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INTERNATIONAL SMART GRID
ACTION NETWORK

Interoperability of digital (ICT) systems in the energy sector

How to Improve the Interoperability of Digital (ICT) Systems in the Energy Sector

Discussion paper

ISGAN Annex 6 Power Transmission & Distribution Systems
Focus area “System Operation and Security”

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Discussion Papers

ISGAN discussion papers are meant as input documents to the global discussion about smart grids. Each is a statement by the author(s) regarding a topic of international interest. They reflect works in progress in the development of smart grids in the different regions of the world. Their aim is not to communicate a final outcome or to advise decision-makers, but rather to lay the ground work for further research and analysis.

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Acronyms and Abbreviations

AAF	Agricultural Architecture Framework
BAP	Basic Application Profile
BAIoP	Basic Application Interoperability Profile
CIM	Common Information Model
CMMI	Capability Maturity Model Integration
DER	Distribution System Operation
DICOM	Digital Imaging and Communications in Medicine
DoE	Design of experiments
ENTSO-E	European Network of Transmission System Operators for Electricity
EUT	Equipment Under Test
GWAC	GridWise® Architecture Council
HL7	Health Level 7
ICT	Information- and Communication Technology
IEC	International Electrotechnical Commission
IES	Integrating the Energy system
IHE	Integrating the Healthcare Enterprise
JRC	Joint Research Centre
LCIM	Levels of Conceptual Interoperability
MAF	Maritime Architecture Framework
NETHA	National E-Health Transition Authority
OPC UA	Open Platform Communications / Unified Architecture
OSI	Open Systems Interconnection Model
RAMI 4.0	Reference Architecture Model for I4.0
SCIAM	Smart City Infrastructure Architecture Model
SG IMM	Smart Grid Interoperability Maturity Model
SGAM	Smart Grid Architecture Model
SG-CC/RA	Smart Grid Coordination Group/Reference Architecture Working Group
SGILab	Smart Grid Interoperability Laboratory
SIA	Seamless Integration Architecture
TF	Technical Framework
TSO	Transmission System Operation
VPP	Virtual Power Plant

Executive summary

Although, the capability for seamless technical integration is subject to many challenges, the problem, however, is not the lack of adequate technical standards – suitable standards, solutions and/or best practices are available for the energy domain. The problems arise due to the absence of a governance of processes and its resulting implications. The lack of central stakeholder which has “control” over the system-of-systems in scope prevents the development of holistic and system-independent solutions, e.g. in the context of Smart Grids. Moreover, the so called ‘wicked’ complexity of the problem makes it increasingly difficult to find a consensus between the stakeholders beyond the lowest common denominator [1], [2].

However, it can be observed that community-driven management approaches are suitable alternatives to cope with this kind of wicked problem in systems enginnering. This way, not only the Integrating the Healthcare Enterprise (IHE) initiative from the healt domain has been able to establish itself as a driver for interoperability in the health care sector, but the Integrating the Energy System Austria (IES) project from Austria showed that the community-driven approach is also finding positive resonance in the energy sector. In this particular respect, the community-based approach does not only increase the general acceptance, but also facilitates the ability to adapt to changing business needs and technological developments by an increased agility compared to ‘traditional’ standards for conformance and certification from standardization bodies.

Furthermore, it must also be taken into account that no technical standard or key concept alone can guarantee ‘perfect’ interoperability. For example, Common Information Model (CIM) or International Electrotechnical Commission (IEC) 61850 describe suitable information models for their very individual scope that are able to represent the relevant Use Cases in Secondary It perspective substation automation, but they do not define a context and, therefore, do not guarantee so called ‘pragmatic’ interoperability. The case studies and the experiences from the healthcare sector show that these individual methodologies complement each other and in combination are able to improve interoperability significantly utilizing concepts addressing different levels of interoperability. In order to achieve interoperability between the individual systems a common understanding on the technical (syntax), informational (semantics) and the organizational (pragmatics) level needs to be achieved. While the syntactical level focuses on the technical data and numerical (binary) values, the semantical level is about embedding these data into a sahred context by providing a meaning. Finally, the pragmatic level focuses on the purpose that the data is needed to fulfil at the (business) process level.

For example, the IEC 62559 Use Case Methodology is suitable to provide the context on an abstract business Use Case level as well as on a more detailed system level Use Case for the implementation of business functions by defining precise communication processes in a structured way. However, the IEC 62559 Use Case Methodology is only suitable to a limited extent for defining the individual transactions of a business function (services vs services in context), so that the complementary use of interoperability / integration profiles is recommended. As this in turn leads to a variety of inhomogeneous documents representing different aspects and views of the interoperability requirements, a unified structure seems to be appropriate, as the Technical Framework of the IHE or the IES initiative shows.

Consequentially, the key concepts do not serve to develop additional missing standards, but to facilitate the coordination of interoperability issues between the constituent systems. In this way, the concept of profiling (respective tailoring) / documentation can be highlighted from both theory and practice as the core principle that requires appropriate governance. In order to perform interoperability tests beyond simple conformance tests, it is essential that two vendor-independent systems have implemented the very same integration profile of a Use Case, thus, providing more context. For this purpose, it is mandatory to publish the integration profiles in a freely accessible way which allows for a third party (with appropriate preparation time) to implement the profiles and to test them against each other within an appropriate test event. The Connectathon (sometimes referred to as ‘Plugfest’) is an annual event that brings together the various providers (e.g. OEM - Original Equipment Manufacturer) who have implemented the previously published integration profiles. In accordance to the IHE, all test runs are evaluated by independent experts, so called ‘Judges’. Once a system has successfully passed all necessary tests, the vendor is allowed to publish an so called *Integration Statement*. Such statement tells the customers which specific Use Cases and integration profiles a given system is designed to support. Furthermore, the results of the Connectathon are not only used to validate products, but also to validate and improve the integration profiles for future iterations itself and, consequentially, in combination substantially reduces the distance for integration.

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1. Introduction on Interoperability Improvement

The energy supply is facing major challenges due to the reduction of CO_2 emissions, the integration of renewable energies as well as a decentralisation of energy generation. Since this can only be achieved by digitising the energy sector, it is necessary to seamlessly and reliably link ICT systems and smart devices from different actors with heterogeneous systems so that they are able to communicate intelligently and to ensure a stable power supply. Therefore, the overarching goal is to enable interoperability between the (digital) systems in smart grids and to secure it in the long term.

1.1. Motivation & Problem Statement

Based on the categorization of systems given by Haberfellner et al. [3], the electric power grid evolves from a massively interconnected system into a complex system [4]. While the traditional power grid is characterized by a certain level of diversity, variety and scale, the Smart Grid is characterized by a certain dynamic and alterability of its structure [3], [4].The Smart Grid can be therefore defined as a two-way information and electricity exchange where ICT systems and smart devices from various stakeholders with heterogeneous systems have to interact seamlessly and reliable with each other in order to provide a stable power supply [5], [6]. As a consequence, the traditional engineering paradigms can no longer be applied effectively and efficiently and the necessity for standardization becomes increasingly crucial as the system becomes more dynamic. This additional dynamics imply that the system-of-systems as a whole requires the capability to reorganize or reconfigure its structure and, therefore, to build and destroy links between the constituent systems dynamically [7]. Such capability, however, can only be realized by appropriate standards which facilitate seamless integration and reduce the distance for integration [8].

However, interfaces are traditionally negotiated between the communicating systems based on their specific requirements, leading to proprietary solutions. Proprietary solutions, however, may work fine for their specific requirements, but prevent the (seamless) integration of additional systems. As a result, the unnecessary high integration costs are slowing down the progress and wide-spread adaption of smart technologies within the energy sector due to often insufficient interoperability and interchangeability of digital systems from various vendors. The capability for seamless integration therefore creates well-defined integration points that allow new automation components and businesses to be interconnected with reasonable effort and without any interference with the overall system [8].

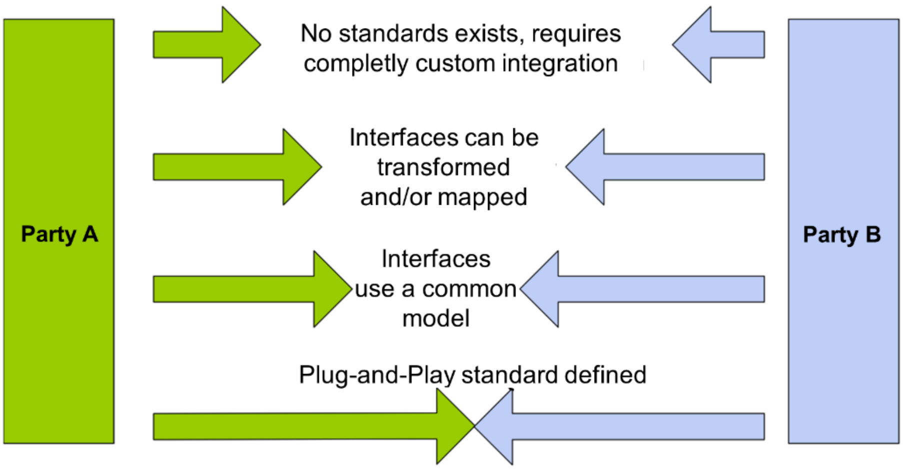

Figure 1 Distance to integrate [8]

Figure 1 illustrates the additional integration efforts of party A and party B whose distance to integrate decreases with the degree of standardization. As a consequence, in order to integrate an unpredictable number of heterogeneous systems in the near future, sustainable Smart Grid solutions need the ability the ability for seamless integration; hence the ability for plug-and-play. Thus, reducing the distance to integrate has a direct impact on the integration costs of all future initiatives [8].

In order to achieve interoperability between the individual systems a common understanding on the technical (syntax), informational (semantics) and the organizational (pragmatics) level needs to be achieved. While the syntactical level focuses on the technical data and numerical (binary) values, the semantical level is about embedding these data into a context by giving them a meaning. Finally, the pragmatic level focuses on the purpose that the data is needed to fulfil. Here, for example, political and regulatory aspects. Although a range of standards have already been established to promote interoperability in the energy sector, these standards cannot ensure practical interoperability. For example, standards are usually written in natural language, which is why they can be misinterpreted, for example. As a result, the standard can be interpreted ambiguously by different vendors, contain gaps or even errors and contradictions. Thus, allowing different interpretations and, therefore, implementations of the same standard. As a consequence, it is not uncommon that even if several systems implement the same standard, they are not fully interoperable to each other, as abstracted in **Figure 2**. For this reason, ordinary compliance tests to the standard are not sufficient. It is mandatory to test the independent systems to their practical interoperability to each other.

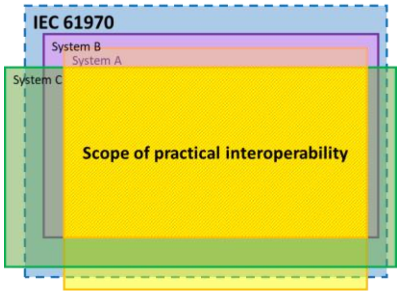

Figure 2 Scope of practical interoperability

1.2. Objectives and Context of the Discussion Paper

This report is prepared within the framework of ISGAN Annex 6 (http://www.iea-isgan.org/our-work/annex-6/). The work of Annex 6, on Power Transmission & Distribution Systems, promotes solutions that enable power grids to maintain and improve the security, reliability and quality of electric power supply. This report is the outcome of an activity within the focus area *System Operation and Security*. The main objectives of this focus are centered around the question: "*How to improve the interoperability of digital (ICT) systems in the (electric) energy sector?*". This discussion paper will therefore present and discuss various approaches for designing the system-of-systems, different approaches for enabling and verify the ICT-interoperability in Smart Grids and motivate the need for interoperability improvements in energy sector. Accordingly, in order to investigate this question, these two sub-questions are first examined:

1) Which approaches are commonly used to improve the interoperability of digital (ICT) systems in (electric) energy sector?
2) Which approaches to improve the interoperability of digital (ICT) systems in other sectors / domains can be learned from?
3) What can be learned from?

Figure 3 positions this discussion paper into the ISGAN context.

ISGAN (http://www.iea-isgan.org)

ISGAN is the short name for the Internetationl Energy Agency (IEA) Implementing Agreement for a Co-operative Programme on Smart Grids (ISGAN). ISGAN aims to improve the understanding of smart grid technologies, practives, and systems and to promote adaption of related enabling government policies. ISGAN's vision is to accelerate progress on key aspects of smart grid policy, technology, and related standards through voluntary participation by governments in specific projects and programs.

ISGAN Annex 6

ISGAN Annex 6 - Power Transmission and Distribution Systems focuses on both transmission and distribution systems related challanges in the development of Smart Grids.

ISGAN Annex 6 Focus area System Operation and Security

The main objectives of this focus are centered around the question: “*How to improve the interoperability of digital (ICT) systems in the (electric) energy sector?*”

Discussion Paper on "*How to improve the interoperability of digital (ICT) systems in the (electric) energy sector?*”

Figure 3 Discussion paper embedded within the ISGAN context

Subsequently, different case studies with different approaches, methods and/or practices are presented, compared and analysed in order to get a comprehensive overview. The paper is organized in seven sections as follows:

- Section 1 provides an introduction and motivates the need for interoperability improvements.
- Section 2 outlines background discussions and key concepts of interoperability in Smart Grids.
- Section 3 provides the case studies on how standards are adapted by the industry in order to improve ICT-interoperability.
- Section 4 compares the various approaches based on the findings of section 2 and 3.
- Section 5 finally summarizes all results from theory and practice within a comparative summary.

2. Background Discussions and Key Concepts

The section introduces how standardization activities are organized in different parts of the world, e.g. by the IEC at international level and M/490 to CEN/CENLEC and ETSI at European level. The following sections presents different approaches on how to realize, document and verify interoperability in the Smart Grid. The main emphasis will be on the use of appropriate tools and methodologies, such as the Smart Grid Architecture Model (SGAM) and the IEC 62559 Use Case Methodology. Both methodologies promote interoperability in the energy system as they contribute to address the issue that different stakeholders with heterogeneous systems come together for developing joint Smart Grid solutions. Later in this chapter, a complementary approach from the healthcare domain, which was developed by the *Integrating the Healthcare Enterprise* (IHE) initiative, will be presented and compared.

2.1. Considering the Smart Grid as a System-of-systems

In order to categorize and highlight the various challenges posed to the engineering of systems-of-systems and, subsequently, to the engineering of Smart Grids, there are a number of different classifications, which categorize the system-of-systems in accordance to the problem under investigation. In this way, the different classifications represent different perspectives and challenges of the same subject. While Haberfellner et al. [3] emphasizes the increasing dynamics and heterogeneity, which highlights the need for interoperability and standardization on the technical level, Maier [9] distinguishes systems-of-systems based on the socio-technical perspective, which implicitly describes why the standardization within systems-of-systems becomes increasingly problematic with the increasing dynamics and heterogeneity. Since the engineering of systems-of-systems can vary fundamentally in its scope and complexity, Maier distinguishes systems-of-systems by the way they are managed and governed, as depicted in **Figure 4**.

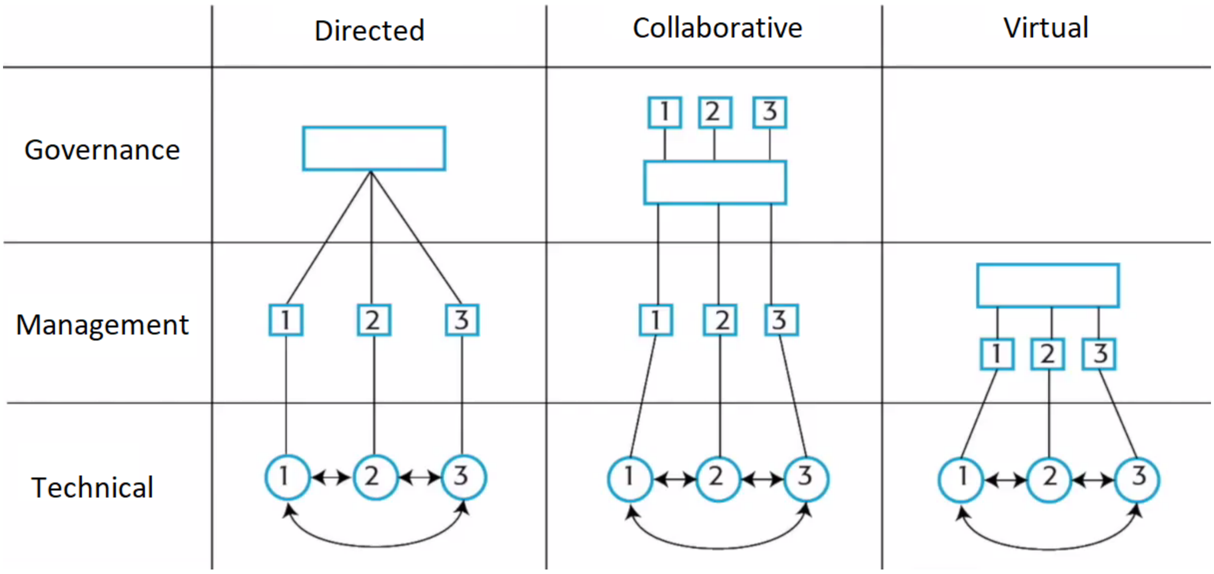

Figure 4 System-of-systems classification [10]

Based on Maier's classification, the overall consent within the discipline of systems engineering is that collaborative systems-of-systems, as is the Smart Grid, are the most challenging [11]–[14]. Due to the managerial and organizational independence of its constituent systems, these systems are challenged by a so-called wicked problem complexity. With its origin from social planning, these type of problems cannot be solved correct or wrong, just good or bad with a reference to a point of view [15]. A solution to a wicked problem depends on how the problem is framed and is always coupled to other problems from different perspectives. In the case of such collaborative system-of-systems, the system-of-systems is composed of autonomous and self-sufficient subsystems. These constituent systems are useful systems by their own, having their own development, objectives and resources [1]. Although the constituent systems are collaborating in order to meet shared goals, they have their own prioritized business objectives accompanied by their own point of view. Consequentially, every system has, due to its operational and managerial independence, its own individual starting point, requirements, understanding of the problem and, thus, preferred solution based on the value it expects to get from the different actions [16]. However, an acceptable solution for one system will most likely result in an unacceptable result for another system. In consequence, the absence of a central authority and leadership leads to the situation that there is no holistic perspective on the system-of-systems.

2.2. IEC 62559-2 Use Case Methodology

Use Cases typically function as one of the first elements of system specification in software and systems engineering processes and therefore offer a sound foundation by facilitating the collection, analysis and documentation of requirements. According to ISO/IEC 19505-2:2012, a Use Case is defined as follows:

> “*A Use Case is the specification of a set of actions performed by a system, which yields an observable result that is, typically, of value for one or more actors or other stakeholders of the system.” -* ISO/IEC 19505-2:2012 [17]

Hence, Use Cases address business-related issues and specify the behaviour within different scenarios (e.g. communication patterns or different outcomes) that the subject can perform in collaboration with one or more actors [17].

As the collaboration of multiple autonomous and independent subsystems represents a central aspect for the realization of Smart Grid-solutions, the overall project managements requires a structured, organised and unified way to describe the various Use Cases of the Smart Grid and its components [18]. Accordingly, the *IEC Syc Smart Energy* developed the so-called *Use Case Methodology* which has been specified within the IEC 62559-2 [19]. The IEC 62559 Use Case Methodology provides a standardized way to describe and specify such relationships.

The so-called *Use Case Template* provides a general description as well as the means to specify individual contents of the Use Case in more detail, such as the actors, exchanged information objects and further requirements associated to the Use Case. Hence, the Use Case Methodology is used to describe the complex energy system solutions of the actors with their different perspectives, to characterize the interactions between the components and, therefore, to prevent interoperability issues between all systems at an early stage [18]. Thus, by focusing on the different perspectives of a Use Case, the IEC 62559-2 Use Case-Template promotes a common understanding and, therefore, interoperability between all involved actors. The Use Case template also consists of eight different parts, which are the:

- Description of the Use Case
- Diagrams of use the Use Case
- Technical details,
- Step-by-step analysis,
- Information exchanged
- Requirements,
- Common terms and definitions,
- Custom information

Within the description of the Use Case, general information is provided, which are, for example, the name of the Use Case, the version management, the scope and objectives, a narrative description, Key Performance Indicators as well as Use Case Conditions. Moreover, the Use Case template consists of a Use Case diagram, which aims to provide an understanding and overview of the Use Case procedure. The following section of the Use Case template consists of the technical details, such as actor information. Moreover, a step by step analysis should describe possible scenarios of the Use Case. The next section provides information exchanged in the scenario steps. Further, the requirements are optional, which are defined in different categories. Moreover, the following section provides common terms and definitions that are written down in a glossary. Finally, custom information could include the key and the value that refers to a specific pair.

2.3. Smart Grid Architecture Model

With the aim of identifying gaps in Smart Grid standardization, the Smart Grid Architecture Model (SGAM) was developed by the Smart Grid Coordination Group/Reference Architecture Working Group (SG-CC/RA) within the European standardization mandate M/490 as a holistic perspective on Smart Grid Architectures [6]. The SGAM framework combines the different domains of the physical subdivisions of the energy value chain (based on the NIST Conceptual Model [5]) with the different zones of energy management (based on the automation pyramid). Correspondingly, the main objective of the SGAM is to improve standardisation activities in order to achieve interoperability between the different electrical energy supply systems.

2.3.1. Background of the SGAM

The definition of the various interoperability layers in SGAM was based on the GWAC-Stack, which initially based on the introduced levels of interoperability: syntactical, semantical and pragmatical. The GridWise Architecture Council (GWAC), In the GWAC-Stack, eight levels of interoperability were described. The lower three interoperability levels "basic connectivity", "network interoperability" and "syntactic interoperability" are described as technical drivers. Semantic understanding" and the "business context" are classified as informational drivers and the upper three levels "business procedure", "business objectives" and "economic/regulatory policy" as organisational drivers. For the SGAM, these eight levels were combined into five levels, which also include syntactic, semantic and pragmatic aspects of interoperability [6].

By representing the interactions between the individual components of a given Use Case, the SGAM is particularly suitable for the representation of the overall Smart Grid architecture and its associated interoperability requirements between the constituent systems. In order to adequately represent the interoperability requirements as defined by the GWAC-Stack while preserving the applicability of the framework, the eight interoperability categories of the GWAC-Stack have been consolidated to the five layers as depicted in **Figure 5**.

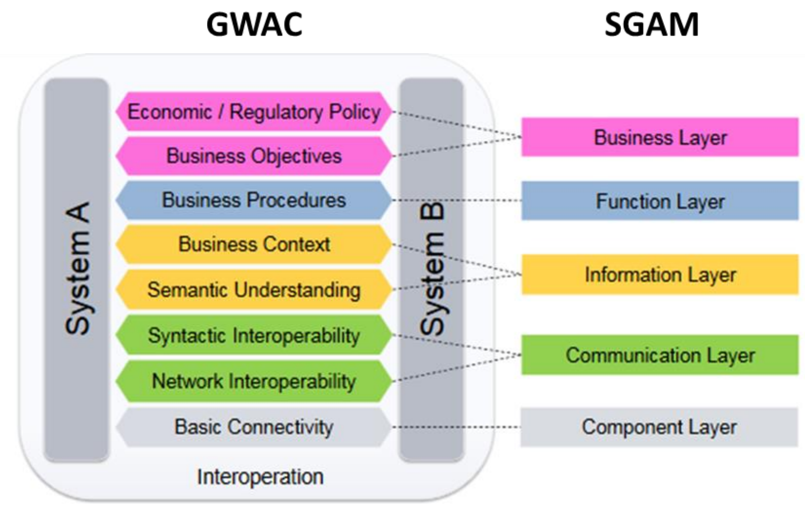

Figure 5 Grouping the GWAC-Stack into the SGAM interoperability layers [6]

In this way, the SGAM is able to leverage a common understanding of the overall Smart Grid architecture, the responsibilities as well as the communication paths with its associated interfaces and interoperability requirements between all constituent systems. Although the SGAM reduces misunderstandings and their associated interoperability problems, it does not necessarily prevent the development of proprietary solutions. Thus, in order to prevent proprietary solutions and, therefore, to prevent an arbitrary growth (from a systems-of-systems perspective), the so-called *IEC 62357 Seamless Integration Reference Architecture (SIA)* provides an appropriate guidance for decision-makers. The SIA uses broadly established standards and allocates them within the SGAM Framework in accordance to the respective domains and zones they apply to. As a result, if individual components of a Smart Grid are also represented in SGAM, the SIA can be used to derive the recommended standards for the respective components. Moreover, on the basis of analyses of the SGAM model, possible gaps in the ICT architecture, especially in terms of integration/interoperability between systems, can be identified at an early stage, thus enabling an efficient and cost-effective implementation due to facilitating the capability for a seamless integration.

2.3.2. Design and structure of the SGAM

Next to the five interoperability layers, the structure of SGAM is based on five domains, which are depicted no the x-axis. The domains plane divides the Electrical Power Supply into the individual sections:

- Bulk Generation: The bulk generation is responsible for the large volume power generation.
- Transmission: The transmission system operator is responsible for the controlling and operating of the transmission grid. These grids comprise voltage level of 220 kV to 380 kV in Europe.
- Distribution: The distribution system operator is responsible for controlling and operating the distribution grid. These grids comprise lower voltage levels and are connected to the end consumers.
- Distributed Energy Resource, DER: Distributed energy systems are small scale power generators or storage technologies, which are often connected to the households, such as photovoltaic systems.
- Customer Premises: The customer / prosumers are the end consumers of electricity.

The y-axis of the SGAM reflects the automation pyramid.

- Process: The process zone comprises the physical equipment of the energy supply.
- Field: The field zone contains protection, control and monitoring equipment.
- Station: The station zone refers to a spatial aggregation of the field zone, e.g. local system.
- Operation: The operation zone represents the higher-level control of the energy system, such as distribution network control.
- Enterprise: The enterprise zone contains commercial and organizational processes.
- Market: The market zone refers to market operations and interactions.

The SGAM enable a structured location of the individual elements of the zones and domains in the higher-level Smart Grid context and provides the visualization of individual aspects of the Use Cases. As above introduced, five interoperability layers derived from the GWAC stack, which are necessary for achieving the overarching goal of interoperability. The following distinctions

- Business Layer: The business layer has a business perspective and comprises economic and regulatory aspects of the Use Case, such as KPIs.
- Function Layer: On the function layer, functions and services between components from an architectural point of view are depicted.
- Information Layer: On the information layer, transmitted information objects and data models are represented.
- Communication Layer: The communication layer shows protocols and mechanisms for information exchanges within the Use Case.
- Component Layer: The component layer depicts the physical distribution of the components that are involved.

Hence, the resulting SGAM framework leads to a structured presentation of a smart grid system as a whole as well as presents a separate consideration of individual interoperability aspects.

By combining the domains and zones of the electric energy system, the resulting (SGAM) plane is able to reflect the entire energy conversation chain of a Use Case, which allows a system-oriented view and mapping of the individual components of the Smart Grid and, thus, holistic analysis of the overall architecture. Thus, the SGAM layer is a structured plane for the depiction of Smart Grid architectures. The NIST Conceptual Model is used to combine monitoring and control processes at the control level and to combine them within the automation pyramid. Additionally, the SGAM framework complements the plane with different perspectives, the so-called interoperability layers (based on the GWAC-Stack [20]) which are consolidated in a three-dimensional framework as depicted in **Figure 5**.

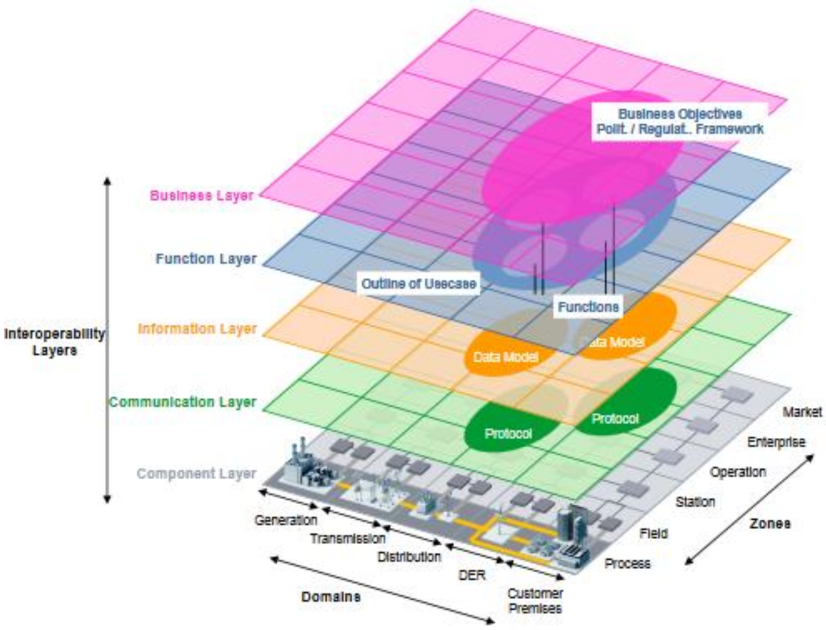

Figure 6 SGAM Framework [21]

2.3.3. Application of the IEC 62559 Use Case-Methodology and SGAM

The IEC 62559 Use Case- as well as the SGAM-Methodology can be used on its own, but they work seamlessly and elicit data based on a common meta-model shared by the ISO 42010 [21] architecture standards and supplement each other [4], [22]. The dynamics of the static SGAM with the processes and exceptions can be documented in an IEC 62559 template while the individual solutions can be classified within the SGAM as a reference designation system [4]. Although the IEC 62559-2 Use Case Template is not part of the SGAM modeling, it contains the information necessary to model the use case with SGAM. The components of the Use Case template and how they relate to the SGAM are shown **Figure 7**.

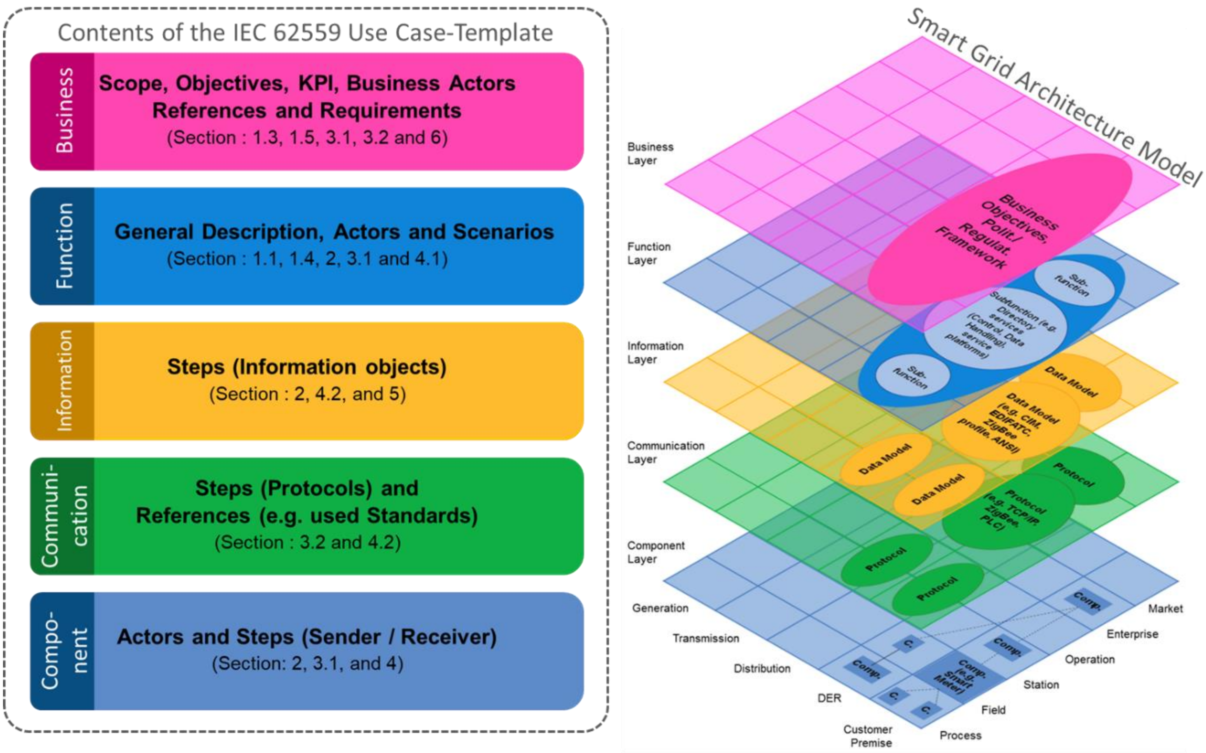

Figure 7 From Use Cases to SGAM [6], [18]

2.4. Interoperability Profiles

The concept of the so-called interoperability profiling serves the development of consistent, unambiguous and strict specifications of the interoperability requirements for a given Use Case [6].

The *Basic Application Profiles* (BAP) are based on domain-specific descriptions of basic application functions and are intended to represent a recommended implementation of the substation automation functions defined in IEC 61850. Consequentially, BAPs can be regarded as a subset of the respective standard which strictly and exclusively specifies only mandatory elements by (mainly) adding constraints which must be implemented in order to realize the given Use Case. Furthermore, analogous to the Use Case-Methodology, multiple independent profiles can be used as building blocks in order to implement other more complex applications by combining them.

While BAPs provide an implementation strategy, the so-called *Basic Application Interoperability Profiles* (BAIoP) extends this strategy with adequate testing approaches at different levels (e.g. unit, integration, and acceptance tests) which are intended to ensure interoperability. As a consequence, BAIoPs also includes additional information about inter alia the device configuration and test configuration, test cases for the BAPs, specific service descriptions and engineering frameworks for the development of data models and communication infrastructures, which together enable the testing of a proposed system.

2.5. The Smart Grid Interoperability Maturity Model

In order to achieve interoperability, a coordinated improvement process and a community culture between all stakeholder in the Smart Grid is required, which is sensitive to interoperability concerns [20].

To develop such process, the Grid Wise Architecture Council (GWAC) developed the so-called *Smart Grid Interoperability Maturity Model* (SG IMM) [20]. Maturity models allow to measure the current status and progress of e.g. technologies as well as to identify gaps in its development to enhance technologies in a continuous improvement cycle. Accordingly, the

SG IMM provides the means to evaluate the progress of interoperability in the Smart Grid community as well as to foster an interoperability-aware culture with individual and shared roadmaps for enhancement.

The SG IMM, thus, adopts a system-of-systems perspective and summarizes the core characteristics that contributes to the improvement of interoperability in a simplified framework, which is shown in **Figure 8**. Concluding, it can be used to evaluate, assess and compare the cross-organizational interoperability or the maturity of the overall Smart Grid initiative under consideration of the three levels of interoperability "*Technical*", "*Informational*" and "*Organizational*" and their cross-cutting issues / areas „*Configuration and Evolution*", „*Operation & Performance*" and „*Security and Safety*".

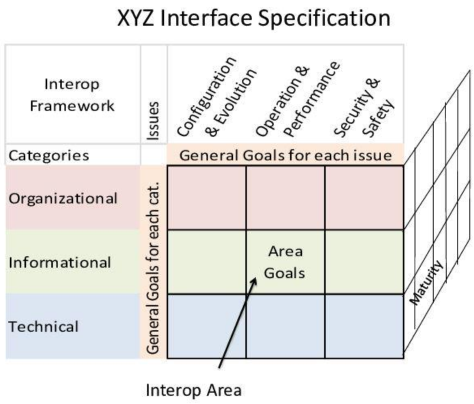

Figure 8 Simplified Interoperability Framework for SG IMM [20]

The different dimensions or aspects that are able to improve the interoperability are consolidated for this purpose. A direct comparison of these key concepts shows that the different concepts also address different issues associated with interoperability:

The first dimension is *Management,* which assumes that an adequate standardization governance leads to the improvement and the overall acceptance of standards. Moreover, an adequate governance prevents the development of proprietary solutions and the consequent arbitrary growth of interfaces.

The second dimension is documentation, which is presumes that a technology-independent representation of the communicating systems allows a net-centric conceptualization of the overall Smart Grid ICT-architecture, supports the coordination processes between the various actors and facilitates the derivation of implementation strategies (especially requirements and design) for the individual Use Cases.

The third dimension is integration, which assumes that strict, consistent and unambiguous specification of standard-based interfaces at all levels of interoperability to prevent assumptions and misunderstandings during implementation.

The fourth dimension is the testing. Since standards are partly written in a natural language, misunderstandings cannot be fully avoided. To verify the practical interoperability between two independent systems or implementations, it must be validated under strict test specifications.

2.6. Standardization and Interoperability in other Domains

Interoperability is not a unique problem of the energy domain. It is a challenging problem in all IT-supported domains, since the most legacy IT as well as OT systems were originally developed as isolated stand-alone solutions, which now need to be integrated to a larger system-of-systems. Due to unique general conditions, however, different domains are only comparable to a limited extent. For example, the military capabilities are less dependent on "voluntary" collaboration, due to a certain degree of an overarching governance and authority and, thus, a significantly reduced socio-technical/wicked complexity. The Smart City domain, for instance, builds on the methods of the energy domain with e.g. the SCIAM (Smart City Infrastructure Architecture Model) as a derivation of the SGAM [23]. However, the realization of future synergies, with e.g. the maritime sector based on the *Maritime Architecture Framework* (MAF) or agricultural sector based on the *Agricultural Architecture Framework* (AAF), should also be envisioned [24], [25].

In a direct comparison, however, especially one approaches can be identified which could make a decisive contribution to improving interoperability in the energy sector: The *Integrating the Healthcare Enterprise* (IHE) initiative of the healthcare sector.

The IHE [26] is a global non-profit initiative which aims to ensure a secure and coherent transfer of information between the involved IT in the healthcare sector, which is comprised of a variety of unique methods. The first difference compared to other standardization activities or initiatives is that IHE was formed by an association of medical information system manufacturers and, thus, was and is driven by industrial stakeholders. Accordingly, the IHE is not about the development of basic standards, but rather about facilitating existing standards and bringing together the various healthcare IT system users and suppliers within a more professional and collaborative environment [27]. For this purpose, the IHE developed a holistic approach as depicted in **Figure 9**.

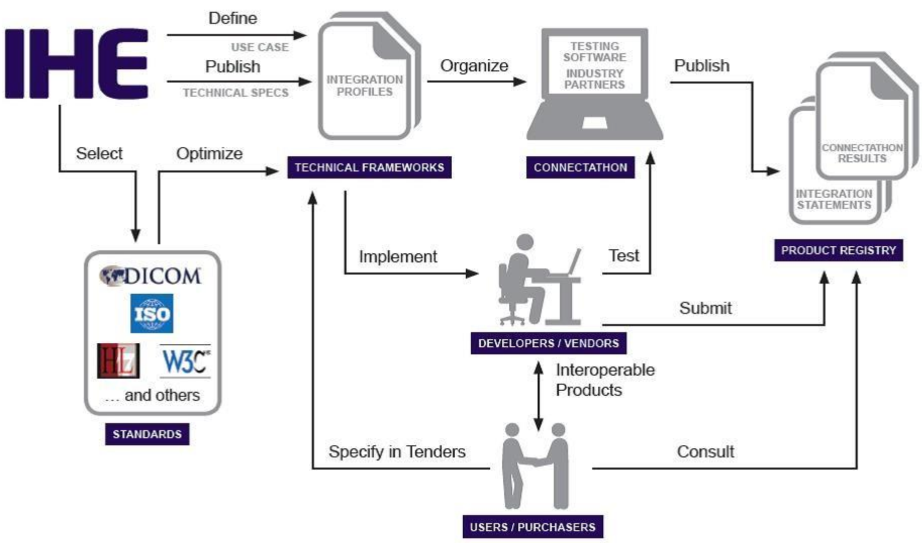

Figure 9 The IHE approach [28] based on ISO/TR 28380-1 [29]

Centrally, this process includes a holistic approach in terms of governance, documentation, implementation and testing. Accordingly, the IHE follows a community driven approach whereby the domain and technical experts from industry decide which Use Cases are critical.

Based on these Use Cases, the technical experts jointly elaborate the detailed specifications for the respective communications and their various transactions by using only established standards as HL7 and DICOM. For this purpose, the IHE approach relies on the public development and availability of the so-called integration profiles, which are essentially similar to the BAPs of the 61850 standard of the energy sector. In the case of IHE approach, however, these profiles are only one component of their superior *Technical Framework*. Technical Frameworks are rigorously structured documents which provide a comprehensive informative as well as normative guidance for implementing the defined integration capabilities of a dedicated a business case, so that interfaces can be completely understood, without any restrictions and inconsistencies. Once the Technical Frameworks are fully specified, they are adapted by the industry.

In order to verify the practical interoperability of the different implementation of the vendors, peer-to-peer tests are carried out at carefully planned and supervised *Connectathons*. A Connectathon, as a socio-technical methodology, enables a wide range of stakeholders to collaborate agilely during a full week face-to-face. The Use Case driven integration profiles, which specify the requirements for the communication process, allow to perform cross-system interoperability tests under real environmental conditions and, moreover, to jointly identify, discuss and eliminate errors on site and in depth. The discrepancies identified in the process serve as feedback to improve the integration profiles. By this means, the annual IHE Connectathon provides vendors with a platform to test and verify the interoperability of their systems based on the Technical Frameworks. The interoperability tests themselves are organized and executed with the support of *Gazelle* – a dedicated test platform developed by the IHE optimized for interoperability tests. Analogous to BAIoPs of the 61850 standard, well-defined test processes, communication procedures as well as success and failure scenarios in according to the integration profiles are implemented in Gazelle for each Use Case, which serve to test the manufacturers' systems against each other according to the test specification. Finally, the test results of successful participations of the Connectathon are annually published – Which system is interoperable to which other system in which Use Case.

3. Case Studies

The first section focuses on international case studies, which describe how standards are adapted by the industry in order to improve ICT-interoperability. For this purpose, the three case studies "*Integrating the Energy System Austria*", "*CIM profiling and proof of interoperability within the scope of CIM IOP test activities (CIM Connectathons)*" and "*SGILab des Joint Research Centre (JRC) of the European Commission*" were included, which aim to improve the interoperability in the energy sector are presented in this section.

Due to the diversity in scope and context of the different case studies, a shared and comparable framework is required. Consequentially, the background and the approach of the respective case study are presented first. Afterwards, the case studies are classified in accordance to the GWAC stack for an additional comparability.

3.1. Case Study: Integrating the Energy System (IES) Austria

3.1.1. Background

The objective of the research project "IES Austria – Integrating the Energy System" is the development of a holistic and modular process chain capable of enabling interoperability in the Smart Grid across all development phases - requirements engineering, design, development and testing [30]. Based on a preliminary analysis of this project, which showed that the IHE approach already addresses the overall process of software and systems engineering, the IES project aimed to adapt the IHE methodology to the energy sector, under consideration of the domain-specific characteristics. Thus, the IES adopted and migrated the established and matured IHE methodology on achieving interoperable IT based healthcare systems [30]. For this purpose, the methods of the energy domain were investigated on how they overlap with those of the IHE. On this foundation, an appropriate gap analysis was performed.

The use of harmonized technical standards is a key requirement for cost-effective system integration. Communication standards allow certain flexibility in their implementation, so that interoperability can only be achieved through a normative application of these standards. This is done in the specification of so-called interoperability profiles. However, a direct comparison revealed that the most special distinction was the strong focus on the testing phase with the "Gazelle" an open-source test machine and the Connectathon as a socio-technical event to validate the practical interoperability between two or more systems within a given Use Case [31].

Consequentially, the IES successfully developed Smart Grid related Technical Frameworks, installed and configured a Gazelle test machine instance and also successfully hosted a small scale Connectathon. Now, IES provides a common understanding and a unified framework to develop and reuse solutions for data exchange [30].

3.1.2. Approach taken

The IES methodology provides a transparent, manufacturer-neutral and cooperative process to define interoperability profiles and to test perform interoperability testing of ICT systems. For this, IES provides a tailor-made service offer for every step of the process chain. Domain experts are accompanied in a moderated process in the specification of interoperability profiles. Manufacturers who have implemented the public available interoperability profiles are supported in the preparation and implementation of interoperability tests [32].

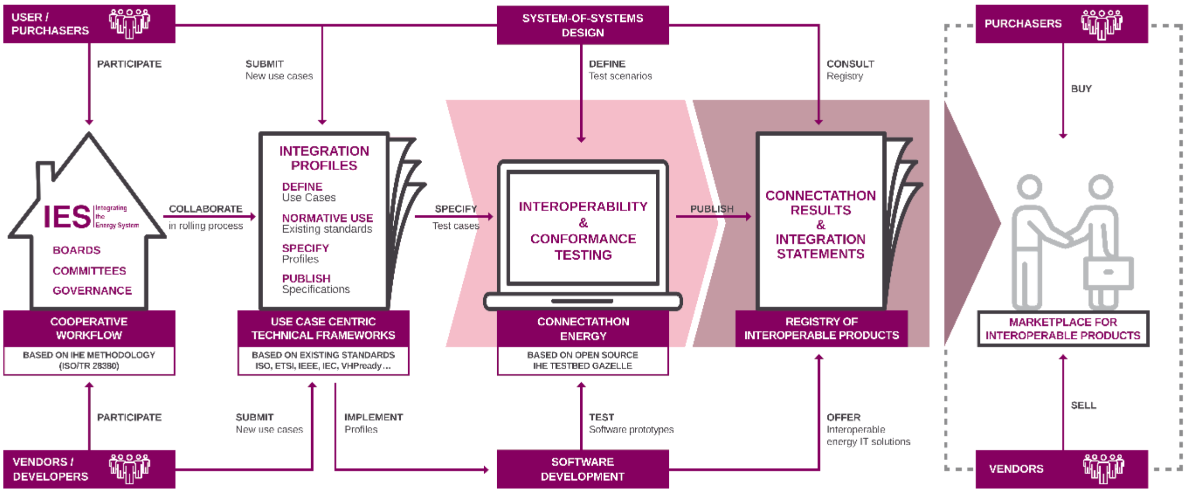

Figure 10 The IES methodology [32]

As **Figure 10** shows, this approach consists of three modules, which are facilitated and improved by an continuous recurring process based on four phases (extracted from [32]):

1. Identify Use Cases where interoperability is an issue and specify these by identifying system borders and requirements.

- Assign an interoperability issue to a domain (identify where the issue belongs to)
- Write a Business Overview (define actors, the environment and the general issue)
- Describe Business Functions (use the Use Case Method and UML Use Case diagrams)
- Reuse Integration Profiles where possible (save specification and test effort)

2. Jointly identify how interoperability issues can be prevented and specify the requirements normatively as Integration Profile.

- Evaluate which standards can be used to fullfil the Use Case requirements
- Specify the process to realize a Business Function (UML sequence diagram)
- Define the actors and transactions (decompose Meta-Actors into modules)
- Draw an Actors-Transactions Diagram (visualize interaction)
- Specify additional communication and security requirements

3. Test independent prototype solutions against each other on annual plugfest and iteratively improve the Integration Profile.

- Specify test cases and test sequences according to Integration Profile specification
- Add test cases, procedures, description and criteria to test environment (Gazelle)
- Create and integrate/implement conformity validation tools (e.g., Schematron configuration files)
- Execute test cases with at least two independent peer vendors
- Validate recorded messages/traces and log evaluated test results (impartial monitor)

4. Publish interoperability test results for each participant/vendor.

- Publish which vendors successfully tested an Integration Profile (Results Browser)
- Get written approval of interoperable implementation (Integration Statements)

3.1.3. Summary

With its holistic approach the IES addresses with its Technical Frameworks all levels of interoperability, which can be classified in accordance to the GWAC-Stack as depicted in **Figure 11**.

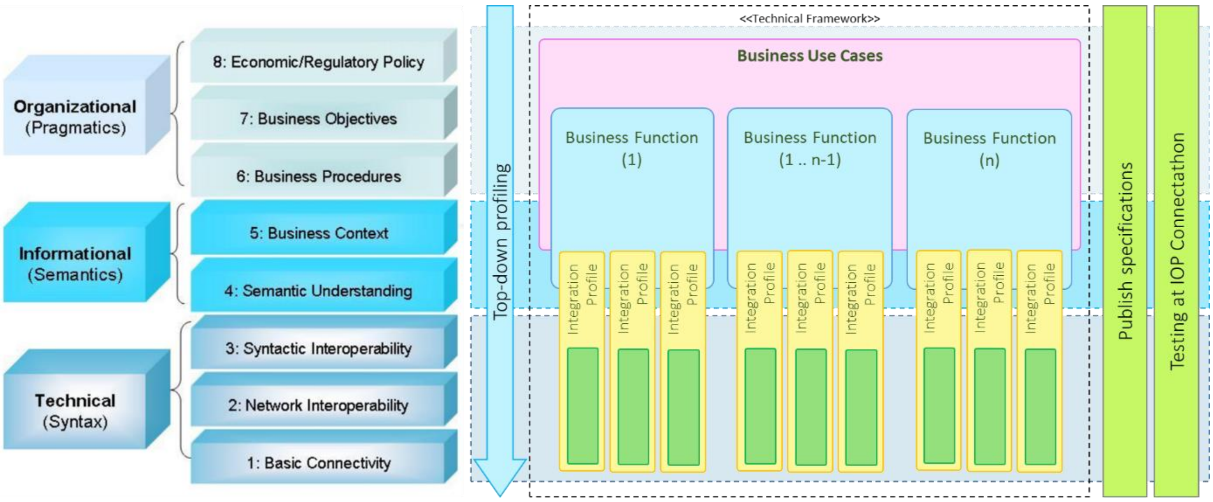

Figure 11 Case Study: IES Austria categorized in accordance to the Interoperability Context-Setting Framework

Table 1 provides a consolidated overview of the key characteristics of the IES approach.

Table 1 Case Study: IES Austria summarized key characteristics and information

Case Study	IES Austria
Location	Austria, EU
Duration	2016 to 2019
Homepage	http://www.iesaustria.at [Accessed: 20-Jul-2020]
Management	+ Community driven based on industrial interests. + Offers process support for the specification of the Technical Frameworks e.g. through moderated workshops where users and manufacturers jointly determine the requirements and functionalities. + All the specifications / integration profiles are freely accessible online. + Integration profiles are continuously improved based on the Connectathon results.

Documentation	+ Uses public repositories. + Uses the IEC 62559-2 Use Case-Template. + Uses SGAM and UML. + Uses Technical Frameworks. + Uses only established best practices and standards, which solve Use Case-related interoperability issues as e.g. CIM or IEC 61850.
Integration	+ Publication of integration statement. Such statements tell the customers which specific Use Cases and integration profiles a given system is designed to support. + Reference implementations are used. - Integration metrics are only used indirectly.
Testing	+ Uses the Gazelle testing platform for conformance testing, interoperability testing and documentation. + Hosts of annual recurring Connectathons. + Uses rigorous test specifications which are derived from the integration profiles. These are comparable (but not based on) BAIoPs. + Publishes the test results.

3.2. Case Study: CIM profiling and proof of interoperability within the scope of CIM IOP test activities (CIM Connectathons)

3.2.1. Background

DIN-Connect is an innovation promotion program owned by DIN and DKE as national IEC-Bodies. It aims to promote innovation using the instruments of normalization and standardization. New standardization projects are to be initiated and innovative research results transferred to the market. Consequentially, the so-called *Anwendungsregel* (application rules) do not serve the purpose of standardization, but rather the provision of guidelines in accordance with common best practices and standards in order to facilitate the industrial adaption [33].

The application rule on "*CIM Profiling and proof of interoperability within the scope of CIM interoperability test activities at CIM Connectathons*", therefore, aimed to adapt and facilitate the learnings from IES with a special focus on CIM and CIM profiling. However, the objective was not to develop a separate approach, but a guideline that integrates the CIM profiling activities appropriately into the overall IES process. Accordingly, the Technical Frameworks and their integration profiles, which were developed under the guidance of this application rule, can be fully integrated and jointly managed within the scope of IES activities.

3.2.2. Approach

This application rule describes the necessary measurements and a standardized process for the development and documentation of CIM-based interoperability profiles, the prequalification of test processes and the actual validation of interoperability within the scope of Connectathons. The general process consists of four consecutive phases, shown in **Figure 12**.

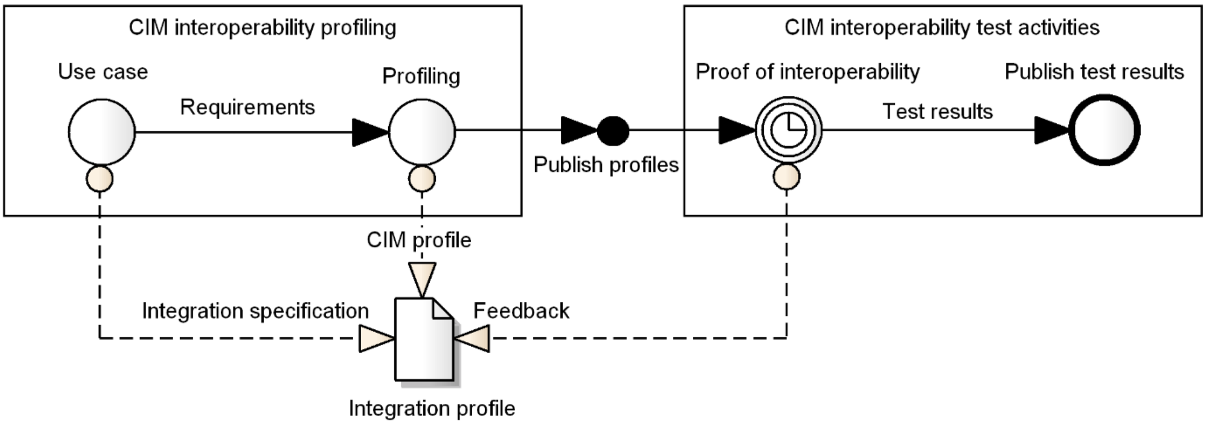

Figure 12 The DIN-Connect methodology

Since CIM profiles by-design provide technology-neutral or generic information objects, individual information objects can be interpreted differently in different Use Cases despite contextualization of their content.

Phase 1 "Use Case" is to be understood as a precondition and phase 4 "Publish test results" as a mandatory post condition of the CIM interoperability test activities. The first two phases of "CIM interoperability profiling" include the following activities:

1. Use Case: First of all, business Use Cases have to be identified, which require communication with other systems and therefore have an IOP relevant Use Case.

- Description of the business scenario and the functions required for implementation (Business Functions).
- Identification and description of the system boundaries, system context and requirements.
- Description and specification of the concrete business functions and the actors involved.
- Specification of the communication processes or transactions required to implement the business functions.

2. CIM profile: It must then be specified (and possibly identified) how the interoperability problem previously identified in the business Use Case can be prevented or eliminated.

- Specification of transaction contents as CIM profile.
- Specification of the transactions as an interoperability profile.
  a. Splitting the CIM profile into payloads.
  b. Adding CIM headers and technical connection setup.
- Generation of instance data for prequalifying interoperability tests.

Interoperability tests require that two manufacturer-independent systems have their respective counterparts implement the same integration profile. For this purpose, it is mandatory to publish the integration profiles developed in phase 1 and 2 in a publicly accessible way. This allows a third party (with reasonable preparation time) to implement these.

3. Interoperability testing: After the specified integration profiles have been implemented by several independent systems, interoperability can be tested in the scope of Connectathons.

- Use Case-based testing of prototypes and the independently implemented integration profiles.
- Specification of test cases and test sequences according to the integration profiles.
- Creation of test cases, procedures, descriptions and criteria within the test environment.

4. Test results: The test results of the Connectathon are to be published for each participant.

- Freely available publication of the interoperability test results of all participants.

3.2.3. Summary

With its holistic approach the IES addresses with its Technical Frameworks all levels of interoperability, which can be classified in accordance to the GWAC-Stack as depicted in **Figure 13**.

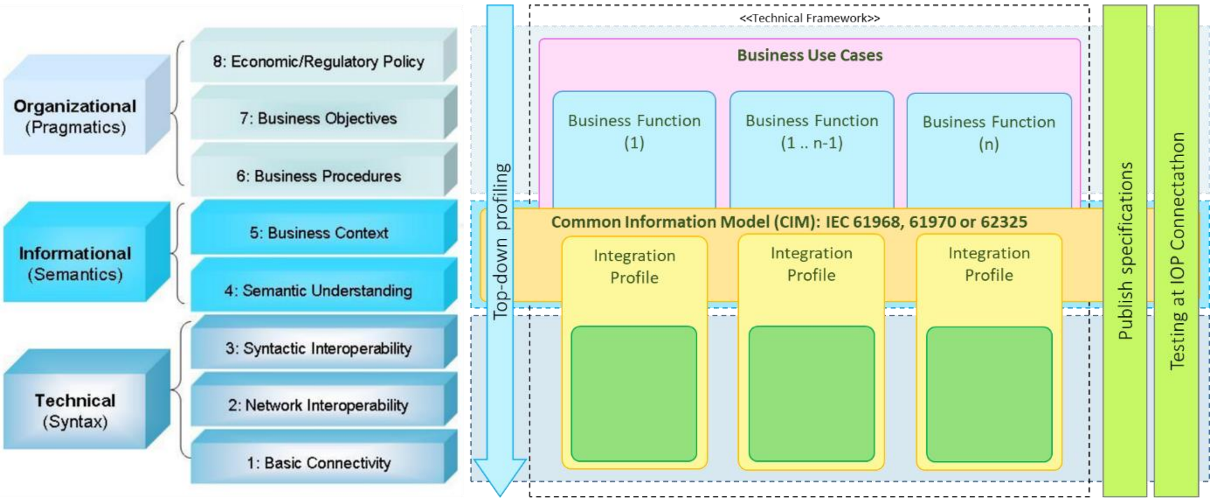

Figure 13 Case Study: DIN-Connect categorized in accordance to the Interoperability Context-Setting Framework

Table 2 provides a consolidated overview of the key characteristics of the IES approach.

Table 2 Case Study: CIM Profiling and Connectathons summarized key characteristics and information

Case Study	CIM profiling and proof of interoperability within the scope of CIM IOP test activities (CIM Connectathons)
Location	Germany, DKE as national IEC-Body
Duration	2019
Homepage	https://www.dke.de/de/mitmachen/foerderprogramme/din-connect [Accessed: 20-Jul-2020]
Management	+ Community driven based on industrial interests. + Joint identification of interoperability-relevant business Use Cases and functions.
Documentation	+ Recommends public repositories. + Uses the IEC 62559-2 Use Case Template. + Uses Technical Frameworks. + Uses only CIM standards based on IEC 61970, IEC 61968 and IEC 62325.
Integration	+ Reference implementations are used. + Expects instance data (of the respective profiles) for automated conformance tests as pre-qualification.
Testing	+ Recommends a community driven and rigorous testing process and general conditions in compliance and within the scope of IES Connectathons.

**The Case Study does not provide the required means, but references the requirements defined in the IES initiative and supplements those with CIM-specific traits.*

3.3. Case Study: SGILab of the Joint Research Centre (JRC) of the European Commission

3.3.1. Background

The Smart Grid Interoperability Laboratory (SGILab) of the Joint Research Centre of the European Commission [34] with locations in Petten (Netherlands) and Ispra (Italia) is a platform to enable interoperability tests for Smart Grid components. This is done in the form of experimental procedures, simulations and emulators according to accepted standards. The SGILab is a hardware laboratory with different storage devices, loads and generators, which map the power grid by means of various simulations and also implement the ICT infrastructure and test new business cases and services. It is also linked to other hardware labs in the Netherlands and Italy (partly with simulators to provide distribution and transmission networks).

The goal of the hardware laboratory is to provide a real-time simulation for the power grid so that hardware tests can be performed to verify that the components can be integrated into the power grid and that they are interoperable. External manufacturers will also be given access to test their products for interoperability.

3.3.2. Approach

The JRC Smart Grid Interoperability Lab focuses more on the interoperability of technological (hardware / software) implementations according to proposed standards used in conjunction with applicable reference architectures.

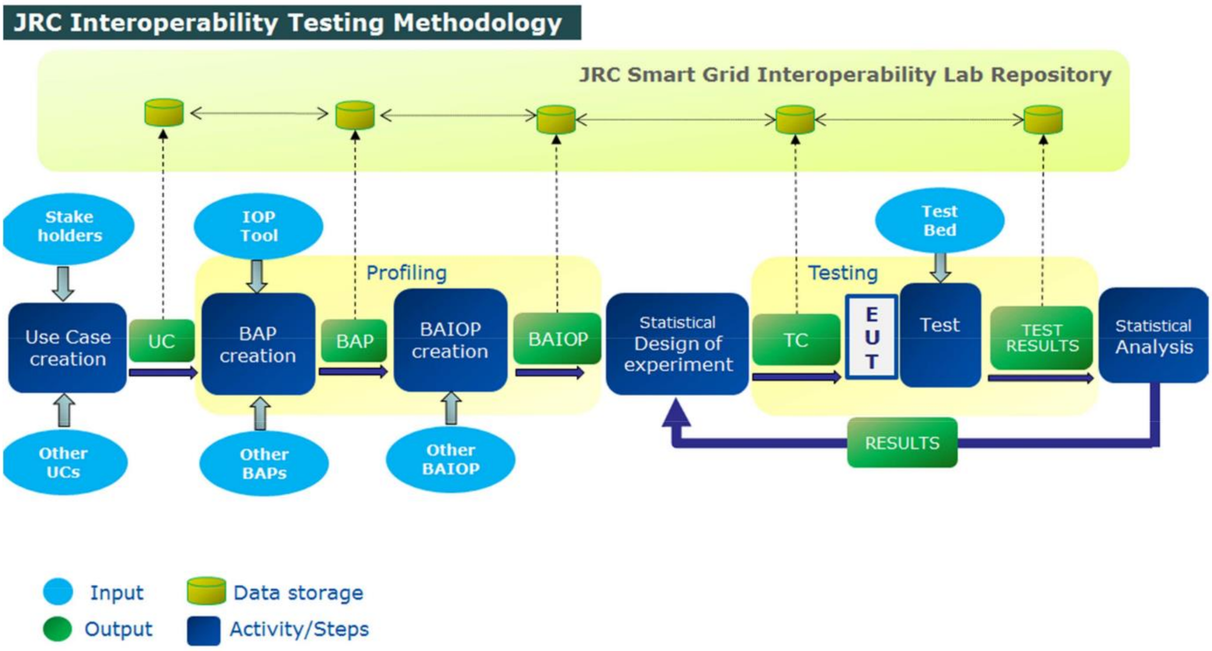

Figure 14 The SGILab interoperability testing methodology [34]

As

Figure 14 shows, this approach consists of a six-step process (extracted from [34]):

1. Use Case Elaboration: Description of the functionality of physical devices in the form of Use Cases, which should be tested in a special case.

- Specify the first set of Use Cases that can be performed in the laboratory, based on the availability of test beds and on the methodology of interoperability testing.
- Selection of the *Equipment Under Test* (EUT): Define a physical device that communicates with other devices.

- Existing repositories should be examined and existing Use Cases selected. In this phase, the contributions of Smart Grid actors and Use Cases repositories, as shown above, will be used.

2. Basic Application Profiles creation.
    - Related to the described functionality in the Use Cases BAPs are created, which are used as Building Blocks to implement a standard.
    - Selecting the standards applicable to the specific profile.
    - Profiling of the semantic and syntactic models: specify in detail how a particular standard (or set of standards) is to be used and which options from the standards are used in which way.

3. Basic Application Interoperability Profiles creation.
    - Selection of test cases for the described functionality in relation to the BAPs.
    - This extension contains, to add: the device configuration, the test configuration with communication infrastructure (topology), the BAP related test cases, the specific capability descriptions and the engineering framework for data modelling (instances) and the communication infrastructure (topology, communication service mapping)
    - Definition of number of BAIoPs based on BAPs possible combinations.

4. Statistical Design of experiments (DoE):
    - By means of Use Cases, BAPs and BAIoPs, test cases are specified for the physical devices, providing step-by-step instructions for execution.
    - In addition, the accompanying test documentation is created.
    - Assemble the experiment: The external conditions for the test are analyzed and provided in the laboratory to make the test results comparable.

5. Testing
    - Conformance testing: The implementation/device in concern is tested against a test tool or a reference implementation of the respective standard.
    - Interoperability testing: Verify that implementations actually work and interact effectively to achieve the expected results.
    - Simulating or imitating real-world scenarios to detect potential functional or communicational incompatibilities and to illustrate the effects of a lack of conformity or compatibility.

6. Statistical Analysis of experiments
    - Analysis of test results and experiment design.
    - The results are documented and the Use Cases, BAPs and BAIoPs are adjusted if inaccuracies or errors are detected during the tests.

3.3.3. Summary

With its holistic approach, the SGILab addresses the semantical and syntactical interoperability, which can be classified in accordance to the GWAC-Stack as depicted in **Figure 13**.

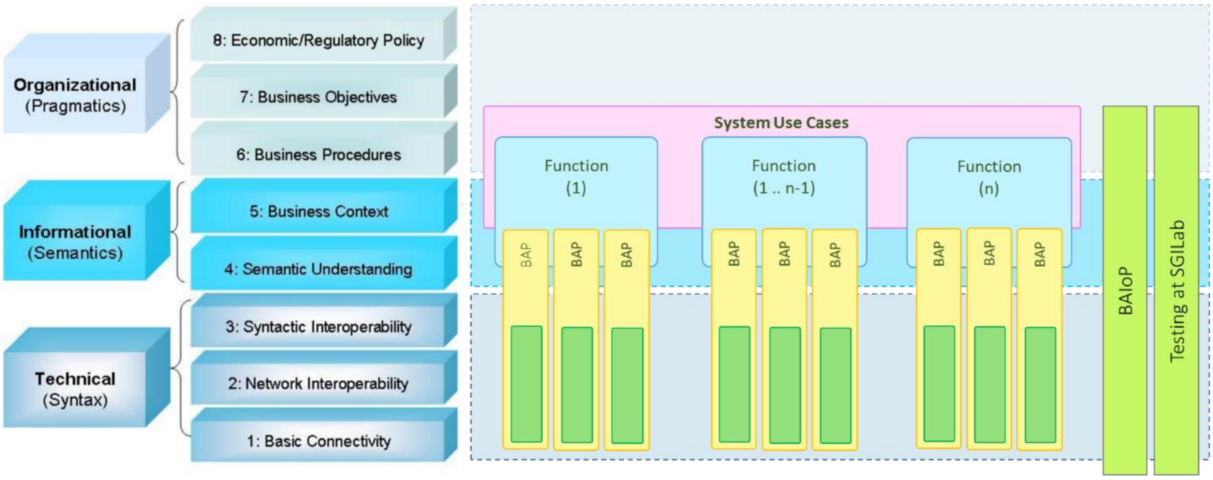

Figure 15 Case Study: SGILab categorized in accordance to the Interoperability Context-Setting Framework

Table 3 provides a consolidated overview of the key characteristics of the IES approach.

Table 3 Case Study: SGILab summarized key characteristics and information

Case Study	SGILab of the Joint Research Centre (JRC) of the European commission
Location	Petten, Netherlands and Ispra, Italia (EU)
Duration	2010 (ongoing)
Homepage	https://ses.jrc.ec.europa.eu/sgil-petten [Accessed: 20-Jul-2020]
Management	+ Uses public repositories. - Managed by project agreements.
Documentation	+ Uses public repositories. -/+ Uses SGILab Use Case-Templates (an adoption / deviation of the IEC 62559-2 Use Case-Template), which focuses on the semantic and syntactic interoperability. + Uses SGAM and UML. - Does not specify the organizational interoperability.
Integration	+ Uses SGILab Use Case-Templates which focuses on the semantic and syntactic interoperability. + Uses reusable integration profiles based on BAPs. + Reference implementations are used. + Integration metrics are recorded.
Testing	+ Uses a testing platform for conformance testing, interoperability testing and documentation. + Uses strict test specifications which are derived from the integration profiles (BAIoP). + Analysis and publication of test results. - Does not test the organizational interoperability.

3.4. Case Study: H2020 InterFlex project

3.4.1. Background

The H2020 Interflex project [35] explored pathways to adapt and modernize the electric distribution system in line with the objectives of the 2020 and 2030 climate-energy packages of the European Commission. Six demonstration projects were conducted in five EU Member States (Czech Republic, France, Germany, the Netherlands, and Sweden) in order to provide deep insights into the market and development potential of the orientations that were given by the call for proposals, i.e., demand-response, storage, and energy system integration.

A methodology was defined, based on the SGAM to compare six different demonstrators in five EU member states. In particular, an SGAM clustering approach was set up in order to group devices and actors within common entities. The results of this analysis showed that the Use Cases and interfaces were comparable between the demonstrators, but the chosen solutions or protocols were specific to each demonstrator. This analysis also highlighted that real connections between devices are always orthogonal: domains are crossed in the same zone (horizontal link), and zones are crossed in the same domain (vertical link). As a result, two main alternatives were identified to realize a diagonal link: the "upper-bound" alternative connects the domains at a high-level zone (operation, enterprise, or market), while the "lower-bound" alternative connects the domains at a low-level zone (field, station or process).

Various flexibility services defined according to demo Use Cases were validated at AIT's SmartEST [36] and Digital Labs in order to assess the interoperability between involved components and sub-systems including the flexibility, the flexibility requestor and the aggregator. Four case studies were conducted which explore the activation of flexibilities to provide voltage support and congestion management. These tests were performed based on hardware-in-the-loop techniques. Furthermore, two case studies were performed in order to evaluate the interoperability based on the specific hardware device used for flexibility. A major feature of this test was that it was conducted remotely, the test was initiated locally (Austria), with access to the hardware located at an alternative location (Netherlands).

3.4.2. Approach

The study includes the assessment of six case studies that have been analyzed from the interoperability perspective and in accordance with the SGAM approach. Within InterFlex, the DSO oriented flexibility services required communication between the DSO and several devices which were facilitated through an intermediate actor, thereby, defining the upper and lower bound architecture.

1. Use Case development: Once these architecture models were defined, six case studies were developed based on the JRC Smart Grid Interoperability validation methodology [34] in order to define the test cases which consider voltage support and congestion management based on the upper and lower bound architectures. An overview of the methodology is shown

in Figure 16 [37]. The methodology is also used to develop the profiling procedure based on the BAP and the BAIOP.

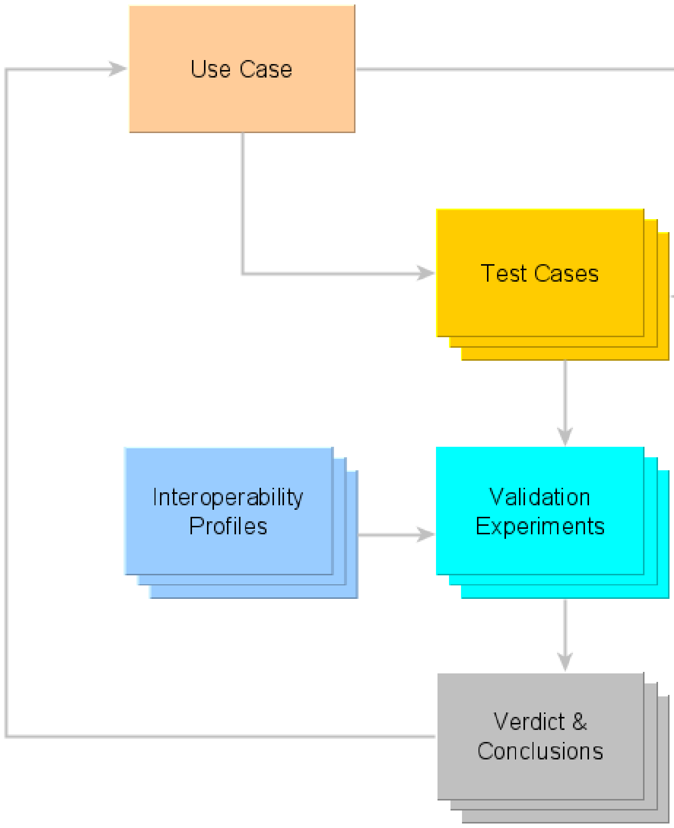

Figure 16 InterFlex Interoperability testing methodology [37]

2. Flexibility architecture: The flexibility architecture was developed based on the specifications of the project. A description of each of the architectures is described as follows:

- An aggregator (or energy management system), which is connected to the DSO from the Enterprise or Market layer on the SGAM. The aggregator is then responsible for the connection to the specific device within the DER or Customer premise on the SGAM. This is considered as the upper bound approach as the cross-domain connection is made at the upper zones.
- A *Remote Terminal Unit* (RTU), which can be owned and/or operated by the DSO, allows for a local connection to the device within the Field zone. This is considered the Lower bound approach, as the cross-domain connection is made at the lower zones.

3. Interoperability profiles: Once the Use Case creation phase is complete, the BAPs are defined according to the respective communication technologies which have been implemented in InterFlex, with the consideration for possible future technologies. Once the BAPs have been defined, the respective BAIOPs are being specified according to each of the respective interfaces considered in the Use Case.

4. Test cases: For each of the architectures, i.e., upper and lower bound, the exchange of information between the DSO and the Device depends on one or more communication links. In line with the various communication technologies available, an evaluation with respect to their relevancy from the perspectives of each of the actors is conducted.

5. Validation experiments: The validation tests were set up and conducted within the AIT SmartEST [36] and Digital Lab after the construction of a testbed. The testbed is designed and

set up according to each of the specific use cases with the consideration for the requirements of respective actors and corresponding interfaces that were validated.

3.4.3. Summary

Table 3 provides a consolidated overview of the key characteristics of the AIT approach.

Table 4 Case Study: SGILab summarized key characteristics and information

Case Study	**H2020 InterFlex project**
Location	Austria, EU
Duration	2016 to 2019
Homepage	https://interflex-h2020.com/
Management	+ Managed by project agreements.
Documentation	+ Sufficiently documented + Integration is reputable with predictable efforts + Reference implementation exists + Uses well established BAP interfaces
Integration	+ Testing plan and test cases exists + Uses experimental validation using the real-time power grid simulator (OPAL-RT)[1] + Network emulator (NRL CORE) + Physical ICT network with Ethernet switch and cables +Co-simulation message bus and co-ordination components (AIT Lablink)[2] + HIL Co-simulation message bus and co-ordination components + Considers BAIOPs for rigorous testing
Testing	+ Uses the IEC 62559-2 Use Case-Template. + Uses SGAM and UML. + Uses Technical Frameworks. + Uses public repositories whenever possible. - Some parts have restricted access.

4. Gap Analysis

For an appropriate gap analysis, the diversity of the different aspects that contribute to a sustainable interoperability must be considered equally. Although it has to be taken into account that all aspects are mutually complementary, the analysis requires a distinction between the governance, the methods and frameworks that are designed to promote interoperability and the actual implementation of the systems.

In order to provide a more comprehensive overview of the consolidated results in **Table 5**, a distinction was made between those methods which can be regarded as widely established by corresponding de facto standards and those potential methods which have been successfully tested but have not yet been widely adopted in the energy sector.

[1] "OPAL-RT technologies," [Online]. Available: www.opal-rt.com/. [Accessed January 2021].
[2] Austrian Institute of Technology, "AIT Lablink," [Online]. Available: https://github.com/AIT-Lablink.

Table 5 Methodologies classified in accordance to the SG IMM requirements and interoperability categories

		De facto standard				Future opportunities		
Interoperability level	Governance area	IEC 62559-2 Use Case methodology	SGAM	Integration Profile (e.g. BAP)	Test specification (e.g. BAIoP)	(Technical) Committee (community driven)	Technical Framework (consolidated)	Connectathon (or plugfest)
Organizational	Management					(++)		
	Documentation	++	+				(++)	
	Integration	+	+	+			(++)	(+)
	Testing				+			(++)
Informational	Management					(++)		
	Documentation	+	+	++			(++)	
	Integration	+	+	++			(++)	(+)
	Testing				+			(++)
Technical	Management					(++)		
	Documentation	+	+	++			(++)	
	Integration	+	+	++			(++)	(+)
	Testing				+			(++)

++	Issue is fully considered as defined by the SG IMM
+	Issue is partly considered as defined by the SG IMM
	Issue is not considered as defined by the SG IMM

Management Although it can be observed in the various initiatives and projects that the management of standards, documentation, integration and testing is usually handled in a project-specific manner, initiatives such as IES (or e.g. the ENTSO-E for TSO communication) can be identified as exceptions. However, the energy domain lacks an overall accepted, collaborative and community driven governance which supports the development and documentation of adequate *Technical Frameworks* and respective integration profiles in accordance to community requirements and provides the necessary means for integration tests.

Management requirements / potentials based on identified best practices:

- Provision of a repository for Technical Frameworks.
- Integration profiles / Technical Frameworks are published and freely available to foster a wide adoption by industry.
- Integration profiles / Technical Frameworks are managed in collaboration by the community to foster the overall acceptance of the industry.

Documentation As **Table 5** shows, the energy domain already provides most of the necessary methods. However, although these methods complement each other, they are often considered independently. For example, the concept of the *Technical Framework* is not superior to existing methods, but provides a higher-level structure to harmonize the individual artefacts of the individual methods in a more standardized and structured fashion, which consolidates all interoperability levels and serves as a full-fledged integration guide.

Documentation requirements / potentials based on identified best practices:

- Are always based on established standards or best practices to prevent proprietary solutions.
- Concretize the applied standard and only specify mandatory aspects to prevent interpretations.
- Adoption of Technical Frameworks:
  Although the application or development of profiles are common in the energy sector, such profiles usually focus only on semantic and syntactic interoperability of a system Use Case. The missing perspective on pragmatic interoperability can be adequately complemented by the IEC 62559-2 Use Case-Template and the SGAM methodology.
  However, in order to specify the relationships and to promote a consistent and standardized higher-level structure between the individual documents with regard to the system Use Cases of the profiles, the business Use Cases and business functions, the additional usage of Technical Frameworks is recommended.

Testing As the IHE shows, an annual *Connectathons* or *Plugfests* contributes to the continuous and community driven improvement of the specifications and the general acceptance by industry. The IES case study showed that this holistic approach also works in the energy system and has received positive resonance.

Testing requirements / potentials based on identified best practices:

- Periodical organization Connectathons or Plugfests where independent manufacturers can test their practical interoperability against each other.
- Use conformance testing as a prerequisite for interoperability testing.
- Add test cases, procedures, description and criteria to the test environment / platform based on the demands of the community.
  - Execute interoperability test cases with at least two independent peer vendors.
  - Validate recorded messages / traces and log evaluated test results.
  - Documenting and publishing the test results of the Connectathon for each system and tested Use Case.

Integration Integration profiles or specifications are a crucial part of the documentation, for testing and, consequentially, for the repeatable Integration with predictable effort.
However, interoperability is traditionally realized bottom-up – from the technical level to the organizational level.

Integration requirements / potentials based on identified best practices:

- Development and usage of integration profiles (e.g. BAPs).
- Usage of profile- and Use Case-based simulators to enable pre-qualifying tests and to reduce basic errors in advance.
- Adoption of test specifications (e.g. BAIoPs) as an integral part of integration profiles / Technical Frameworks, which contains the creation of test cases, procedures, descriptions and criteria within the test environment.

5. Comparative Summary

Although, the capability for seamless integration is subject to many challenges, the problem, however, is not the lack of adequate standards – suitable standards, solutions and/or best practices are available for the energy domain. The problems arise because of the absence of a governance and its resulting implications. The lack of an authority which has “control” over the system-of-systems prevents the development of holistic and system-independent solutions. Moreover, the wicked complexity of the problem makes it increasingly difficult to find a consensus beyond the lowest common denominator [1], [2]. However, it can be observed that community-driven management approaches are suitable alternatives to cope with this kind of wicked problem. This way, not only the IHE initiative has been able to establish itself as a driver for interoperability in the health care sector, but the IES project showed that this approach is also finding positive resonance in the energy sector. In this respect, the community-based approach does not only increase the general acceptance, but also facilitates the ability to adapt to changing business needs and technological developments by an increased agility compared to traditional standardization bodies.

Furthermore, it must also be taken into account that no standard or key concept alone can guarantee interoperability. For example, CIM or IEC 61850 describes suitable information models that are able to represent the relevant Use Cases, but they do not define a context and therefore do not guarantee pragmatic interoperability. The case studies and the experiences from the healthcare sector show that these individual methodologies complement each other and in combination are able to improve interoperability significantly. For example, the IEC 62559 Use Case Methodology is suitable to provide the context on an abstract business Use Case level as well as on a more concretized system level Use Case for the implementation of business functions by defining precise communication processes in a structured way. However, the IEC 62559 Use Case Methodology is only suitable to a limited extent for defining the individual transactions of a business function, so that the complementary use of interoperability / integration profiles is recommended. As this in turn leads to a variety of inhomogeneous documents representing different aspects of the interoperability requirements, a unified structure seems to be appropriate, as the Technical Framework of the IHE or the IES initiative shows.

Consequentially, the key concepts do not serve to develop missing standards, but to facilitate the coordination of interoperability issues between the constituent systems. In this way, the concept of profiling / documentation can be highlighted from both theory and practice as the core principle that requires appropriate governance, serves as the basis for test activities. In order to perform interoperability tests beyond simple conformance tests, it is required that two vendor-independent systems have implemented the same integration profile of a Use Case. For this purpose it is mandatory to publish the integration profiles in a freely accessible way which allows a third party (with appropriate preparation time) to implement the profiles and to test them against each other within an appropriate test event. The Connectathon (sometimes referred to as Plugfest) is an annual event that brings together the various providers who have implemented the previously published integration profiles. In accordance to the IHE all test runs are evaluated by independent experts. Once a system has successfully passed all necessary tests, the vendor is allowed to publish an Integration Statement. Such statements tell the customers which specific Use Cases and integration profiles a given system is designed to support. Furthermore, the results of the Connectathon are not only used to validate products, but also to validate and improve the integration profiles for future iterations itself and, consequentially, in combination substantially reduces the distance for integration.

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Appendix – Structure of Technical Frameworks

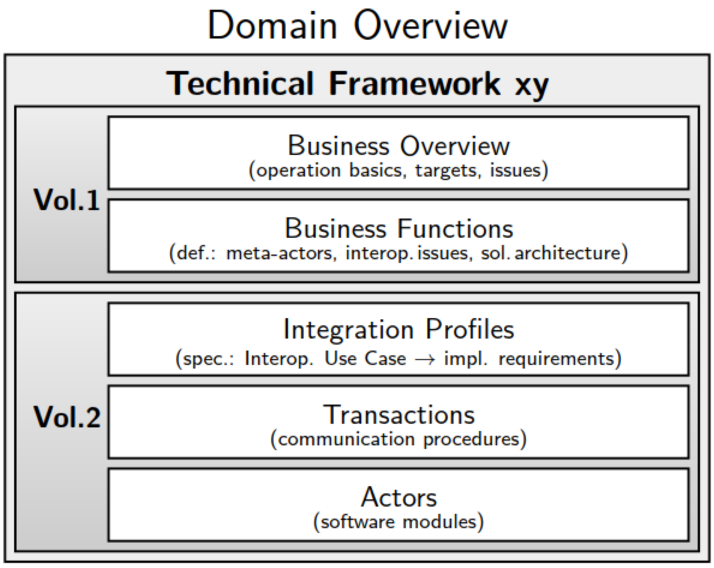

Figure 17 Structure of a Technical Framework [31]

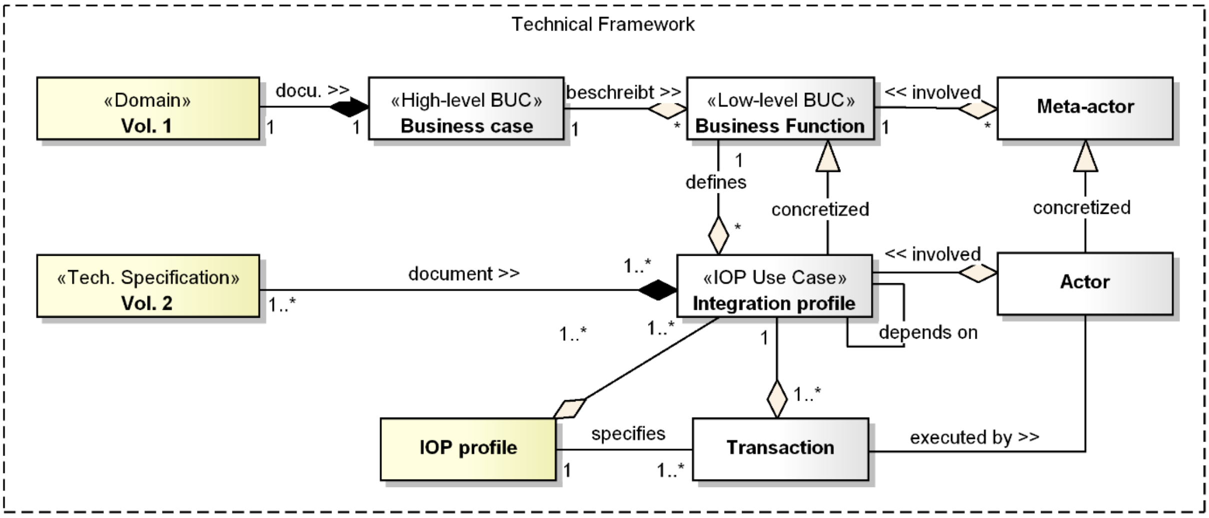

Figure 18 Structure of theTechnical Framework (as an UML structure diagram)