Adopting the IEC Common Information Model to Enable Smart Grid Interoperability and Knowledge Representation Processes

N. B. Hargreaves, S. M. Pantea and G. A. Taylor

Abstract Information interoperability is a key process underpinning the development of flexible and efficient electrical networks capable of integrating large-scale renewable and conventional energy technologies into smart grids to supply consumers with sustainable energy. The smart grid concept requires technologies ranging from smart meters to utility-level energy management systems to share information on an unprecedented scale. The availability of data and information about grid systems will also increase dramatically as the smart grid develops but its value and usefulness will depend on the degree to which it can be formed into representative knowledge of the real smart grid. At the heart of power utility and smart grid information interoperability is the IEC Common Information Model (CIM), a suite of open international standards addressing energy management, asset management, and market systems. This chapter discusses the philosophy and processes underpinning smart grid information interoperability to enable power utilities to build and control the emerging smart grid and it elaborates upon how the CIM fits within a standardized power system interoperability framework. It will explain how model-driven information integration using the IEC CIM can be implemented by utilities to leverage the value and validity of data into realistic knowledge representations of smart grid reality and address the need for situational awareness, business intelligence, and process efficiency.

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1 Introduction

The grand vision for sustainability can be accredited to The Club of Rome's report, "Limits to Growth" [1] for setting the stage upon which environmental sustainability was raised as a crucial issue alongside the economic development of society. Its theme was later championed by the UN-sponsored Earth Summit in Rio de Janeiro in 1992. Since then, in various legislative guises, sustainability has been receiving mixed acceptance into the *triple bottom line* of economics, society, and the environment. In recognition of the centrality of energy to all of these considerations however, there is a general acceptance of the need to link energy conversion and transfer with sustainability. The chapters of this book testify to the current pursuit for sustainable energy being an essential pillar supporting our continued presence on Earth, alongside others such as biodiversity and the availability of environmental services perhaps. The smart grid, as a principal means of integrating the conversion processes and transport of sustainable energy, addresses many of the parameters we associate with this new paradigm, including decarbonization, security of supply, energy security and infrastructure lifecycle refresh. It is thus an essential element in our pursuit of sustainability. What makes the smart grid *smart* is its ability to flexibly respond to changes in both supply and demand while maintaining an optimum economy and reliable service. This would not be possible without a high degree of intelligible interaction, known as *interoperability* between its many systems and their components. The "integral component" of interoperability is effective information exchange, which like a shared language in linguistics enables parties speaking different native languages to understand each other. *Understanding* in this case depends on a common semantic model, syntactic agreements for message composition and knowledge of the context to which the information exchange is associated. Development of the International Electrotechnical Commission (IEC) CIM aims to satisfy these essential requirements for enabling interoperability in support of a functional smart grid. However opportunities arise from wide deployment of common semantic model-driven applications, to leverage the value of data and measurements made for situational awareness into a closer representation of smart grid reality. Such knowledge representation reinforces the possibility that the smart grid could herald our evolution in energy management from the "age of information" into the "age of 'intelligence," a vision shared by the "Internet of Things" concept which is just as dependent on a semantic backbone [2]. This chapter will discuss these issues and present the theory behind interoperability in the context of the smart grid as well as the IEC CIM as an evolving core semantic model standard supporting smart grid interoperability and knowledge representation.

2 The Smart Grid Concept

The smart grid has been described as a *cyber-physical* entity, which reflects the emergence of an increasing interdependence between the “hard” and “soft” infrastructure it is made up of [3, 4]. A striking contrast between electricity networks of the past and present is the rapid rise of data availability from a wider range of sensing technologies. Notwithstanding the advancements in network and generation processes, these are driving the rapid reformation of the modern electricity industry. Tighter integration with market, service, and consumer domains is being enabled but extension of the scope of the smart grid to other energy prime movers such as gas and possibly water is conceivable in future. Management of the smart grid is challenged by the increase in data volume and the requirement for interoperability. For example, some 50 million electricity and gas smart meters are to be installed in the UK alone in the next 7 years. The smart grid requires a guiding intelligence that extends from domestic to transmission voltages across generation to service provider domains. Its reflexive nature, supported by Information and Communications Technology (ICT) systems, is undisputed [5].

Electricity transmission networks are already smart but with the addition of renewable and Variable Energy Resources (VERs), Distributed Energy Resources (DERs), and Advanced Metering Infrastructures (AMIs) a holistic approach to conceptualization of the smart grid is necessary, covering not only the domain of transmission but also distribution, storage, generation, markets, service providers, and customers [6]. To establish the role and importance of the CIM and associated standards in the information networks that support operation of the physical electricity networks, it is necessary to frame them within the smart grid concept. In practical terms, this understanding is also essential to making the business cases necessary to justify investment in the changes to power utility information architecture and infrastructure. In responding to the greater flexibility and responsiveness called for in smart grid capabilities these business cases acknowledge the need to manage and leverage the value of the increasing amounts of available data that will not be possible without an established standards framework relating to generally agreed conceptual models of what the emerging smart grid actually is [7].

The origins of the smart grid concept have been described in [8] and the US Department of Energy (DoE) initiating research and development [9], with outcomes such as the Electric Power Research Institute (EPRI) *Intelligrid* programme. The strategic prerogatives for sustainable energy and security, functionality, and management of electricity networks have formed the basis of smart grid development initiatives around the world [10–13]. In [14] the European Commission (EC) views the smart grid as having an essential role in achieving the “20/20/20 Targets” set for the European Union (EU) countries. EC mandate M/490 is the umbrella directive for smart grid development coordination and has driven the formation of the Joint Working Group (JWG), also known as the “Smart Grids Coordination Group” (SC-CG), comprising CEN, CENELEC, and ETSI standards development organizations. Previous EU mandates already existed for the development of open smart metering standards (M/441) and electric vehicle charging standards (M/468). These initiatives lead us to a broad functional definition of a smart grid having at least the following characteristics:

- Maintains and enhances security of supply (self-healing).
- Facilitates connection to low carbon generating plant.
- Enables innovative demand-side technologies and strategies.
- Facilitates further consumer choice over energy management by providing tariff-based choices.
- Features a holistic communications system providing greater clarity of the grid state and allows it to operate in a way coherent with its decarbonization priorities (reflexive).
- Allows optimization of cost and carbon impacts upon networks.

Given its broad scope, which effects millions of stakeholders and draws upon massive investment to realise, it is imperative that the conceptual models drawn from different viewpoints of the smart grid are widely accepted and established as reference architectural standards. Reed et al. highlight this point by indicating, while different players define the smart grid according to their particular perspectives, it will be difficult to arrive at consensus on gaps in standards and technologies without a standard definition [15]. Two models are continuing to converge and form the dominant standard for high-level smart grid conceptual reference architectures however. These are the National Institute of Standards and Technology (NIST) "Conceptual Architectural Framework" [16] and the EU SG-CG "Smart Grid Reference Architecture" [17]. The NIST framework is based upon seven interoperating domains comprising, "Bulk Generation, Transmission, Distribution, Customer, Operations, Markets and Service Provider." The SG-CG architecture, or Smart Grid Architecture Model (SGAM), generally corresponds to the NIST reference architecture but has extended it with the addition of an eighth domain for "Distributed Energy Resources." Its three-dimensional presentation reflects the flexibility of the smart grid in a range of manifestations from centralized to noncentralized, as well as accommodating forward-looking local area energy systems such as micro-grids.

3 The Theory of Interoperability

Rather like the Internet, the smart grid is a coupled "system of systems" requiring strong coordination across the participating domains and their subsystems. The NIST and SG-CG reference architectural models reflect the need for a disparate number of technologies and functional domains to interoperate effectively. Different definitions of *interoperability* exist but in the context of the smart grid it should incorporate the following characteristics:

- A capability between two or more systems, networks, organizations, applications, components, processes, or devices to exchange meaningful information that is readily usable.
- A shared understanding of the exchanged information.
- An expectation of the response to such information that is agreed upon.
- A requisite quality of service in terms of security, reliability, and fidelity even though the information may be exchanged over different systems, infrastructures, or regions.

The GridWise® Architecture Council (GWAC) was formed by the US DoE to lead on promotion of interoperability between the entities in the USA that make up the smart grid in recognition of interoperability as a key enabler of the smart grid as a whole. The GWAC "Stack" methodology [18] has now been adopted by NIST and the SG-CG as an interoperability reference framework between the different domains and actors in their models. By being integrated into the dominant conceptual reference architectures this interoperability framework has become fundamental to our conceptualization of smart grid interoperability. Although not standardized in itself and modifiable to suit the context, it remains an important reference to what we mean by interoperability. The GridWise® vision acknowledges the premise that ICT will revolutionalise the planning and operation of the power grid, just as it has in other business domains (such as healthcare, telecoms, and finance), and that ICT will form the *nervous system* that integrates smart grid technologies.

The GWAC Stack comprises eight levels in its conceptualization of *end-to-end* interoperability, ranging from "Basic Connectivity" at the physical level of component interoperability to "Economic/Regulatory Policy" at the organizational level where it incorporates Business Objectives and Procedures. "End-to-end" interoperability is a term used to describe effective interoperability across all levels between its extremities. It is within the *Informational* layers of "Business Context" and "Semantic Understanding" in the middle of the Stack, that the IEC CIM can be deployed. These layers form the bridge that transfers meaning in the form of *syntactic conformity, semantic understanding*, and *context* from the signals arising from the lower technical layers (mainly concerned with physical interoperability), upwards to the Business Objectives and Policy layers at the top of the Stack. This is of critical importance as it is necessary for the business components involved at each level to share information between themselves and others (as in an enterprise-to-enterprise scope) in order to achieve their tactical and strategic objectives (Fig. 1.) This can only happen if they are working in a sympathetic and federated manner across their boundaries of jurisdiction with full understanding of message content and close conceptual conformance with actual reality.

Any "standard approach" to interoperability must be scalable and be able to recognize agreements established at component interfaces as well as boundaries of jurisdiction. Scaling-up will inevitably encounter hierarchical, organizational, and structural challenges, such as when different business domains interoperate or integrate with an Enterprise Data Model (EDM) because of the use of different

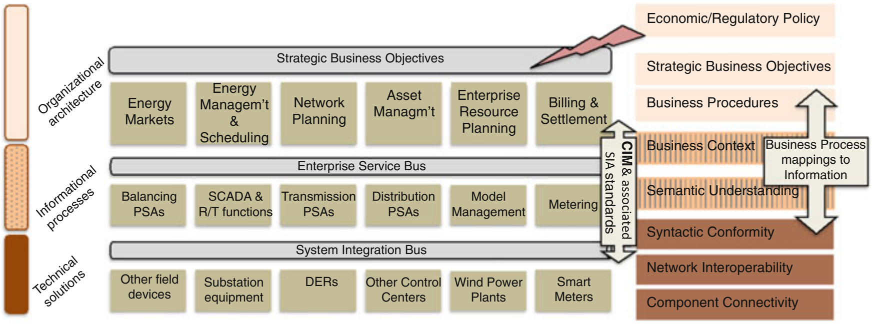

Fig. 1 A Typical smart grid organizational architecture identifying the role of the IEC CIM in supporting end-to-end interoperability

models. In the case of wider manifestation of the smart grid such as with system operation and intersystem operation [19], it will also be necessary to interoperate across enterprise boundaries. A Transmission System Operator (TSO) will have to interoperate with Distribution Network Operators (DNOs), requiring novel infrastructure protecting security, privacy, and service level agreements [20]. Nevertheless, from a resilience point of view, the smart grid is also composed of small and in some cases autonomous operations, such as with DER and protection systems management, which could reduce the scope and scaling challenges. Despite the scalability of the smart grid, therefore, many of the processes to establish interoperability will be cross-cutting issues, effective at all levels of scale. Ambrosio and Widergren in [21] discuss many examples of cross-cutting issues including resource identification, time synchronization, security, and privacy that are important to establish interoperability at any level of the smart grid.

Data model exchange within the context of utility information integration is a key part of the interoperable *glue* between corporate objectives in terms of business positioning and Power System Application (PSA) solutions that facilitate the enterprise orientating as intended. It is likely therefore that the *form* of the information architecture will *inform* the function of the enterprise and raise the question of whether it is fit for purpose [22]. Such an appraisal informs the need for enterprise architecture to be coherent with corporate objectives and regulatory constraints. Connecting this concept to the “solutions level” (levels 1–4 in the GWAC Stack) of the enterprise, especially in times of rapid market change, places greater emphasis upon *information integration* and the removal of legacy system obstacles such as data silos and manual trans-literation interfaces between bespoke systems.

Tolk has addressed these concerns in his *Levels of Conceptual Interoperability Model* (LCIM), and observed that the “conceptual ideas of the enterprise and the implementation details of the systems” often do not connect [23]. This may be due to inappropriate architectural design but also that the interoperability of legacy systems within a complex multisystem architecture cannot always be *decidable* in advance. Examples of undecidable problems (there is no algorithmic solution but a result relies upon a good heuristic) include questions such as, "Is the specification complete or minimal?" "Is the order of two modeled actions independent or requiring orchestration?" In [23] Tolk proposes that the utility of enterprise architecture to fully support interoperability develops through three broad stages.

- Integratability—concerns physical and technical connectivity of systems, including hardware, networks, firmware, and protocols.
- Interoperability—concerns software and firmware to support information exchange through the use of common semantic models.
- Composabililty—concerns the alignment of the use of models as conceptual abstractions of reality for given business intentions.

The LCIM was created to present these related issues in a consistent framework that exposed six levels of interoperability, ranging from "Technical" to "Conceptual" Interoperability. These levels rise from the physical concern of infrastructure communications to the more abstract concern of the interoperability composition in meeting the objectives it was conceived for. At the center of this hierarchy we find "Semantic Interoperability" linking the "Syntactic" level to the "Pragmatic" interoperability level. The Syntactic level deals with protocol challenges while the Pragmatic level deals challenges of interpreting message patterns. The LCIM was adopted and informed the creation of the GWAC Stack framework, underpinning the centrality of the IEC CIM and the importance of ICT interoperability to smart grid control and integrity as it infuses all levels of the energy domain.

System architectures are developed to fill the gaps in enterprise capabilities. The architecture should map to the detail of the functional requirements but in a rapidly developing environment like the smart grid where there is added pressure to evolve the enterprise alongside multiple independent stakeholder interventions, the risk of Conceptual Interoperability intentions misaligning with actual interoperability outcomes are high. Tolk identifies some major practical challenges to maintaining interoperability in alignment with the overall conceptual design:

- Interoperability satisfies the needs of a limited number of stakeholders due to independent interventions and becomes unaligned with enterprise interoperability concepts.
- The implementation suffers from not being maintained in step with the latest developments.
- The diversity of smart grid developers, regulators, implementers, and other actors are not as aligned as desirable.
- Interventions of one kind have negative secondary impacts on other systems.

These are familiar concerns to system integrators within electricity utilities involved in developing greater interoperability at PSA and enterprise levels. They are especially likely to develop in situations without hierarchical supervision and coordination of stakeholder interventions and where insufficient attention is paid to cross-cutting challenges. The fourth issue is particularly relevant to the topic of resource identification. Where multiple independent actors who share a common domain exist, the opportunity for the same network entity or resource (such as a power transformer, substation, circuit breaker, or process) to be identified differently is very real. Within a single actors' model of the network, this may not give rise to ambiguity but when models are exchanged and shared with other actors the issue of resource identity can cause conflicts in semantic understanding and disrupt interoperability. It is a vexing challenge to the application of a common information model across multiple PSAs and business domains where there are multiple uncoordinated points of data entry.

3.1 Systems Engineering Interoperability

Rather like the Internet, the smart grid is a coupled "system of systems" requiring strong coordination across the participating domains and their sub-systems. Taking a systems engineering approach at the PSA-to-PSA level, the use of metadata is important in assessing the possibility for, and then supporting interoperability. Between two PSAs with a common operational intention there would be the need for three sets of metadata, one set describing each PSA and the third describing the design for the desired functionality. It is then possible for an assessment of composable interoperation between heterogeneous PSAs to be made, subject to the decidability of the interoperability outcome as previously discussed. Ralyté et al. say that due to the complexity of the interoperability challenge across multiple domains, including business and technology, it is not possible to find a solution to the decidability problem captured by a single method. They discuss a Situational Method Engineering (SME) approach to interoperability problems that involves modularized reusable *method chunks* to compose situation-specific interoperability solutions as they arise [24]. Hug et al. [25] support this view from an information systems engineering perspective and say even the use of standardized metamodels may reveal the limitations of a "one-size fits all approach" in future. This could mean, as the use and understanding of metamodels becomes more widely appreciated, we see the need for more situational metamodel engineering (SMME) to underpin process interoperability in the power industry. Such a Model Driven Engineering (MDE) approach would employ the key principles of a standardized method to building the metamodel appropriate to the situation, and a general trend toward the use of higher levels of abstraction.

Similarly, this has already started to happen within the power industry through developments involving the IEC CIM as a *domain ontology* [26]. For example, in [27], Britton and deVos recognize, "The trouble with a global information model is precisely that *global* is a pretty big area to manage." They see the value in the CIM moving from an "explicit interface specification role to a design methodology role" and the possibility for it to underpin a service-oriented architecture (SOA). SOA is a software model in which the concept of a *service* is an abstraction of a function used by an application [28]. Services either provide information, or change data from one state to another. A service is a function that may be *reusable* within a business process [29]. Once these functional components of the business process have been identified and related to a semantic model, it becomes possible to model them into an efficient structure, such as to emphasize the value of service reusability, interoperability, and open-availability of data. In this way modeling can be used to drive better understanding of business processes and further their integration within the enterprise.

3.2 Interoperability and Service-Oriented Architecture

SOA can therefore further the scope of interoperability through closer integration of Business Process Management (BPM) to reusable information message exchanges that call for different service operations. Such an approach is summarized by Soley in [30], where he sees BPM design being linked to SOA infrastructure by the “vital bridge” of Model Driven Architecture (MDA). MDA is underpinned by the use of metadata standards to adapt business process models to service requirements in a changing environment such as the smart grid. MDA, itself based on the principles of Model Driven Design (MDD) [31] can also aid in the recovery of design knowledge from existing applications through its use of standards. This approach has been adopted by McMorran et al. to develop transformation applications for CIM-structured metadata files to the Siemens Power System Simulation (PSS/E) standard for model exchanges supporting PSA–PSA interoperability [32, 33].

Another important aspect of SOA is that it opens the way for data to be shared across an enterprise by way of a web service. Web Services Description Language (WSDL) is a commonly supported means of describing the necessary interactions between a service requester and a service provider. It rests as a separate layer upon the data architecture of the enterprise, independent of the code required to implement the service but offering the potential to develop common interfaces for various types of interactions, which leverage the value of software assets as well as data resources. As this web-based approach also opens the number of data access points, security becomes a greater consideration to protect the integrity of proprietary data and system functionality.

In this way, SOA enables a looser connection to the service provider technology and enhances the scope to offer vendor-neutral solutions. In [34] Cao et al. also propose the use of the CIM within an SOA to address information-islanding problems encountered within Enterprise Application Integration (EAI) challenges. Khare et al. [35] develop this theme, describing the use of an Enterprise Service Bus (ESB) within the SOA to “simplify and manage interconnectedness.” They also describe the use of metadata within “design patterns” to support interoperability problem description and contribute to process design for common modeling practices such as CIM extension, profiling, and model validation.

Announcement and discovery of metadata underpins the ability to access and leverage the available data and services in an interoperable infrastructure. Rohjans et al. [36] propose a SOA based on the Open Platform for Communications (OPC) Unified Architecture (UA), a standardized server-client architecture specification (see IEC 62451) that embraces security, platform independence, and information models to support interoperability. Their approach brings together a general automation industry SOA solution (OPC UA) for access to real time and historical data and events, to run semantic web services that interact with the Platform Independent Model (PIM) provided by the CIM. Service descriptions are provided by metadata annotations derived from Web Service Modeling Language (WSML) ontology.

3.3 Interoperability and CIM

Neumann and Nielsen in [37] refer to *profiles*, or context-constrained sets of CIM classes that make up the Common Power System Model (CPSM) and the Common Distribution Power System Model (CDPSM) [38, 39]. These "sub-models" of the CIM are accredited standards in themselves and like other available profiles address "common integration patterns" within interoperability challenges and therefore resemble the approach to situational interoperability advocated above. The earliest releases of the IEC CIM were designed to only support interoperability of control center applications [40, 41]. As packages of classes are now added to it that refer to the operation of more diverse aspects of the smart grid, it is conceivable that "method chunks" of the reference metamodel could be applied to interoperability challenges yet to come. Effort is also being made on the harmonization of adjacent standards, such as IEC 61970 with IEC 61850 [42, 43] and IEC 60870 [44] in the interest of extending interoperability across different conceptual metamodels. The power of standards-based metadata at all levels of interoperability described in the LCIM then becomes evident, subject to the limitations of one-size-fits-all, in supporting composable solutions appropriate to the capability-requirement gaps within the enterprise architecture.

Metadata plays a key role in the absence of a fully self-organizing system of systems, in which operational systems have built-in evidence of their components' functionality, necessary for their level of interoperability to be evident to the other interoperating parties. We may currently approach this level of *self-evidence* by exploiting the built-in rules in Resource Description Framework (RDF) and Extensible Markup Language (XML) notation in "knowledge representation" [45, 46] but these form only the surface of interactions between our enterprise component systems at present. Deeper evidence of the capacity for interoperability in future could be evinced from meaning encoded into the structure of the metadata, thus raising the attraction of standard forms of metadata as in the cases of the IEC Common Information Model standards. The intention of building this kind of "structural intelligence" into our metadata models would be to make it possible to see some degree of self-organization (perhaps similar to biological systems) at the interface between interoperating entities. This degree of interoperability could then extend the current aim of “self-description” and “self-discovery” for advanced distribution automation systems for example.

4 Use Cases

Smart grid interoperability depends on standards used by the diverse range of equipment and processes it is composed of. Standards also ensure against premature obsolescence and support security implementation within the technologies they apply to. Utility PSA and equipment interface requirements have driven the need for a reference ICT standards architecture that can be mapped to the conceptual smart grid reference architectures to satisfy actor interaction requirements. The linkages between the standards architecture and smart grid conceptual architecture are *use cases.* These describe the series of events involving an actor and a technology or process, necessary to execute the intended smart grid capabilities and functions. In this sense, by forming the essential connection between a subject and its objective, the use case reflects the notion of the “subject-predicate-object” *triple* familiar within RDF notation. The scope for standards extension, modification or for new standards to be included in the reference architecture widens as the use cases for smart grid information and communications integration increase.

Use cases vary in the detail of their specification according to NIST by being either “prescriptive” or “descriptive” [16]. The latter omits the specification for the implementation of the use case but describes the actor and functional requirements of the intended goal. Rigorous definition of use cases is therefore advisable to avoid confusion not only over the objective of an intended functionality but also to limit duplication of standards development effort. The reference for defining smart grid use cases according to the EPRI IntelliGrid methodology is given in IEC Publicly Available Specification (PAS) 62559 [47]. Its application process under M/490 is given in [48]. Smart Grid use case repositories are being developed in the EU and the USA with one of the most mature managed by EPRI [49] (see also the NIST Interoperability Knowledge Base [50]).

5 Smart Grid Standards Architecture

In [16] NIST identify 75 existing standards and 15 high-priority gaps in support of smart grid interoperability, in addition to cyber-security issues, as a starting point for standards development and harmonization by standards setting and development organizations. Sixteen Priority Action Programs (PAPs) have been initiated by NIST to address areas in which standards need revision or development to complete the standards framework according to their smart grid vision. The IEC Standardization Management Board of Technical Committee (TC) 57 identified over 100 standards and standard parts in a strategic review of power system information exchange [51]. Both of these studies concluded however, that only a small number of standards lie at the core of smart grid interoperability and they can be organized into a corresponding layered reference architecture described in IEC/TR 62357 [52]. This reference SOA shows how these standards relate to each other, require harmonization and presents the gaps where further standards development work is required. In general all standards setting and development organizations advocate a collaborative approach to the development of open standards for the smart grid, with the reuse of existing standards as far as possible.

Rohjans et al. in [53, 54] conduct global surveys of smart grid standardization studies and confirm that the IEC/TR 62357 standard, also known as the "Seamless Integration Architecture" (SIA), represents a general consensus of what are the core smart grid standards, subject to two additional standards. These are IEC 61400-25 series: Communications and Monitoring for Wind Power Plants and IEC 62056: Companion Specifications for Energy Metering (COSEM). In Fig. 2, the standards groups included in the IEC SIA and the additions recommended above are shown in simplified form to support the smart grid organizational architecture of Fig. 1. The cross-cutting issue relating to cyber-security is addressed by the standards group on the left hand side of Fig. 2. The evolution of IEC/TR 62357 reflects the broadening scope of TC 57 in step with smart grid use cases from its original charter of "Power System Control and Associated Telecommunications" to "Power System Management and Associated Information Exchange." Generally this change reflects the shift in emphasis from lower level interconnection protocols to abstract information models in the higher levels of the architecture as the number of business functions needing to interoperate with PSAs has increased with smart grid evolution. The TC57 architecture generally follows the form of the GWAC Stack layers 1–7, as it ascends from standards concerned with communications relating to the connectivity of field devices through to information exchanges to support business processes and enterprise objectives. Due to the wide range of perspectives upon what is a smart grid from the countries surveyed, maintenance of the SIA as a central reference is a priority to keep abreast of smart grid evolution. Recommended initial work to extend the SIA would include CIM standards for DER and the increasing number of CIM profiles, electric mobility, and charging, as well as relevant standards referring to the OPC UA.

The middle layers of the GWAC Stack are in transition from a technical to an organizational focus requiring information interoperability. These "Informational" layers correspond to "Business Context" and "Semantic Understanding." They align with the CIM standards IEC 61970, IEC 61968 in IEC/TR 62357. In IEC/TR 62357-1 [55], a further standard, IEC 62352, is added to the CIM. These standards make up the current specification for the IEC Common Information Model (CIM) and broadly apply to the functions of EMS application integration, distribution system application integration and energy market system communications integration respectively. Their importance has been described by NIST as central to

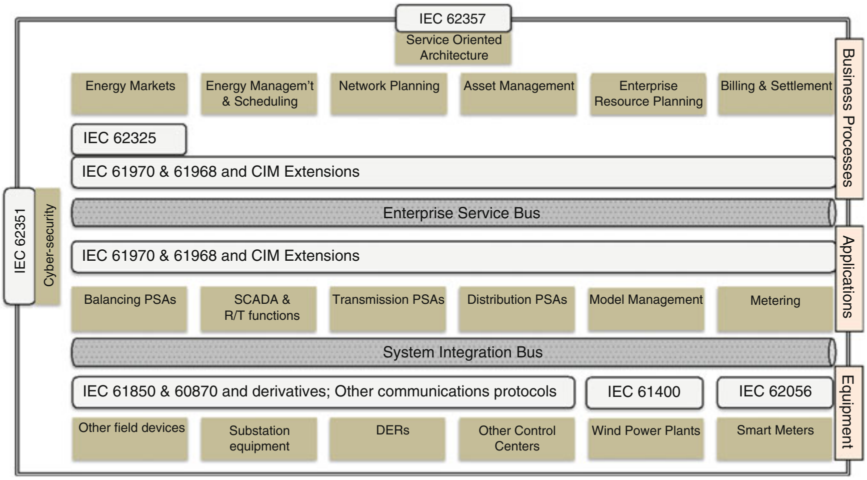

Fig. 2 A simplified representation of IEC TR 62357-1, Seamless Integration Architecture. Standard series are shown with additions representing monitoring and control of wind power plants and smart metering

the foundations of smart grid interoperability [56]. The specific designations for the CIM standards are IEC 61970-301, IEC 61968-11, and IEC 62325-301. Recent development of IEC 62325 to suit a European energy market context is ongoing and a finished extension to this standard is expected to be published by the IEC in 2014.

The EU Task Force for Smart Grids, Expert Group 1, have analyzed smart grid interoperation from the three perspectives of Transmission, Distribution, and Home, and have also summarized international standards harmonization initiatives in [57]. Their standardization methodology recommends a top-down approach with three levels, taking into account Mandate M/441 to ensure that smart metering is included in wider smart grid application standards. The three levels are as follows:

- Harmonize smart grid use cases in member states.
- Harmonize smart grid data modeling and description language.
- Harmonize communication protocols.

A further significant standards framework in support of a SIA is the Institute for Electrical and Electronic Engineers (IEEE) Smart Grid Interoperability Reference Model (SGIRM) [58], which addresses interaction between the actors within the 7 domains identified in the NIST Conceptual Architecture Framework. Its focus is upon interface architectures and data flow characteristics from three architectural perspectives: communications, power systems, and information technology platforms. It provides a scalable model of functional interoperability that can be extended as the scope of the smart grid evolves.

6 The IEC Common Information Model (CIM)

The significance of the CIM standards relates to their function as a scalable and extensible semantic model for power systems. An authoritative description of its design and class composition is given in the associated IEC Standards (IEC 61970-301, IEC 61968, and IEC 62325) and it is further described in [59–61]. Misconceptions about the CIM in terms of its use in database design and the "CIM compliancy" of technology interfaces are addressed in [62]. The structure of the CIM is designed to be flexible. It is object-oriented and presented as a Unified Modelling Language (UML) class model. Flexibility of the model derives from its properties of *extensibility* and *scalability*. Extensibility applies when new objects not available within the standard set are needed, they can be added, underlining the *open* nature of standard model. If these additions are considered of general use and subject to subsequent interoperability testing, they can become inducted into the internationally standardized version [63].

Examples of IEC CIM extension to suit utility use cases are numerous and reflect business case evolution in managing the smart grid through use of Model Driven Architecture (MDA). Extensions to the CIM can be categorized for different purposes, such as widening its domain scope into substation equipment representation [64] or High-Voltage Direct Current (HVDC) modeling [65], to extending its ability to represent dynamic models for contingency analysis [66]. As it is canonical in its design, it is possible to integrate new "packages" of UML classes with dependency to the Core package as the scope of use cases for information exchanges widens. Nielsen and Neumann give a good overview of the processes associated with CIM extension management in [67]. An important recommendation from consensually accepted definitions of smart grid standards identified in [53] featured extension of the SIA to accommodate DERs. With respect to future smart grid operational requirements, this recommendation was responded to in [68] with a proposed design for an energy storage extension comprising a package of classes addressing control of grid-scale energy storage technologies. The CIM is also being used as the design basis for a variety of new model-driven applications including state estimation [69], wide area measurement [70], and secondary equipment management [71].

The CIM is designed to be *scalable*, such that if a subset (or profile) of the standard reference classes are sufficient to model a given use case in a particular context then the rest of the reference metamodel can be ignored. Well-established profiles such as the CPSM and CDPSM have already been mentioned but the tendency to profiling for reusable functionality within the exchange of network models has become more common. The second edition of the European Network of Transmission System Operators for Electricity (ENTSOE) profile version 2.0, which was based upon CIM release 15, is an example of a combination of a bundle of standardized CIM profiles, each referring to specific functionality, including:

- Geographical profile, IEC 61968-13;
- Equipment profile, IEC 61970-452;

- Diagram layout profile, IEC 61970-453;
- State variables profile, IEC 61970-456;
- Topology profile, IEC 61970-456;
- Dynamics profile, IEC 61970-457.

The relationships between CIM UML classes are structured to provide a standardized object-oriented modeling architecture. It is a canonical taxonomy in the form of packages of UML class diagrams *referring to* the components of power utility networks with functional definitions and measurement types to a high degree of granularity. Wang and Van Ausdall give an overview of how business data semantics are represented in the CIM and propose some rules to clarify the UML modeling concepts used [72]. They describe how an XML *namespace* defines the scope of a class name and observe how a CIM class name (and therefore the concept represented by that CIM class) must be unique within the CIM XML namespace to maintain the integrity of the CIM logical model. This raises the distinction between the CIM as a static logical model, a standard conceptual representation of smart grid components, and the *instantiation* of CIM objects in models created by PSA CIM adaptors to represent their functional data models.

Power system applications use the CIM as a reference logic when processing CIM models for export and import. CIM metadata files communicated between PSAs vary in size depending on the scope of the modeled network (for example, a transmission system with complex topology) as well as the detail of the CIM representation of network parameters being communicated. With the most detailed representations of complex networks made up of millions of CIM objects forming multi-Gigabyte sized files, concerns over the amount of data, and the capacity to handle it within the smart grid environment may arise. This topic has been acknowledged and addressed by McMorran in [73] in which a number of strategies are discussed for reducing the size of, and handling, communicated CIM files. The principal strategies for handling large CIM representations of power system networks include communication of layered representations of a network constrained to CIM profiles (see profiles above); the use of difference models (see IEC 61970-552) that only update the status of larger parent models as changes to them occur; the use of compression technologies such as the ZIP file format that can perform better than 20:1 compression on CIM RDF XML. It is unlikely therefore with RDF forming the backbone of communicated CIM files that any great stress will be placed on the data communications and storage capabilities within the smart grid environment.

The semantic definitions and logical integrity of the exchanged model depends on the CIM standards but its “physical” integrity or connectivity depends upon a system of object identification provided by RDF. RDF links objects together by means of a triple, defining a subject in relation to an object using a *predicate*. The predicate as a system of address is used to form the identity description of the object and is generated within the CIM adaptor of the PSA when processing a CIM model. An instantiated model of CIM objects must conform to the logic and semantic definitions of the standard CIM static model but will only use a portion, or profile, of its set of CIM classes to represent the real network. If each interoperating PSA places its instantiated CIM objects within the same namespace, such as "xmlns:CIM," then the opportunity for object identity *collisions* will arise when these models are shared [74]. This is because the namespace defines the scope of validity for an object identity just as it does for the semantic descriptions of the object. Identity collisions therefore are a vexing problem currently challenging smart grid PSA interoperability.

6.1 The CIM as Ontology for the Electrical Power Domain

If we consider a model as "an abstraction of reality according to a certain conceptualisation" [75], then these standardized models, as meta-conceptualizations *representing* PSA data models, support the view of the CIM as a metamodel in accordance with [76, 77]. The canonical nature of the CIM in giving rise to a range of submodels (profiles) that describe specific context-constrained applications enable it to also be described, in terms of a "model of models" which concurs with the Object Management Group (OMG) definition of a metamodel [78].

Harmonization with other existing information models, such as the IEC 61850 substation automation standard, to widen the integrated semantic standards framework supporting smart grid interoperability is seen as a priority. Gruber defines ontology as a "specification of a representational vocabulary for a shared domain of discourse—definitions of classes, relations, functions and other objects" [79]. As the scope of the CIM extends, placed at the heart of a harmonized federation of standards, it conforms to Gruber's definition of ontology for the smart grid domain. In this sense ontology supports the description of our knowledge about a domain, linking the IEC CIM to knowledge representation of the smart grid. This proposal is fundamental to the capacity of the CIM within the smart grid domain for knowledge representation and sharing. Chandrasekaran et al. argue it is not the representational vocabulary of the domain that defines the ontology as much as the conceptualizations that the vocabulary is intended to capture [80]. Careful analysis of the objects and their relationships within the domain is required to create the vocabulary and conceptualizations necessary for true representation of the domain reality and explains why CIM development is marked by much debate amongst domain experts as well as the importance of interoperability testing. For, as Uslar et al. indicate in [81], the strength of the CIM as a domain ontology not only depends on the expertise of the domain experts building it, but also extending its application to link control center ICT with field-automated devices while further developing the SIA.

6.2 Harmonization of the CIM with Other Standards

Regarding the link between the CIM and field devices, Santodomingo et al. [43] discuss the harmonization of the CIM with IEC 61850 (substation control language) using an ontology matching approach that required the use of Web Ontology Language (OWL) to represent semantic correspondences between the two standards. Their methodology was based on a top-down application of service descriptions that were used to annotate CIM metadata mentioned in [36]. The CIM and IEC 61850 ontologies supported a layered framework created to bridge the semantic definitions of their classes and attributes and the relationships of these entities. In this way the harmonization of these two standards, designed from different origins and for different purposes but now increasingly required to interoperate to develop smart grid functionality, is being established.

In another initiative, linking the CIM to IEC 60870 for high-voltage meter control and management is described [82]. The semantic alignment of these two standards is seen as part of the development of the Spanish smart grid. Mapping of the classes from the IEC 60870 protocol to the CIM was reported as straightforward and described in the sense of aligning one “service” to another. The sense of model classes representing services is another indication of the way the CIM lends itself to SOA. What is more, with the application of ‘Simple Protocol and RDF Query Language’ (SPARQL) the opportunity to interrogate RDF databases annotated with metadata makes possible the benefits of the Semantic Web paradigm. SPARQL is designed to seek out query matches with RDF triples for data stored in an RDF format such as CIM RDF XML. In this case the use of multiple namespaces, as metadata annotation of the meter data captured in CIM RDF XML, enabled the machine-to-machine (M2M) access required by the query. This methodology presents another example of how a layered architecture builds interoperability between the source of data and an end use. Whereas the use of Web Ontology Language (OWL) as a layer will focus on the resource description logic, SPARQL will focus on the knowledge representation of the RDF triple.

7 Information Integration and Knowledge Representation

Knowledge representation (KR) reinforces the possibility that the smart grid could herald our evolution in energy management from the “Age of Information” into the “Age of ‘Intelligence.” This vision, shared by the State Grid Corporation of China in their “Framework and Roadmap for Strong and Smart Grids” [83] would bring energy management within the realm of “Internet of Things” [2].

The pivotal importance of a semantic model to support understanding within KR is underlined by its central position in the GWAC Stack and therefore interoperability. Whether it is to provide a standard means for message exchange between PSAs operating with heterogeneous perspectives of the smart grid, or a standardized interface specification, the CIM's platform independence and ability to support information integration is strengthened as a domain ontology. Neumann et al. recognize that the rapid growth of the CIM gives rise to questions about its scope and how best to apply it to a variety of roles ranging from information management and systems integration to information exchanges and application modeling [84]. It could eventually be viewed as a combination of ontologies made from the packages of UML classes of which it is composed, or as part of a federation of ontologies when considered amongst other smart grid standards as well as OPC and MultiSpeak. Either way, it has a range of applications that depend to a greater or lesser extent on the *richness* of the semantic language to convey the meaning of vocabulary and conceptualizations.

Quirolgico et al. in [85] assert self-managing systems in a domain comprising disparate applications, devices, components, and subsystems depend on a formal ontology to support knowledge interoperability and reasoning. While they were referring in this case to a computing and networks environment, these are some useful pointers to the evolving role of ICT within the smart grid. Not least the importance of full and formal semantic definitions within the vocabulary of the CIM as well as the capability of the languages used for construction and messaging to convey the intended meaning and knowledge representations within the ontology. This is in the interest of reducing the burden of a priori knowledge and reasoning on the part of the participating PSAs. In [86] Tang et al. make the point that the presence of ontology not only serves to promote knowledge sharing across different departments but also makes knowledge reuse available when there are changes to domain technologies through innovation. In [87] Sourouni et al. say ontologies can be employed at different levels of understanding. Examples of these range from contributing to the specification, reliability, and reusability of systems, through making data exchange easier, up to full functional interoperability of data and function.

Referring to the role of the IEC CIM within the "Semantic Understanding" layer of the GWAC Stack, we may then consider the need for richer information transport not simply supporting information interoperability but *knowledge interoperability* in future smart grid systems. The latter will depend on the ability of the encoding language to support the knowledge and reasoning constructs intended by the semantics and metadata of the ontology. Semantics are supported by the formality of the CIM descriptions and are combined with metadata using the schema definitions carried by the schema language for machine interpretation. The XML schema definition (XSD) is used to specify the structure and contents of an XML file, and therefore also serves to validate its contents. OWL is designed to explicitly represent the meanings of terms and their relationships in the vocabularies of ontologies. Thus for purposes requiring a higher degree of knowledge representation it may be necessary to consider as schema language, the use of the more powerful Web Ontology Language (OWL) over CIM RDFS expressions in future.

The value of framing the CIM as a metamodel in recognized terms is that we can utilize established methods from related domains such as Artificial Intelligence and Computer Science. For example we can envisage the CIM occupying "Level M2" of OMG's "Four Layer Hierarchy" [88]. Thus metadata models derived from the CIM become instances of the data models belonging to PSAs at “Level M1”, which in turn are composed of instances of data at “Level M0”. Each level higher is an abstraction of the level below it and supports opportunities for integration of a wider range of conceptualizations of smart grid reality. Hargreaves et al. report on a methodology using this convention to create a CIM-based metamodel repository as a means of smart grid knowledge representation and development [89]. Alignment of different PSA conceptualizations of the same electrical network helps to optimize power utility processes and understanding of smart grid reality. As the repository integrates CIM-based metadata models aligned over boundaries marked by semantically common power system resources, a fuller knowledge representation of the smart grid reality comes into focus. While semantic commonality is a requisite for boundary alignment, identification of the same power system resource, derived from different PSA meta-conceptualizations, usually differs due to the different processes for data manipulation employed in each PSA. The issue of multiple identities attributed to the same object is a common feature in human nature where understanding the distinction between one object identity and another often depends on *context*. As the PSA metadata models are encoded in CIM RDF XML, the use of an XML namespace to “contextualise” each PSA representation provides the means to maintain resource identities in their original form while at the same time rendering them receptive to alignment within the repository. In this way an integrated metamodel repository can offer a rich environment for information integration and knowledge extraction across utility business domains as well as forming the basis of a central network model management system [59]. Such a resource will become of increasing importance with the integration of large-scale renewable power generation and storage facilities as the smart grid develops.

8 Conclusion

This chapter began by explaining the importance of the smart grid for integrating novel energy processes and technologies to deliver sustainable energy. Depending on interoperability to be reflexive to the changes in supply and demand as well as deliver energy with optimum reliability and economy we examined the centrality of the IEC CIM within model-driven interoperability processes. The value of semantic modeling in building ontology was then discussed leading to the proposal that combined with syntactic agreement provided by schema definitions and management of context provided by namespace, a metadata model repository can leverage the value of PSA data models into KR for better business understanding of smart grid reality. Using this design pattern, we can advance in accordance with interoperability at all levels, including data to data (D2D), model to model (M2M), application to application (A2A), and enterprise-to-enterprise (E2E) in building the vision for the smart grid to move from the age of information toward the age of intelligence.

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