensor dictionary and reasoner compliant with those standards: SAREF (SAREF-Core, SAREF4ENER, and SAREF4BLDG), IEC 61360 Common Data Dictionary, and W3C SOSA/SSN, employed within our semantic datasets, SPARQL queries, and rules. We have analyzed the following limitations of SAREF specifications which highlights the need of our unified dictionary explained in Section II.

- **Measurement types**: `saref:Property`, `m3:MeasurementType` and `sosa:ObservableProperty` are similarly designed.
- **Inconsistency, lack of unification, or duplication** are found for naming such as `saref-core:TemperatureSensor` and `saref4agri:Thermometer`, it demonstrates the complexity to search for the right terms and handle synonyms. We also have to deal with missing concepts and handle cross-domains (e.g., weather forecasting is dependent to energy; there is no SAREF for weather forecasting).
- **Sensor data values**: `saref:hasValue`, `m3:hasValue`, and `sosa:hasSimpleResult` are similarly designed; all can be used within our semantic datasets, SPARQL queries, and rules.
- **Units**: `saref:isMeasuredIn` and `m3:hasUnit` are similarly designed; all can be used within our semantic datasets, SPARQL queries, and rules. Ontologies' main goal is to explicitly describe the data, descriptions such as `saref:TemperatureUnit` does not exactly remove ambiguities regarding the unit used such as Celsius or Fahrenheit which might lead to mistakes with automatic reasoning.
- **Unifying sensor metadata**: We structure sensor data in Table I and Table IV: 1) sensor name, 2) the produced measurement, 3) the associated unit (e.g., `Watt` to be more explicit than `saref-core:PowerUnit`). There is a need of domain experts to verify synonyms (e.g., solar radiation UV, Solar Panel, Photovoltaic). Each row of the Table (sensor, measurement, unit), is implemented within the M3 ontology designed and maintained since 2012, (see also the M3-lite[12] refined for the FIESTA-IoT H2020 European-funded project running from 2015 to 2018) [35]. SAREF is supported by ETSI M2M since 2015.
- **Provenance metadata**: SAREF does not keep track the provenance of the information. For each sensor, we reference sources such as scientific publications or project deliverables referenced on the LOV4IoT ontology catalog project (Section III and Table III)). Similarly, the S-LOR project (see Section III) suggests reasoning mechanisms (e.g., rules) for specific sensor type. It is not provided by SAREF.
- **Interlinking ontologies**: our proposed solution, compared to SAREF, is to link and unify existing ontologies to achieve semantic interoperability. We added links such as `rdfs:subclassOf`, `owl:equivalentClass`, and `rdfs:seeAlso`. SAREF or W3C SOSA do not consider the IEC 61360 - Common Data Dictionary standard[13] that we address in Table I and Table IV.
- **IoT Alliance**: Our work is taken as a baseline in AIOTI[14] (Alliance for the Internet of Things Innovation) WG03 Standardization Semantic Interoperability white papers [3] [5].

V. Conclusion and Future Work

Designing energy efficiency applications requires cross-domain knowledge acquired from heterogeneous communities

[12] https://github.com/fiesta-iot/ontology/blob/master/m3-lite.owl

[13] https://cdd.iec.ch/cdd/iec61360/iec61360.nsf/TreeFrameset?OpenFrameSet

[14] https://aioti.eu/

(e.g., home/building, weather, air quality). Integrated machine interpretable knowledge implemented within ontologies help when domain experts are not available. Our experience and expertise are shared within standards (e.g., editors of the ISO/IEC 21823-3 IoT semantic interoperability). Future work will consider "How to do the real actuation?" (switch on/off devices) once the reasoner is providing the suggestion.

Interconnect Use Cases: The SAREF-compliant sensor dictionary and rule-based reasoning is *a first step towards the development of more sophisticated applications*, left for future work such as: 1) reducing electricity bill, 2) energy consumption diagnosis, 3) voltage control of residential building, 4) enabling smart parking services, and 5) need of minimum X kW immediately for emergency, Y kW until 6 pm, Z kW surplus.

As a long-term solution, we will infer meaningful value from IoT data generated by devices using more sophisticated Artificial Intelligence technologies. Ideally, we also plan to contribute and be fully compliant with more standards such as W3C SSN/SOSA, W3C Web of Things, and iot.schema.org.

ACKNOWLEDGMENT

This work has partially received funding from the European Union's Horizon 2020 research and innovation program under grant agreement Interconnect No. 857237, StandICT.eu 2023 No. 951972, and AI4EU No. 825619. We would like to thanks project partners for their valuable comments. The opinions expressed are those of the authors and do not reflect those of the sponsors.

REFERENCES

[1] "ETSI TS 103 410-1: "SmartM2M; Smart Appliances Extension to SAREF; Part 1: Energy Domain"," ETSI, 2017.

[2] ISO, "ISO/IEC 21823 Semantic Interoperability: Interoperability for Internet of Things Systems Part 3 Semantic Interoperability," 2020.

[3] M. Bauer *et al.*, "Semantic IoT Solutions - A Developer Perspective (Semantic Interoperability White Paper Part I)," 2019.

[4] M. Bauer, H. Baqa *et al.*, "Towards semantic interoperability standards based on ontologies (Semantic Interoperability White Paper Part II)," 2019.

[5] P. Murdock *et al.*, "Semantic Interoperability for the Web of Things," 2016.

[6] A. Gyrard, C. Bonnet, K. Boudaoud, and M.Serrano, "LOV4IoT: A Second Life for Ontology-based Domain Knowledge to build Semantic Web of Things Applications," in *IEEE International Conference on Future Internet of Things and Cloud*, 2016.

[7] B. Kitchenham, R. Pretorius, D. Budgen, O. P. Brereton, M. Turner, M. Niazi, and S. Linkman, "Systematic Literature Reviews in Software Engineering– A Tertiary Study," *Information and software technology*, 2010.

[8] M. Noura, A. Gyrard, S. Heil, and M. Gaedke, "Automatic Knowledge Extraction to build Semantic Web of Things Applications," 2019.

[9] M. Noura, A. Gyrard *et al.*, "Concept Extraction from the Web of Things Knowledge Bases," in *International Conference WWW/Internet 2018*. Elsevier, 2018, Outstanding Paper Award.

[10] I. Esnaola-Gonzalez, J. Bermúdez, I. Fernandez, and A. Arnaiz, "Semantic prediction assistant approach applied to energy efficiency in tertiary buildings," *Semantic Web Journal*, 2018.

[11] P. Brizzi, D. Bonino, A. Musetti, A. Krylovskiy, E. Patti, and M. Axling, "Towards an Ontology Driven Approach for Systems Interoperability and Energy Management in the Smart City," in *International Multidisciplinary Conference on Computer and Energy Science*. IEEE, 2016.

[12] D. Bonino *et al.*, "Rule-based Intelligence for Domotic Environments," *Automation in Construction*, 2010.

[13] M. Lefrançois, J. Kalaoja, T. Ghariani, and A. Zimmermann, "The SEAS Knowledge Model," 2017.

[14] G. Burel, L. S. Piccolo, and H. Alani, "Energyuse-a collective semantic platform for monitoring and discussing energy consumption," in *International Semantic Web Conference*. Springer, 2016.

[15] M. Kofler, C. Reinisch, and W. Kastner, "A Semantic Representation of Energy-Related Information in Future Smart Homes," *Energy and Buildings*, 2012.

[16] F. Radulovic, M. Poveda-Villalón, D. Vila-Suero, V. Rodríguez-Doncel, R. García-Castro, and A. Gómez-Pérez, "Guidelines for Linked Data Generation and Publication: An Example in Building Energy Consumption," *Automation in Construction*, 2015.

[17] M. Kolchin, D. Mouromtsev, and S. A. Arustamov, "Web-based Visualisation and Monitoring of Smart Meters using CQELS," in *TC/SSN@ ISWC*, 2014.

[18] S. Dey, D. Jaiswal, R. Dasgupta, and A. Mukherjee, "Organization and Management of Semantic Sensor Information Using SSN Ontology: An Energy Meter Use Case," in *International Conference on Sensing Technology (ICST)*. IEEE, 2015.

[19] R. Dasgupta and S. Dey, "A Comprehensive Sensor Taxonomy and Semantic Knowledge Representation: Energy Meter Use Case," in *International Conference on Sensing Technology (ICST)*. IEEE, 2013.

[20] T. A. Nguyen, A. Raspitzu, and M. Aiello, "Ontology-based Office Activity Recognition with Applications for Energy Savings," *Journal of Ambient Intelligence and Humanized*, 2014.

[21] A. Groza, "Data structuring for the ontological modelling of wind energy systems," *arXiv preprint arXiv:1510.03179*, 2015.

[22] J. Kott and M. Kott, "Generic Ontology of Energy Consumption Households," *Energies*, 2019.

[23] C. Lork, V. Choudhary, N. U. Hassan, W. Tushar, C. Yuen, B. K. K. Ng, X. Wang, and X. Liu, "An Ontology-Based Framework for Building Energy Management with IoT," *Electronics*, 2019.

[24] D. Küçük and D. Küçük, "OntoWind: An improved and extended wind energy ontology," *arXiv preprint arXiv:1803.02808*, 2018.

[25] R. Santodomingo, M. Uslar *et al.*, "Rule-Based Data Transformations in Electricity Smart Grids," in *International Symposium on Rules and Rule Markup Languages for the Semantic Web*. Springer, 2015.

[26] H. Wicaksono, P. Dobreva, P. Häfner, and S. Rogalski, "Methodology to Develop Ontological Building Information Model for Energy Management System in Building Operational Phase," in *International Joint Conference on Knowledge Discovery, Knowledge Engineering, and Knowledge Management*. Springer, 2013.

[27] Q. Zhou, S. Natarajan, Y. Simmhan, and V. Prasanna, "Semantic Information Modeling for Emerging applications in Smart Grid," in *International Conference on Information Technology-New Generations*. IEEE, 2012.

[28] A. Fensel, S. Tomic, V. Kumar, M. Stefanovic, S. V. Aleshin, and D. O. Novikov, "Sesame-S: Semantic Smart Home System for Energy Efficiency," *Informatik-Spektrum*, 2013.

[29] T. Linnenberg, A. W. Mueller, L. Christiansen, C. Seitz, and A. Fay, "OntoENERGY - A Lightweight Ontology for Supporting Energy-efficiency Tasks," in *International Conference on Knowledge Engineering and Ontology Development*, 2013.

[30] J. Han, Y.-K. Jeong, and I. Lee, "Efficient Building Energy Management System Based on Ontology, Inference Rules, and Simulation," in *International Conference on Intelligent Building and Management, Singapore*, 2011.

[31] Y.-G. Cheong, Y.-J. Kim, S. Y. Yoo, H. Lee, S. Lee, S. C. Chae, and H.-J. Choi, "An Ontology-Based Reasoning Approach Towards Energy-Aware Smart Homes," in *Consumer Communications and Networking Conference (CCNC)*. IEEE, 2011.

[32] A. Crapo, K. Griffith, A. Khandelwal, J. Lizzi, A. Moitra, and X. Wang, "Overcoming Challenges Using the CIM as a Semantic Model for Energy Applications," in *Grid-Interop Forum, GridWise Architecture Council*, 2010.

[33] A. Crapo, X. Wang, J. Lizzi, and R. Larson, "The Semantically Enabled Smart Grid," *The Road to an Interoperable Grid (Grid-Interop)*, 2009.

[34] A. Gyrard, M. Serrano *et al.*, "Sensor-based Linked Open Rules (S-LOR): An Automated Rule Discovery Approach for IoT Applications and its use in Smart Cities," in *International ACM Smart City Workshop (AW4city) at WWW*. ACM, 2017.

[35] R. Agarwal, D. G. Fernandez, T. Elsaleh, A. Gyrard, J. Lanza, L. Sanchez, N. Georgantas, and V. Issarny, "Unified IoT ontology to enable interoperability and federation of testbeds," in *IEEE WF-IoT*, 2016.