Context-awareness and the Smart Grid: Requirements and Challenges

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Abstract

New intelligent power grids (*smart grids*) will be an essential way of improving efficiency in power supply and power consumption, facilitating the use of distributed and renewable resources on the supply side and providing consumers with a range of tailored services on the consumption side. The delivery of efficiencies and advanced services in a smart grid will require both a comprehensive overlay communications network and flexible software platforms that can process data from a variety of sources, especially electronic sensor networks. Parallel developments in autonomic systems, pervasive computing and context-awareness (relating in particular to data fusion, context modelling, and semantic data) could provide key elements in the development of scalable smart grid data management systems and applications that utilise a multi-technology communications network. This paper describes: 1) the communications and data management requirements of the emerging smart grid, 2) state-of-the-art techniques and systems for context-awareness and 3) a future direction towards devising a context-aware middleware platform for the smart grid, as well as associated requirements and challenges.

Keywords: `Context-awareness, Smart Grid, Sensor Networks, Middleware`

1. Introduction

Smart grids will transform the methods of generating electric power and the monitoring and billing of consumption. The drivers behind the development of smart grids include economic, political and technical elements. Major initiatives have been launched in Europe by the *EU Commission* [1] and the *European Electricity Grid Initiative* [2]. In the US, overall policies are set out by the *National Science and Technology Council* [3] while grid modernisation is specifically described in a report by the *GridWise Alliance* [4]. The main policy drivers for power grid development are as follows:

- Promote the integration of distributed renewable power sources (e.g. wind, solar, wave and tidal power, geothermal, biofuel);
- Provide significant reductions in carbon dioxide (CO_2) emissions through the phasing-out of fossil fuel power plants. This is to help meet agreed world targets in reducing greenhouse gases and combatting climate change;
- Promote the use of electric vehicles as an alternative to fossil fuelled transport systems;
- Renew and upgrade older grid transmission infrastructure to provide greater efficiency and security of supply;
- Introduce two-way *"smart"* metering to facilitate both power saving and power production by consumers;

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Apart from these policy drivers, power production and distribution will also have to operate in an increasingly deregulated and competitive market environment. Consequently the existing infrastructure needs to be upgraded to meet the projected challenges and demands. This upgrade will include the introduction of computational intelligence in all parts of the power network. It is this intelligence that will ultimately make the grid 'smart'. The principal smart grid trends and systems are surveyed in detail by Fang et al. [5]. Their survey distinguishes between (a) smart infrastructure for energy, information and communications; (b) smart management and control and (c) smart protection system for reliability analysis, failure protection, security and privacy. For each of these main headings they describe challenges in deployment, the range of technologies that might be used, the requirement for new standards, interoperability issues and the need for further research. It is clear from the range of technologies and standards available that there will be no unique smart grid infrastructure or architecture. However any smart grid infrastructure will require that electronic sensors be deployed not only in the power grid but also in consumer premises (homes, buildings, factories etc.). The sensors will monitor all aspects of power production, distribution and consumption.

A multi-technology communications network will link these sensors with higher level management and control systems. The management and control systems will have access to actuators (switches, relays, circuit breakers etc.), to distributed generation sources and to consumer appliances in order to maintain end-to-end power production and delivery. Gao et al. [6] summarise the communications systems that will be deployed in different segments of the smart grid. A more detailed survey of available communications protocols is provided by Fan et al. [7], who also highlight the challenges of interoperability, privacy, security and application development for smart metering networks. Gungor et al. [8] provide more in-depth information on short-range and longer-range communications technologies and existing smart grid interoperability standards. The surveys describe how the communications network is divided hierarchically into a *Home Area Network* (*HAN*), a *Building Area Network* (*BAN*) and a *Neighbourhood* or *Wide Area Network* (*NAN/WAN*). These networks in turn will feed into a *Field Area Network* (*FAN*) which will also carry data from power production and transmission nodes. However none of the surveys examine either (a) the data processing requirements that will exist between heterogeneous sensors on the one hand and high-level smart grid applications on the other or (b) combining (fusing) the output of different types of sensor to enhance available information. There will be a need for newer types of middleware to address the gap between sensors and applications. Furthermore, sensor network data can be combined in different ways to provide additional context-related information about consumers or the network. Management and control systems will use this data as input to autonomic (self-aware, self-learning) technologies. The general tracking of human behaviour through sensor networks and the development of supporting middleware is currently being studied as part of pervasive computing and context-awareness research.

Context-aware applications are typically based on the notion of *presence* i.e. where consumers are located at a particular time (home, work, leisure), what they are doing, what services they might require in that particular situation (context) and where those services are located in relation to the consumer (Hazas et al. [9]). Three main context entities are, a) *places* (rooms or other locations), b) *people* (single or groups) and c) *things* (objects). Each of these entities in turn can be described by four attributes: identity (a unique identifier), location, status and time (timestamp).

Consumers can be tracked by physical (hardware) sensors that can directly provide location and other attributes. Relevant information can also be obtained from software application sources (sometimes termed *"virtual sensors"*) that are regularly used by a consumer. Other combinations of physical and virtual information (e.g. additional database information) can form *"logical sensors"*. Data from all these sources (physical, virtual, logical) is processed, stored in a knowledge base and can be queried and used for context modelling and reasoning. Early examples of ubiquitous computing systems for location sensing are analysed by Hightower and Borriello [10] who also identify research challenges in sensor fusion (combining data from different sensor types) and ad-hoc location sensing. The idea of smart learning workspaces (classrooms, lecture rooms etc.) was further developed with *Gaia* [11], a *Common Object Request Broker Architecture* (*CORBA*) based platform that offered five basic services: Event Manager, Presence, Context, Space Repository and Context File System. Gaia sought specifically to demonstrate how applications could be customised for an end-user depending on their location and available resources. Smart healthcare, especially for the elderly or other home-based patients is also a growing area of research. Typical applications include location tracking, fall detection, medication administration and medical condition monitoring. The use of wireless sensor networks and context-aware applications in healthcare is surveyed by Alemdar and Ersoy [12]. They identify the main benefits of sensor networks as (a) remote monitoring that allows speedy identification of emergency conditions and (b) providing contextual information from the surroundings to help in deciding whether or not a patient's condition has changed. The challenges they identify include (a) unobtrusive, sensitive and energy efficient wearable sensors; (b) reliable, resilient and secure data communications; (c) context-data organisation and the use of self-learning autonomous applications and (d) protecting privacy while ensuring mobility and scalability.

Apart from pervasive computing, context-awareness is also the foundation for the functions of a distributed autonomic communications and processing network, which can enable properties of self-configuration, self-healing, self-optimisation and self-protecting. Sensor networks and context-awareness will also be integral parts of the emerging *Internet of Things* (*IoT*). The IoT can be defined as a worldwide network of interconnected embedded computing devices based on the *Transmission Control Protocol/Internet Protocol* (*TCP/IP*) suite. Each embedded device will have a unique IPv6 address. Perera et al. [13] surveyed the role of context-aware computing in the IoT and listed three categories of application domain: industry, environment and society. They also identified research challenges in (a) automated sensor configuration; (b) context discovery; (c) acquisition, modelling, reasoning and distribution; (d) selection of sensors in sensors-as-a-service model; (e) security, privacy and trust; (f) context sharing. The smart grid sits mainly in the industry domain but it also has implications for the environment (environmental monitoring) and society (smart buildings, smart cities etc.).

Given the projected deployment of sensors and smart meters in smart grids, a key question is:

"How can context-awareness be incorporated and exploited in the development of smart power grids?"

This paper presents an overview of smart grids and context-aware platforms. We evaluate the key communications and data management requirements of the smart grid, the proposals for unified smart grid data models and the need for middleware. We argue that 'self-awareness' will be a key attribute of the new smart grid that will require advanced automated reasoning based on rapidly changing input data. We then provide a critique of context-aware platforms and their current scope, explaining how context reasoning can be applied to smart grids. Our objectives are to (a) propose an architectural framework for a context-aware middleware platform that could meet the specific smart grid challenges of scalability and interoperability while also supporting advanced applications, (b) map the framework onto the underlying smart grid communications infrastructure in order to identify a realistic data processing hierarchy and (c) provide guidelines on how context-aware solutions can be employed in the different spaces of the smart grid. Smart grid data generation and collection is described in §2 while specific requirements for smart grid *information and communications technology* (*ICT*) are outlined in §3. The characteristics of a self-aware smart grid are in §4 with current trends in context modelling in §5. An architectural framework for smart grid context-aware middleware is described in §6 as well as some context-aware challenges and guidelines for the smart grid. Additional longer term smart grid scenarios and our conclusions are in §7.

2. Smart Grid Data Collection

The accumulation of data from power generation, transmission and consumption sources will provide the input for secure management systems, control systems and consumer applications. Much of the data will come from sensors in the power network, consumer locations (home, building, industry etc.) and microgrids (combined producer/consumer locations). In this section we examine the different data sources and the communications networks that will link them. We also identify nodes where some degree of local data processing would be possible prior to transmission to a higher level processing layer.

2.1. Power Provider Sensors

At some locations, such as power stations, a legacy sensor network will already exist for monitoring all aspects of power generation (temperature, pressure, power output) and will be managed by a local *Supervisory, Control and Data Acquisition* (*SCADA*) system. Other sensors such as *Phasor Measurement Units* (*PMUs*) are used to monitor voltage, current and frequency on main transmission lines and at substations. The PMUs provide valuable data on the state of the network, detecting fluctuations and providing real-time information on power availability [14]. They are relatively expensive so deployment will be limited but they will be vital for quality measurement, load balancing and re-routing of power around overloaded links.

As the smart grid evolves there will be many locations where a sensor network has to be retroactively fitted and it may not be possible or desirable to provide a wired solution. Consequently it is projected that there will be a wide deployment of low-cost, low-power wireless sensors (early and current examples are discussed by Bose [15]) for data collection at all key smart grid infrastructure points. The most widely used communications standard is IEEE 802.15.4

[16] for *wireless personal area networks* (*WPAN*) and covering the physical and *medium access control* (*MAC*) layers. The standard uses unlicensed bands and can provide, for example, 16 channels at 2.4GHz. The maximum data rate is 250kbits/s, the maximum range is typically 10m to 100m.

The ZigBee Alliance has built on IEEE802.15.4 by providing definitions for the network and application layers [17]. The ZigBee sensor network technology allows for multi-hopping to increase the effective transmission range. Networks are self-organising around three types of node: a) a base station, sometimes called a sink node or *personal area network* (*PAN*) coordinator, b) a cluster-head or router and c) an end device. The topologies can be as follows: star, mesh, tree, cluster-tree. Having even a partially meshed structure allows for automatic reconfiguration (self-healing) if one or more sensors fail. The base station will also have a gateway function with an Ethernet port for connection to an external network that will backhaul accumulated data to a processing centre. Another emerging technology built on IEEE 802.15.4 is 6LoWPAN [18], where the objective is to allow *Internet Protocol* (*IP*) networking even over low data-rate wireless systems.

Small wireless sensors have to strike a balance between computational processing power, transmission power range and data storage on the one hand, and the need to conserve battery power on the other. Larger renewable sources such as wind farms will also have specialised embedded sensors, as described by Popeanga et al. [19], for turbine control, blade condition and wind speed monitoring as well as power level. Key aggregated sensor data can be sent from a local control system to a centralised grid control system to present a picture of available power at any time.

Wireless sensors in a power network may have to operate under challenging climatic and electrical conditions. The data transmission capabilities of typical wireless sensors in challenging electrical conditions (power control room, sub-station, underground transformer) was modelled by Gungor et al. [20]. The link quality measurements showed that there was a good correlation between the radio *Link Quality Indicator* (*LQI*)—the chip error rate—and the measured *Packet Reception Rate* (*PRR*)—the ratio of successful packets to total packets transmitted over a set number of transmissions. Consequently, the LQI can be used as a good indicator of both the link QoS and data quality. If the QoS is poor then the data from that sensor should be excluded from any database until the QoS improves.

The fact that wireless sensors will be predominantly battery powered will create ongoing maintenance issues even if the batteries have a long working life. Alternative power for sensors could be obtained from energy harvesting - using power from surrounding sources. Sudevalayam and Kulkarni [21] provide a survey of sensors where power is converted from solar, mechanical or magnetic field sources. They also analyse the implications for parameters such as sensor lifetime, sensing reliability, transmission coverage and cost and show that a reliable (predictable) power source can improve the optimisation of these sometimes conflicting requirements. Power-harvesting wireless sensors for cost effective continuous transmission line monitoring are proposed by Yang et al. [22]. Their *powerline sensornet* would have self-powering modules at regular 1800m intervals along a transmission powerline to monitor selected line parameters, detect faults and communicate via a wireless network with a management centre. A similar type of wireless *"stick-on"* sensor with magnetic field harvesting is described by Moghe et al. [23] for temperature and current sensing. One key objective of developing power-harvesting sensors is to bring down the cost per module so that a large volume of sensors can be deployed across a power transmission network. More research is needed to provide a harvesting system that produces sufficient steady power to guarantee the reliable operation of this type of sensor.

2.2. Consumer Environment Sensors

On the consumption side, sensors deployed in a house or building will track appliance, light and other usage patterns (and hence consumer behaviour). A domestic sensor may communicate through a low-power, short-range self-configuring wireless sensor network (e.g ZigBee). The home gateway and sensors will form a HAN that will supervise the operation of automated appliances. An example of a multi-wireless technology HAN using reconfigurable radio systems is described by Amin et al. in [24]. They propose a method of dynamic spectrum access to improve the data handling capability of access points or base stations. Domestic sensors that are plugged into a mains supply can also communicate through *Power Line Carrier* (*PLC*) systems that route radio signals across the internal electrical wiring. The HomePlug Powerline Alliance promotes high-speed data communications based on IEEE 1901 (Broadband over Power Line) using frequencies up to 30MHz [25]. Hybrid wireless/powerline systems (e.g. HomePlug and WiFi) are also being developed to extend the coverage of powerline carriers in a building. One such hybrid is described by Cohn et al. [26] where wireless sensors operating at 27MHz use the powerline as an antenna to access

Table 1: Smart Grid Sensors

Type	*Typical Roles*	*Environment*	*Powering*
Grid Sensors	PMU power network monitoring (e.g. frequency, voltage)	Variable electrical	Mains power
	Production monitoring (e.g. power level, steam pressure)	Variable electrical	Mains power
	Infrastructure monitoring (e.g. wind turbine blade)	Variable electrical and climatic	Mains or battery power
Consumer Sensors	Smart metering with demand response functionality	Stable	Mains or battery power
	Building monitoring (e.g. temperature, motion)	Stable	Mains or battery power
	Appliance monitoring (e.g. kitchen appliances)	Stable	Mains or battery power

a receiver attached to the powerline. The *Smart Energy Profile 2* (*SEP 2*) is now being developed as a standard by the *Consortium for SEP 2 Interoperability* (*CSEP*). The consortium includes the ZigBee Alliance, the WiFi Alliance, the HomePlug Alliance and the Bluetooth Special Interest Group. The objective is to develop SEP 2 as a for standard home energy management via wired and wireless networks that use IP. The standardisation is a recognition of the role that IP will play not only in the HAN and BAN but also in the higher layer NAN/WAN networks.

One key sensor will be the smart meter, providing two-way power usage information to the producer and the consumer. An overview of smart meter deployment and technologies is provided by Zheng et al. [27] who list the meter functions as follows:

- Two-way communications with a data collection and control centre;
- Data collection, recording and storing;
- Load control through remote connection or disconnection of specific appliances;
- Programming a schedule for some appliances;
- Security against consumer fraud or external cyber attacks;
- Displaying tariff and consumption information.

They describe how in a fully *Automated Metering Infrastructure* (*AMI*), smart meters will communicate with a meter data collection point using a wireless or PLC network. The basic function of the meter is to record a customer's power consumption and send the data at specified intervals (typically 15 minutes) to the power supplier's data management system for processing. There is some debate as to whether or not the home gateway function, sometimes called an *Energy Services Interface* (*ESI*), should be integrated into the smart meter. However, ownership, control and upgrade issues arise if these components are integrated and usually it is assumed that they will be separate though closely coupled units as described by Lee et al. [28].

The main types of smart grid sensors, their functions and the type of climatic or electrical environment they operate in is shown in Table 1. Grid sensors may have to operate in variable climatic conditions (e.g. high wind or low temperature) and/or difficult (noisy) electrical conditions. Consumer sensors on the other hand are placed indoors and operate in a stable climatic and electrical (non-noisy) environment.

2.3. *Microgrids*

Domestic and industrial microgrids providing distributed generation will also be a key part of the emerging smart grid. Domestic microgrids can contain combinations of hydro, wind, solar, fuel cell and *Combined Heat and Power* (*CHP*) units for both space heating and electricity generation. Larger microgrids can provide heat and power for industrial estates, business campuses, hospitals or large educational establishments. The clustering of domestic and/or industrial producers/consumers into *Smart Microgrid Networks* (*SMGN*) would improve reliability and increase load sharing. An example overlay topology for such a network is proposed by Erol-Kantarci et al. [29] where the microgrid clustering is dynamic and based on power generation levels and predicted load.

A hierarchical communications network (home network, intra-microgrid network, wide-area management network) specially designed for distributed microgrid control and based on agent technology is described by Suryanarayanan et al. [30]. This work proposes a mapping of domestic control functions on to a designated node (e.g. a Home Gateway), building a meshed network of these control nodes and providing a long-haul communications links to a wide-area management system. Such a microgrid cluster communications network mirrors the wider smart grid communications network. Future cluster control systems could also support automated reasoning and self-aware applications, providing a high degree of autonomy within the cluster while also managing the flow of power and information to and from the grid provider.

Importing and exporting energy to and from a microgrid cluster presupposes a continuous interconnection with the main grid. The need for local storage only becomes an issue where a local producer (or cluster of producers) wishes to (a) maximise the use of microgrid produced power, (b) manage the trading of power for export or (c) provide an 'island mode' option. In a suburban house or apartment it may not be possible to accommodate a large bank of storage batteries. Furthermore it would only be possible to have a larger cluster-based storage centre if the network infrastructure allowed export and import of power to and from such a centre. The only partial alternative is charging up or drawing down power from the battery of an electric car. Electric car batteries can store different levels of energy depending on the make and model of car. Some car models and their battery capacities (in kWh) are listed below.

- Mitsubishi i-MiEV, 16 kWh [31]
- Renault Zoe, 22 kWh [32]
- Nissan Leaf, 24 kWh [33]
- Tesla Model S, 60 kWh or 85 kWh [34]

Domestic charging in the evening can also put a strain on the local distribution network so some form of staggered charging may be needed like that described by Richardson et al. [35]. Tracking and predicting a car's movements and its state of charge during the day are important issues in determining the availability of stored power or the need for charging power. Electronic sources of information such as a work calendar (Donohoe et al.[36]) or GPS system can provide information on location and time. This dynamic information is important to the microgrid cluster management system in determining the power demands and storage capabilities of cars associated with the cluster.

2.4. *Nanotechnology and the Smart Grid*

Nanotechnology can be described as the engineering of systems at the molecular level to produce a range of materials and technologies. Research areas include chemistry, physics, biology, materials science and engineering. One new nanomaterial is graphene—a one-atom thick form of graphite (carbon) that has great strength, flexibility and conductivity. Another emerging product is nanowires (long structures that can be tens of nanometres in diameter) that can be metallic, semiconducting or insulating. Carbon nanotubes (forms of carbon with a cylindrical structure) can also be engineered in different ways (single walled or multi walled) to give different properties (e.g. metallic or semiconducting). Quantum dots are semiconducting nanocrystals that have projected uses in lasers, solar cells and transistors. Smart grids will benefit from nanotechnologies in key areas as described by Abdelsalam and Abdelaziz in [37]. These areas include:

- **Photovoltaic cells**: better solar absorption and lower cost through the use of quantum dots and nanostructured graphene-based membranes in cells;

- **Wind turbines**: self-cleaning hydrophobic nanocoatings to improve blade performance, stronger but lighter blade materials based on graphene, better lubrication based on nanoparticle lubricants;
- **Energy storage**: nanowire based anodes and cathodes to increase battery capacity and lifetime, graphene based electrodes for more efficient supercapacitors;
- **Fuel cells**: nano-membrane technology and nano-particle catalysts to increase the efficiency of hydrogen conversion.

The use of nanotechnology for solar powered fuel production and supercapacitor storage is described by Chen in [38]. However it is the projected use of *nanosensors* and associated *nanonetworks* that presents a whole new set of challenges and opportunities for data collection in the smart grid. Some nanosensors and nanonetworks will be biologically based and use molecular communications as described by Akyildiz et al. [39]. Electromagnetic nanosensors on the other hand would be based on materials like graphene and would communicate in the Terahertz band [40]. Balasubramaniam and Kangasharju [41] describe some of the challenges of constructing electromagnetic and molecular nanonetworks such as (a) the creation of data collection and routing mechanisms, (b) developing middleware to connect conventional microsensors to nanonetworks and (c) extending current context and service management systems to support nanonetworks. Their work proposes solutions based on microgateways, unconventional routing and context-aware middleware. Nanosensors would add an additional sensing layer to smart grid infrastructure and other associated utility networks and provide a rich source of varied data. This increased volume of data in turn would drive the development of enhanced data management, better automated reasoning and a requirement for new standards and technologies for interoperability.

2.5. Smart Grid Communications Network

The sensors, actuators, smart meters, local management systems and other components of the smart grid will all require a communications infrastructure to facilitate the flow of data and control signals to and from processing centres. Communications systems will vary from long range fixed (e.g. optical fibre) and wireless (e.g. WiMax, cellular) systems to short range wireless (e.g. Wifi, Bluetooth, ZigBee) and PLC systems (e.g. IEEE1901, HomePlug Alliance). The output of a cluster of smart meters can be sent on a wireless or wireline NAN to an aggregation point that can then transmit the combined outputs to the power company using longer range wireless or a fixed transmission FAN. The reliability and availability of such communications systems is analysed by Niyato et al. [42] who assess the impact of the loss of a communications link on power demand optimisation. The power network and overlay communications network hierarchy (HAN/NAN/WAN/FAN) is illustrated in Figure 1 and summarised in Table 2. The infrastructure in the figure is based on current smart grid standards documents and technical papers and does not show specific technologies for each communications layer.

Cognitive radio technologies (the dynamic use of licensed and unlicensed bands) provide one method of constructing hierarchical models for both HANs and NANs, as described by Yu et al. [43], while efficiently utilising available spectrum. NAN technologies are also surveyed by Meng et al. [44] who identify four major challenges: timeliness management, security assurance, compatibility design and cognitive spectrum access. Larger renewable energy centres (wind farms, photovoltaic solar farms) will have similar hierarchies of wireless and fixed communications systems integrated with management systems. Each network type (HAN, BAN, NAN, FAN) will have some form of gateway device controlling access to/from the network and interfacing with a higher-layer communications network.

In the future, these gateway devices will have to support secure machine-to-machine communications (Fadlullah et al. [45]) and would be ideal locations for local data storage, data fusion and some level of automated reasoning. The gateways could also process queries from management and control systems as well as providing fused data for provider and consumer applications. This additional functionality would add to processing overhead but it would distribute automated reasoning and context processing across lower network layers.

3. Smart Grid Data Management

The consequence of sensor deployment in production and in consumption domains is that streams of data of different types, accuracy and priority will be emanating from an extensive network of sensors and smart meters. The

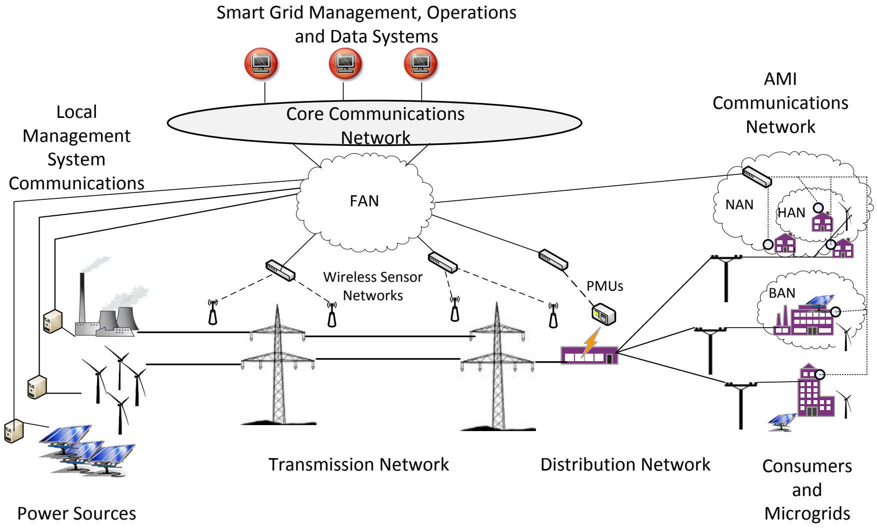

Figure 1: Smart grid power delivery infrastructure with integrated overlay communications networks.

data will be carried by an IP network that will provide seamless connectivity between all IP-enabled nodes. Some data can be processed by local management systems (e.g. a wind farm) while other streams must be routed to centralised or distributed management systems. All these management systems can potentially be expanded to incorporate new processing functions that would exploit sensor data fusion to construct new applications.

3.1. Data Fusion

Data fusion uses computational algorithms to combine information from multiple sources (sensor networks, databases etc.) to achieve better levels of data accuracy, draw inferences from the data and model particular scenarios. Early data fusion methods are presented in Hall and Llinas [46] based on the *Joint Directors of Laboratories* (*JDL*) four level fusion process, which consisted of: (1) object refinement, (2) situation refinement, (3) threat refinement and (4) process refinement. While these fusion methods were directed at weapons targeting systems, the principles can be generally applied to other applications. Object refinement (Level 1) contains the key basic functions of transforming sensed data to a consistent reference frame and units, predict an object's position, assign data to an object and refine estimates of identity or classification. Situation refinement (Level 2) develops a contextual description of the relationships between objects and observed events. Threat refinement (Level 3) projects the current situation into the future and seeks to draw inferences on possible intent and likely outcomes. Process refinement (Level 4) performs process evaluation of the first three levels. The key functions are identifying what information is needed for improvement, determining source-specific requirements (e.g. sensor type, specific sensor etc.) and allocating sources to achieve stated goals.

A survey by Smith and Singh [47] gives more detail and a critique on the variety of mathematical fusion techniques that can be employed at each level in the JDL model. They describe in particular the fusion methods for every stage of

Table 2: Smart Grid Overlay Communications Technologies

Network Type	*Range and Bit Rate*	*Networking Technologies*
HAN	Short range, low bit rate	ZigBee,WiFi, PLC
BAN	Medium range, low bit rate	ZigBee, WiFi, PLC, GPRS
WAN/NAN/FAN	Longer Range, high bit rate	WiMax, 3G/LTE, Fibre

Level 1 object refinement (e.g. Kalman filtering, Fuzzy Logic etc.) and their specific advantages and disadvantages. The bulk of mathematical model development has been at Level 1 but a stable and workable solution for object refinement is a necessary pre-requisite before similar stable solutions can be provided for Levels 2 to 4.

A typical wireless sensor network can be deployed for one specific application (e.g. temperature sensing) and this can be on a small scale. Data fusion may be employed simply to ensure that accurate readings are produced for the monitored area. Combining sensor outputs in an appropriate statistical manner can reduce the impact of a faulty sensor and minimise the effect of variable transmission quality. Data aggregation methods (tree aggregation, gossip aggregation) and their ability to handle faulty sensors are discussed by Chitnis et al. [48] who proposed a hybrid fault-tolerant protocol. Aggregation of this type can be performed at, for example, wireless sensor cluster-heads or base stations before it is forwarded for further processing.

A large multi-sensor network like a smart grid will have to combine the output of multiple heterogeneous sensor networks not just to improve data quality but also in order to build new applications. Fused smart grid sensor data can in turn be combined with consumer profile information and other external database input. Consumer profile information is more stable than sensor information, is subject only to occasional updating and may not require any interpretation. External database information may be relatively static but may be designed for one particular application. As a result, it too may need some interpretation if needed for a different application. When fusing sensor/profile/database data and making this available to a variety of applications it has to be possible to manipulate it in different ways and present it to a variety of *Application Programming Interfaces (APIs).*

3.2. Semantic Sensor Data

Sensors will provide data dynamically either at regular intervals or else in response to a specific query. A sensor network will also have an associated database, which may be deployed in a control node. Apart from the raw data collected by the sensors, this database will contain static information about each sensor (type, identity/address, status) and can store timestamp information. The extra information (*'metadata'*) can be important to higher level systems that query and process sensor data. Combining the output of different sensor networks in order to perform automated reasoning, handle multiple queries and build advanced applications demands a high degree of sensor network interoperability. An emerging method for fostering this interoperability is the use of semantic data. The basic sensor output ('observation') is annotated with sensor metadata to provide added context information that allows computer systems to understand the meaning of specific data items. A semantic data model defines relationships between data items using a standard vocabulary, or *"ontology"*. This allows for better machine interpretation of information, facilitates database integration and permits the building of applications that require inputs from multiple sensor networks. Standardisation activities for semantic data handling are increasingly directed towards web-based technologies and languages such as *Extensible Markup Language* (*XML*) and *Resource Description Framework* (*RDF*) [49]. Groups like the *Open Geospatial Consortium (OGC)* and the *World Wide Web Consortium (W3C)* are also developing standards specifically for the *Semantic Sensor Web (SSW)* as described by Sheth et al. [50]. Smart grid standardisation activities now reflect the increasing use of semantic data in order to meet complex interoperability requirements and this is described in more depth in §3.6.

3.3. Smart Meter Data Management

The data traffic per meter will increase accordingly as (a) more frequent readings are transmitted (e.g. every 15 minutes) and (b) new two-way control functions are required in the meter to allow remote access from the power provider. This type of remote access will be for controlling non-critical appliance usage at peak times (demand response). A method for scheduling the starting and stopping of domestic appliances with feedback to/from the smart meter is described by Iwayemi et al. [51]. The objective is to schedule particular appliances to run at low-tariff times (e.g. washing machines) while also minimising the wait time.

In future a scalable and robust *Meter Data Management System* (*MDMS*) will be required to provide data storage and analytical tools while also interacting with other smart grid management systems and databases. Distributed communications architectures for meter data transfer as well as scalability issues are modelled by Zhou et al. [52]. Three models for MDMS are studied: (a) centralised data and operations management, (b) decentralised data centre and centralised operations management and (c) decentralised data centre and decentralised operations management.

The analysis is based on minimising the cost to the grid operator of both communications resources and the deployment of the MDMS. The results indicate that a multi-site fully decentralised model (option c) is the most scalable but it only becomes truly cost effective at higher data volumes (large number of meters and high frequency of data exchange) and where there is a good range of potential sites for locating decentralised operations centres. This would be the case in a dense urban area where there is a high penetration of smart meters, coupled with multiple grid-operator management sites. In a less dense or rural setting a centralised data and operations centre would be more economical. However only simple (fixed) MDMS location costs are used in the analysis. In reality these costs could vary considerably depending on whether or not the decentralised processing capacity is leased or owned by the operator.

3.4. Management Systems for Generation and Transmission

Power companies currently have legacy SCADA systems. These are usually stand-alone end-to-end power generation and transmission network monitoring and control platforms. However SCADA systems are evolving especially to include a greater variety of distributed generation sources. A multi-technology SCADA system for an operational wind-farm and photovoltaic power system is described by Yu et al. [53]. A SCADA system may be part of a larger *Energy Management System* (*EMS*) that also optimises the performance of generation and transmission systems. Power companies may also have other complementary control systems such as a *Distribution Management System* (*DMS*) for monitoring the performance of the distribution network or an *Outage Management System* (*OMS*) to identify and remedy system outages. Sometimes the only integration between these systems is at an operator level (e.g. a human controller).

There can also be a hierarchy of SCADA systems with, for example, power stations and wind farms having their own monitoring but with higher level supervision from a grid control centre. For smart grid operation these monolithic operating systems will have to be extensively modified to (a) operate over secure TCP/IP networks [54] and wireless sensor networks [55] and (b) perform more complex automated reasoning based on interoperable semantic data models.

3.5. Smart Grid Security

An increase in computational intelligence in power networks also increases the vulnerability to electronic security breaches. Smart grid components (e.g. smart meters) and communications systems will have to be secured against cyber-attacks to prevent fraud, unauthorised access, the corruption of data or to counter threats to network operation. An overview of potential cyber threats is provided by McDaniel and McLaughlin [56]. They argue that existing legislation and technological security systems are not really sufficient to meet future demands. Much more work needs to be done on strengthening national and international regulation, developing more rigorous security tests for vulnerable components and planning for rapid recovery from security failures.

A more detailed survey of security objectives and potential cyber threats is provided by Wang and Lu [57] who also describe how prevention measures like encryption, authentication and key management can meet specific smart grid requirements. Existing security solutions like public key infrastructure (PKI) and trusted computing techniques will need additional standards to meet smart grid needs, as described by Metke and Ekl [58]. The security and integrity of all smart grid data will have to be guaranteed if consumer confidence is to be maintained. An automated 'self-aware' smart grid will place even greater requirements on security systems as it will be critically dependent on reliable data.

3.6. Interoperability and Standardisation

The heterogeneous nature of the components across a smart grid is also driving the need for interoperability and the development of corresponding standards. Interoperability requirements must cover: (a) communications platforms, where standard protocols must be used; (b) data formats, where messages need well-defined syntax and encoding; and (c) message content where a common understanding of the data is needed. Standards are being developed and agreed through international cooperation between organisations such as the *International Electrotechnical Commission* (*IEC*), the *European Telecommunications Standards Institute* (*ETSI*) and the *Institute of Electrical and Electronics Engineers* (*IEEE*).

The IEC 61850 Standard for Substation Automation provided a new way of modelling substation components. The standard specified the *Substation Configuration Language* (*SCL*) and incorporated data transport via TCP/IP and Ethernet. A summary of the standard is provided by Mackiewicz [59]. The development of abstracted data items and services that were independent of underlying protocols was a key feature of the standard and can be applied to a wider area than substations.

The IEC also has developed a *Common Information Model* (*CIM*), a semantic model for data integration to support real-time power company operations (IEC 61970). Naumann et al. [60] describe an example of mapping between IEC 61850 and CIM in order to model automated overcurrent protection. They argue that deeper harmonisation is needed if a higher degree of automated grid protection is needed. Work is now underway by the US *Electric Power Research Institute* (*EPRI*) to develop a harmonised *Unified Modelling Language* (*UML*) model that supports both CIM and SCL [61]. Besides the CIM there is also another widely used specification, *MultiSpeak*, for data exchange in power companies. It too is extensible and is projected to be deployed widely in smart grids. While there is some effort at harmonisation it is likely that both CIM and MultiSpeak will continue in existence.

Also in the US, the *National Institute of Standards and Technology* (*NIST*) and its associated *Smart Grid Interoperability Panel* (*SGIP*) are providing a framework and roadmap for smart grid interoperability [62]. The organisation has produced a conceptual reference model for smart grid information networks to guide future standards work. NIST also recommends the development of a canonical data model—a single semantic model that other semantic models can be mapped on to. This mapping is needed to provide interoperability between the large number of semantic models that the smart grid is likely to contain. Areas for further standardisation as well as a list of existing standards are included in the document.

More specific guidelines for smart grid interoperability are provided in IEEE 2030 [63]. This provides an *Interoperability Architectural Perspective* (*IAP*) for: (1) *Power Systems* (*PS-IAP*), (2) *Communications Technology* (*CT-IAP*) and (3) *Information Technology*(*IT-IAP*). The *Smart Grid Interoperability Reference Model* (*SGIRM*) identifies and defines the interfaces between these domains and the characteristics of the data flows between them. The CT-IAP, for example, categorises all potential entities (networks or end points) and the interfaces between pairs of entities. A three-tier classification of data (critical, important, informative) is provided and a sample mapping shown between some applications and corresponding tier classes. Security objectives (confidentiality, integrity, availability) are also categorised under high, medium and low for each interface. Communications systems for each interface would have to be chosen in the light of these classifications and objectives.

The IT-IAP also describes grid entities (e.g. energy management, transmission substation) and the data flows between pairs of entities. The document specifically recommends the use of harmonised data models (like CIM). It also strongly recommends the use of ontologies (descriptions of concepts) to extract more meaning from data, to create and manipulate data models and to provide easy export to XML or UML. Section 8 of the standard is particularly informative in the analysis of IT interoperability. Developing a higher level ontology for tracking events from different SCADA systems is described by Pradeep et al. [64] based on extensions of CIM.

Devising a fully integrated smart grid communications architecture is a challenge and one that has attracted the attention of major IT companies. Microsoft is promoting a *Smart Energy Reference Architecture* (*SERA*) [65] to provide a bridge between interoperability standards (e.g. CIM) and its own product suite. Similarly, Cisco have produced their *GridBlocks* reference architecture [66] based on an 11 tier reference model. This architecture is also based on emerging interoperability standards such as IEC 61850 and CIM. The move of such companies into the smart grid space indicates a fundamental shift towards a more tightly coupled communications and data processing infrastructure for the underlying power grid. The recommended smart grid use of common data models, ontologies and semantic data representation is in line with software developments in other areas, such as pervasive computing and context-awareness. A middleware platform will be needed to handle this complexity in a smooth and efficient manner and deliver all the necessary functionality for successful grid operations.

3.7. Smart Grid Middleware

Middleware is defined as software that facilitates interoperability between different operating systems and applications. In particular middleware can act as an adaptation layer between a hardware abstraction layer (e.g. a sensor network) and end-user applications. Smart grid middleware will have to handle hardware and software heterogeneity across different sensor types, SCADA systems and smart meters. On the other hand, for the consumer, the middleware would underpin applications such as tracking the daily use of domestic appliances and room usage to build up a consumer profile for flexible tariffing.

A detailed survey and critique of current smart grid middleware is provided by Martínez et al. [67]. They start by summarising trends in middleware and particularly the emergence of semantic data and context awareness. The survey assesses ten different proposed smart grid middlewares based on (a) data security, (b) handling semantic data, (c) supporting service orientation, (d) providing added value services like quality of service and (e) interacting with low-capability devices. Their assessment describes the advantages (e.g. using a service oriented architecture, self-healing, self-organising) and disadvantages (e.g. too computationally demanding for low power devices, no context-awareness) of each platform in meeting these requirements. Some of the middlewares meet the requirements better than others but the authors conclude that no single platform can meet all the requirements. They also conclude that future smart grid middleware will have to support semantic data processing and the use of ontologies for service delivery, service discovery and resource availability. We believe that middleware based on semantic data and ontologies will be a key component in the evolution of a fully self-aware smart grid.

4. A Self-aware Smart Grid

The previous section described some of the challenges that will be presented to smart grid data management systems. The computational requirements of a smart grid may be summarised as follows:

- **Heterogeneity**: providing interoperability between multiple sensor networks, communications gateways, management systems, control systems and advanced applications;
- **Scalability**: increasing computing power to meet growth in (a) demand, (b) consumption, (c) geographic reach and (d) data volume;
- **Dynamicity**: providing control systems and applications that can respond automatically to rapid variations in production, demand, tariffs and customer choices;
- **Security**: guarding against cyber-attack while guaranteeing a high degree of customer data privacy.

In order to meet these requirements the computational intelligence will have to create a *"self-aware"* network with distributed functionality and decentralised autonomic control. This computational intelligence will have to replicate human reasoning and intuition in recognising specific situations and crafting suitable responses.

4.1. Self-aware Smart Grid Applications

The self-aware smart grid would use automated reasoning and semantic data from a variety of consumer and producer sources to deliver applications such as:

- **Demand response**: using sensor and historic information from consumers, production units and the transmission network to perform automated reasoning and hence reduce or increase demand in response to production surges or deficiencies;
- **Situation response**: using dynamic network management and consumer information to identify transmission and distribution network disruptions, dynamically model the situation and programme appropriate corrective action;
- **Power forecasting and scheduling**: deriving forecasts from all potential power sources and matching these to consumption forecasts to compute production schedules;
- **Distributed generation integration and control**: modelling the introduction and characteristics of new power sources and predicting the impact on production and consumption;
- **Charging schedule for electric vehicles**: using consumer and network information to dynamically schedule the charging of electric vehicles to avoid overloading the local feeder network;
- **Distributed storage**: calculating the battery storage potential at any given time of electric vehicles or local battery banks and using this as an input in modelling spinning reserve, network frequency regulation and power balancing.

Table 3: Smart Grid Computational Requirements and Context-awareness

Requirement	*Advantages of Context-awareness*	*Disadvantages of Context-awareness*
Heterogeneity	Models are designed to handle inputs from a variety of sensor types using semantic data and ontologies for interoperability.	Semantic data and ontologies have a higher storage and processing overhead for sensor cluster heads and other control nodes.
Dynamicity	Models are developed specifically to track and process rapid changes in data values.	There is a strong bias towards mobility that may be less applicable in a smart grid.
Scalability	Hierarchical context reasoning can be deployed at different levels in a communications network.	Most of the current models are for specific locations (e.g. a room or building) and their scalability is unproven.
Security	Specific security and privacy requirements are similar to other automated systems.	Larger volumes of semantic data will require scalable security systems suitable for a nationwide smart grid.

Automated context reasoning (as introduced in §1) can be performed to produce, (a) a picture of consumer behaviour and (b) likely (forecasted) requirements in certain locations (e.g. workplace or shopping centre). The intelligence to support context-awareness can be embedded in gateways and management systems across a smart grid communications network.

The advantages and disadvantages of using context-awareness to meet key smart grid computational requirements are summarised in Table 3. It would be possible to incorporate less computationally intensive rules-based reasoning systems into SCADAs for example. Simpler reasoning systems would meet many of the monitoring and demand/situation response requirements at a lower computational and financial cost. However, we believe that the need for more complex automated reasoning (based on semantic data models) in the smart grid will drive the adoption of more dynamic and flexible context-aware decision-making systems. A survey of autonomic network management research by Samaan and Karmouch [68] identifies the use of user and application contexts as a key part of future self-configuring self-healing systems.

4.2. Smart Grid Scenarios for Context-awareness

The following are some scenarios where the incorporation of context awareness and context reasoning can provide specific advantages in developing smart grid applications. These scenarios present snapshots of situations where multi-sensor information has to be queried and processed across a number of smart grid domains.

Situation Response: Powerline sensors indicate to a control system that a transmission line failure has occurred. A situation-response application sends queries for sensor and database information in order to construct an appropriate response. The queries can draw on historical data, meteorological data, network sensor data and consumer sensor data and apply context reasoning to generate a specific course of action. The failed power line was not heavily loaded and the application computes the optimum re-balancing of power supply around the failed link with minimum consumer disruption. This is a more complex task than using a simpler rule-based method for delivering a response. However, the results of the situation response will also be monitored and will add to the knowledge database that the context modelling process can draw on in the future.

Demand Response: A sudden thunderstorm during a spell of fine weather forces consumers to move indoors and causes an unexpected surge in afternoon demand. A demand-response application queries the meteorological office forecasting system and learns that the heavy rainfall will be of short duration. Further queries to tariffing information, available power supplies and local storage systems (electric cars) indicate that the optimum response is to draw down some stored power and restrict the use of non-essential appliances (e.g. clothes driers). The system has already learned that a surge of longer duration would require a different response that could include bringing more power generation online.

Smart Public Lighting: This is the translation of a domestic application (smart home lighting) into a public space. Tonight there is a major football match in a city suburban stadium. The smart public light application responds not only to daylight levels and certain climatic conditions (e.g. fog) but also to sensed human activity in the city and suburbs. All public lighting remains fully on around the stadium until traffic activity drops to a low late-night level. The lighting system application detects this by querying the traffic recording sensor system. Street lights can then be dimmed or selectively switched off (e.g. every second light) until increased traffic activity is again detected (early commuters) or sunrise intervenes.

Electric Car Tracking: A microgrid control system registers the disconnection of a car from a domestic charger in the morning. The controller also has information from the driver's electronic work calendar indicating work start and finish times. The driver accesses a public charge point during the day using an electronic identity tag. The controller uses calendar data, the charging data and historical behaviour data to estimate the likely return time of the driver and the likely state of charge of the car. When this calculation is performed for a cluster of houses, the storage potential of the cars can be projected and a charging schedule can be devised.

Monitoring and predicting the behaviour of consumers, electric vehicles, distributed generators and network components mirrors on a large scale what pervasive computing and context-awareness currently does on a smaller scale. The current state-of-the-art in context-aware modelling and applications is described in more detail in the next section

5. Context Modelling

Context modelling seeks to replicate human reasoning (sensing, thinking, acting) in evaluating situations (*what's happening?*) and making predictions based on sensed information (*what will happen next?*). Context models are usually categorised as, (a) *fact-based* where information is reduced to elementary facts with the aid of intuitive diagrams, (b) *spatial-based*, where priority is given to location information and the perception of space or (c) *ontology-based* where information is structured as concepts and their relationships.

One specific example of a fact-based model, a *Context Modelling Language* (*CML*), was proposed by Henricksen and Indulska [69] using *Object Role Modelling* (*ORM*). The model captures, a) user activities (past, present, future), b) associations between users and communications and devices and c) locations of users and devices. However, it is aimed mainly at particular applications and domains and does not support interoperability.

A spatial context model uses either pre-defined locations (static objects) or positioning systems (mobile objects). The Nexus platform, for example, uses an *Augmented World Model* for supporting mobile and spatially aware applications [70]. Spatial context models are particularly useful where location and mobility are of particular importance but they can be used in other situations as well.

Fact-based models and spatial models have very good context acquisition characteristics but are weaker when it comes to complex context reasoning based on acquired data. Ontology-based context models are seen as better able to provide reasoning and represent complexity by defining appropriate classes, attributes and relationships. Ontologies are based on semantic data and can be written in, for example, *Web Ontology Language* (*OWL*), an XML extension.

A wide ranging critique of the different modelling categories is provided by Bettini et al. [71], who identify key requirements: heterogeneity and mobility, relationships and dependencies, timeliness, imperfection (e.g. incorrect or incomplete), usability of modelling formalisms, efficient context provisioning. They note that no single model (fact, spatial, ontological) can satisfy all requirements, especially the demands of situation abstractions (good semantic interpretations of context) and catering for the uncertainty of context information through different fusion methods. Consequently, a hybrid model (e.g. fact-based/ontological) is proposed as a better way of meeting diverse modelling requirements. This hybrid model has hierarchical levels for, (a) data fusion, (b) fact or spatial context reasoning and (c) ontological reasoning. The authors believe that a hybrid model need not be more complex than a single model yet it would be an effective way of integrating the different reasoning techniques. Researchers so far have concentrated on models with one type of reasoning only (e.g. ontologies) so there are few if any examples of hybrid models for analysis.

The use of ontologies and semantic data is in alignment with smart grid interoperability standards (e.g. CIM) and should provide the basis for smart grid context modelling. This topic is dealt with in more depth in §6.

5.1. Context-aware Middleware

The underlying philosophy of middleware is to facilitate the building of applications from distributed components while hiding the underlying complexity of component acquisition. The acquisition of fused sensor data and its

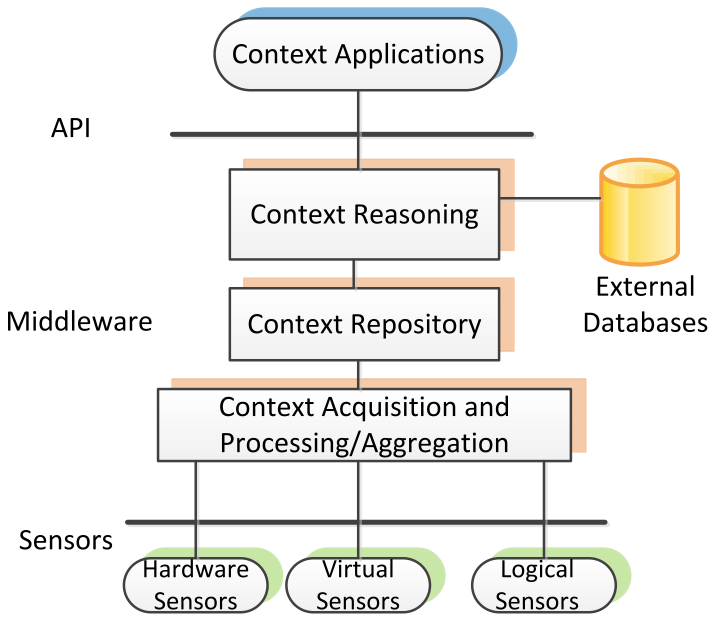

Figure 2: Context-aware middleware provides a processing and reasoning layer between sensors and applications.

subsequent processing for context-aware applications is a similar task. The required computational modelling and reasoning power is unlikely to reside at the sensor level, so it is usually provided in a middleware layer. The more general attributes of a context-aware middleware platform are discussed by Schmohl and Baumgarten [72]. A layered architecture is used by most platforms with sensor interfacing (adaptation, handling heterogeneity) at the bottom, APIs at the top and context reasoning in the centre as shown in Figure 2. The context reasoning may be applied in a centralised context server that facilitates multiple access to remote data sources or it may be distributed over different hierarchical components.

Originally it was assumed that the middleware would provide an interface between applications on the one hand and complex underlying networks on the other in a totally transparent manner. In other words, the middleware would hide all the complexity from the end-users and deliver the same level of service in all cases. However, in context-awareness, both the applications and the underlying network may be very dynamic (especially if mobility is involved) and, hence, the middleware must somehow be adaptable to changing situations. Furthermore, the middleware may not in fact hide all the complexity but provide details of it (e.g. bandwidth, terminal requirements) at higher level as valid context information. The *CARISMA* platform [73] uses reflection methods to allow for inspection and adaptation of middleware by applications and also proposes a method for resolving any conflicts (ambiguities or inconsistencies) that might arise as a result of such adaptation requests.

The smart spaces of the preceding models have been limited in size so far to specific domains (a room or rooms) and with relatively simple, personalised applications. Most of the work is also based on simulations. A multi-domain smart grid with millions of sensors and covering a large geographic area is on a completely different scale. Modelling the smart grid requires the mapping of the real physical world (power generation, transmission networks, consumer sites) into a semantic-data-modelled abstraction that can represent all the possible locations, equipment types, services and management tasks. Ideally the semantic data models would be based on extensions of an existing model such as CIM. A semantic smart grid information model is described by Zhou et al. [74] based on extensions of CIM. They also build component ontologies for key attributes (organisation, infrastructure, weather etc.) and show how a dynamic demand response application can be developed. However, multiple semantic data models are likely to exist in a heterogeneous smart grid so there would have to be an agreed canonical model for interoperability. This abstraction must then be queried in a speedy and efficient manner via middleware in order to support context-aware applications. Methods of modelling a scalable context-aware smart grid are discussed in the next section.

5.2. Scalable Context-aware Smart Spaces

The *Service Oriented Context Aware Middleware* (*SOCAM*) architecture of Gu et al. [75] converts a real physical space (e.g. a room with sensors) into an abstract semantic space (a data model of the room based on sensor data and other semantic data) where context information derived from the sensors can be shared between applications. SOCAM is ontology based and built upon the *Open Service Gateway initiative* (*OSGi*) framework for delivering service oriented applications. Two levels of context reasoning are specified: specific ontologies for a domain (e.g. a room or vehicle) and a centralised high-level ontology for multiple domains.

The physical space/semantic space concept in SOCAM was further developed as a more scalable multi-domain model by Pung et al, in the *Context Aware Middleware for Pervasive Homecare* (*CAMPH*) platform [76]. The objective was to design a platform that could track the movement and welfare of elderly people in the home through a variety of sensors. Apart from considering the home physical space, the model also made provision for interacting with context information from other related physical spaces such as a clinic and a hospital. In this model, each physical space has a designated *Physical Space Gateway* (*PSG*) that receives output from the sensors in the space and performs basic ontology-based context reasoning on these.

The PSG has a context database for storing historical context data and reasoning results and can be deployed as a module on any designated computing platform in the physical space. For example, a building energy management system platform could act as a PSG, taking input from a variety of sensors to compute the current status of energy usage and make short-term predictions. The fact that the PSGs maintain their own context databases means that data storage is distributed horizontally across nodes rather than being deposited in a centralised database. This distribution may be more scalable and avoids a centralised bottleneck but it does have implications when it comes to the efficient routing queries for context information to an individual PSG.

The initial context reasoning is also horizontally distributed across the PSGs. All PSGs are then connected and registered to a system server where the next level of abstraction and multi-space reasoning occurs. This next level of abstraction maps a physical space into a *context space* (or domain). A context space is an abstraction of a collection of physical spaces (e.g. building, home, shop) that have similar attributes and that provide similar types of data. The semantic data from a specific type of sensor in each physical space (e.g. power usage in a house) is then mapped into a cluster of similar context attributes (power usage in a cluster of houses) from other physical spaces. The data mapping is achieved by implementing a peer-to-peer network among adjacent PSGs. This clustering of similar context attributes is called a *semantic cluster*.

Organising context data into semantic clusters is the specific way that queries from applications for context data can be speedily executed. Each context space is modelled as a logical set or 'ring' of semantic data clusters. The system server provides a *context space gateway* function at each ring for maintaining topology and processing queries to/from the ring. The ability to add additional context spaces and semantic clusters aids scalability as does the two-level hierarchical (PSG, context space gateway) context reasoning functionality.

A follow-on platform from Zhu et al., *Coalition* [77], used the same cluster architecture but dealt more specifically with mobile PSGs. A mobile PSG in a smart grid would be located in, for example, an electric vehicle. Both the CAMPH and coalition platforms had a service management layer for service discovery and a context-aware application layer. The semantic clustering in context spaces can be applied to a wide range of physical smart spaces. Having a hierarchical context reasoning structure helps mitigate scalability and latency issues and also adds an element of distribution to the process. However, the CAMPH and Coalition platforms do not show any explicit mapping to an underlying HAN/BAN communications network that would illustrate more clearly their geographical scalability.

The HiCon framework developed by Cho et al. [78] also proposes a hierarchical platform with three context layers: *PocketMon* for personal context, *HiperMon* for regional context and *Efficient Global Infrastructure* (*EGI*) for global context. Each layer has a horizontal context composition with inter-layer communications for vertical composition.

Table 4: Middleware Platform Suitability for Smart Grid Scenarios.

Middleware Platform			Characteristics			
Name	Reference	Year	Heterogeneity	Scalable	Context Model	Smart Grid Mapping
SOCAM	Gu et al. [75]	2004	Yes	No	Ontology	No
Coalition	Zhu et al. [77]	2006	Yes	Yes	Ontology	No
HiCon	Cho et al. [78]	2008	Yes	Yes	Unknown	Yes
SALES	Corradi et al. [79]	2009	Yes	Yes	Unknown	No

These context layers are logically mapped to the structure of the underlying communications networks (HAN, BAN, NAN). This mirrors the smart grid communications network hierarchy and provides a convenient division into local, regional and global. The HiCon framework is scalable for large geographical areas and uses semantic data. However, there is no indication of the exact type of context modelling (fact-based, spatial or ontology) that's actually performed in PocketMon, HiperMon or EGI. Instead reference is made to developers using declarative query languages to express requirements: *Personal Context Monitoring Query* (*PSMQ*) in PocketMon and *Regional Context Monitoring Query* (*RCMQ*) in HiperMon. The current demonstration applications include a taxi-cab dispatch system (UbiCab) and a battlefield command-support system (U-Battle Watcher).

The *Scalable Context-Aware Middleware for Mobile Environments* (*SALES*) from Corradi et al. [79] also uses a hierarchical three-level tree structure with four logical nodes (Central, Base, Coordinator user, Simple user) for efficient context data transmission and query routing. No specific context reasoning techniques are discussed as the paper is focused on measuring the performance of context routing and service location. The platform is aimed more at dense urban environments with a wide variety of sensors and a significant proportion of context related traffic (location updates, frequent queries etc.) that would be typical of city centres or universities. SALES represents a scalable and efficient model for a local region that could be extended to a number of smart spaces such as shopping centres. However, it does not group these areas for wider geographic coverage or higher level context reasoning.

These context-aware middleware platforms—SOCAM, Coalition, HiCon, SALES—have elements that could be adapted to meet the specific requirements of context-aware smart grids. They distribute their functionality in two ways: horizontally across gateways at the same network level (e.g. the Coalition PSG) and vertically (hierarchically) to locations where higher level reasoning is performed. Their characteristics are compared in Table 4 on the basis of handling sensor heterogeneity, scalability for large geographic areas, the context model used and whether or not the middleware can be mapped on to the hierarchical levels of the smart grid communications network (e.g. HAN and NAN).

6. Realising a Context-aware Smart Grid

Building context-awareness into a smart grid will require sub-division into a set of smart spaces that reflect different players (e.g. consumer, provider) and the underlying communications infrastructure. These smart spaces will have both a physical component and an abstract logical component. In this section we describe the mapping of a smart grid into such smart spaces, the challenges that have to be met and potential context-aware middleware to provide appropriate computing functionality. The network of sensors and gateways can be mapped onto corresponding data fusion, processing and automated reasoning points in each smart space. The technology and communications capability of each node will determine the level of functionality that can be supported and the potential for data fusion. Defining a set of smart spaces and the relationships between them must also allow for growth in the smart grid, hence the need for scalability. The different players in the electricity supply chain will have to agree on exchange of information (e.g. meter readings) in a secure manner to ensure privacy, correct billing and the seamless delivery of energy management services.

One possibility is to build an architecture that integrates two different context-aware perspectives: *consumer* and *power provider*, where these two different perspectives can incorporate *cooperative* functionalities that can support self-awareness. For a consumer, these spaces would represent a specific location such as an apartment, office building,

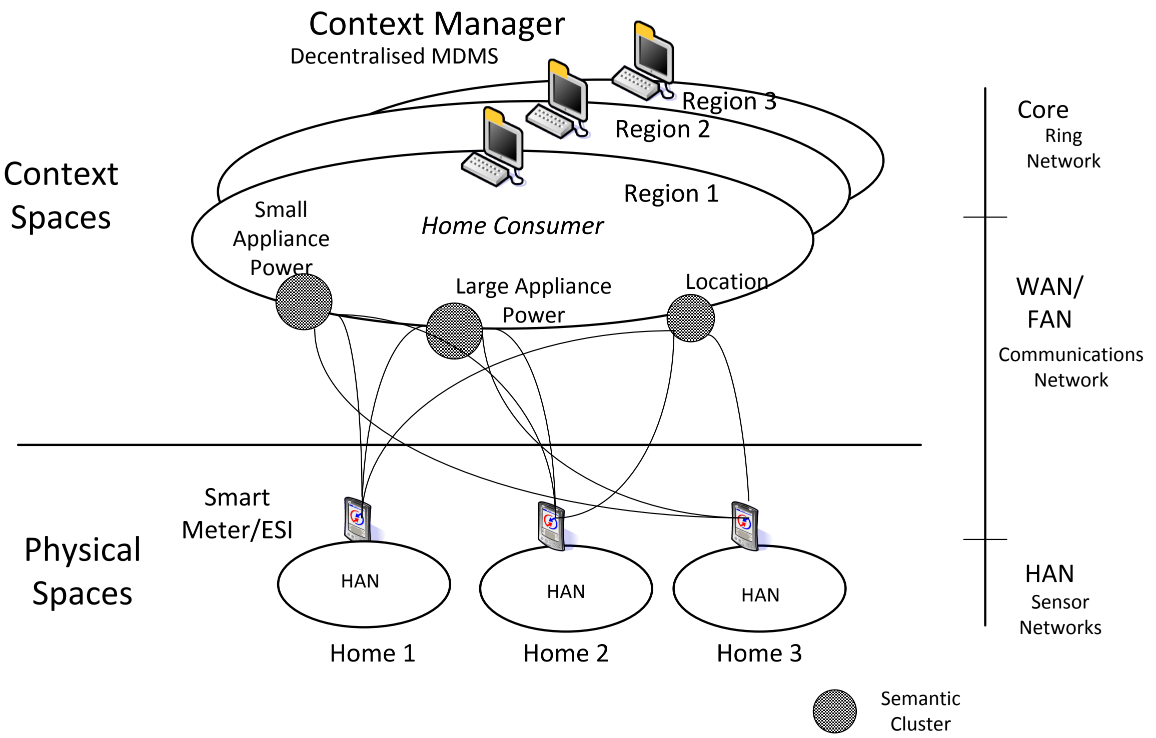

Figure 3: Consumer physical spaces (e.g. HAN) are mapped into regional abstract context spaces containing semantic data clusters.

or factory. For a power provider, the smart spaces will encompass a wider geographical area that would include renewable and conventional power generation as well as the transmission and distribution networks.

6.1. Consumer Smart Spaces

A physical consumer smart space, whether large or small, will have a HAN or BAN and a smart meter/ ESI to control the use of appliances, take sensor readings and register the power consumed. Industrial working groups such as OGEMA 2.0 are producing proposals for an OSGi based multi-function home gateway that would interface with power companies. In future context-awareness for the physical space could be incorporated in this type of gateway.

Consumer physical spaces could then be mapped into corresponding abstract logical *context spaces* consisting of a context space gateway and a set of semantic data clusters with context attributes representing processed sensor data from the physical spaces. Consumer context spaces such as 'home', 'office building', 'server farm' or 'factory' will have semantic clusters such as *controllable power* and *location*. These context spaces might be subdivided (for scalability) either regionally or according to level of power usage as shown in Figure 3. Regional context spaces could then be organised into a single higher level *consumption* context space with a hierarchically superior context space gateway directing queries to the appropriate region or industry segment. The functionality for a consumer context space gateway can reside in, for example, a decentralised MDMS as it would have access to all the necessary smart meters and EISs in the regional physical spaces.

There would also be larger-scale *virtual* consumer physical spaces such as a public lighting network or an electric car charging point network. These virtual physical spaces would have context awareness residing in a public lighting or charge-point network control system. The associated context space functionality could reside in an MDMS that received input from virtual physical spaces. Overall, the consumer context spaces would provide a fine-grained regional view of power consumption at any given time to upper level service management and application layers.

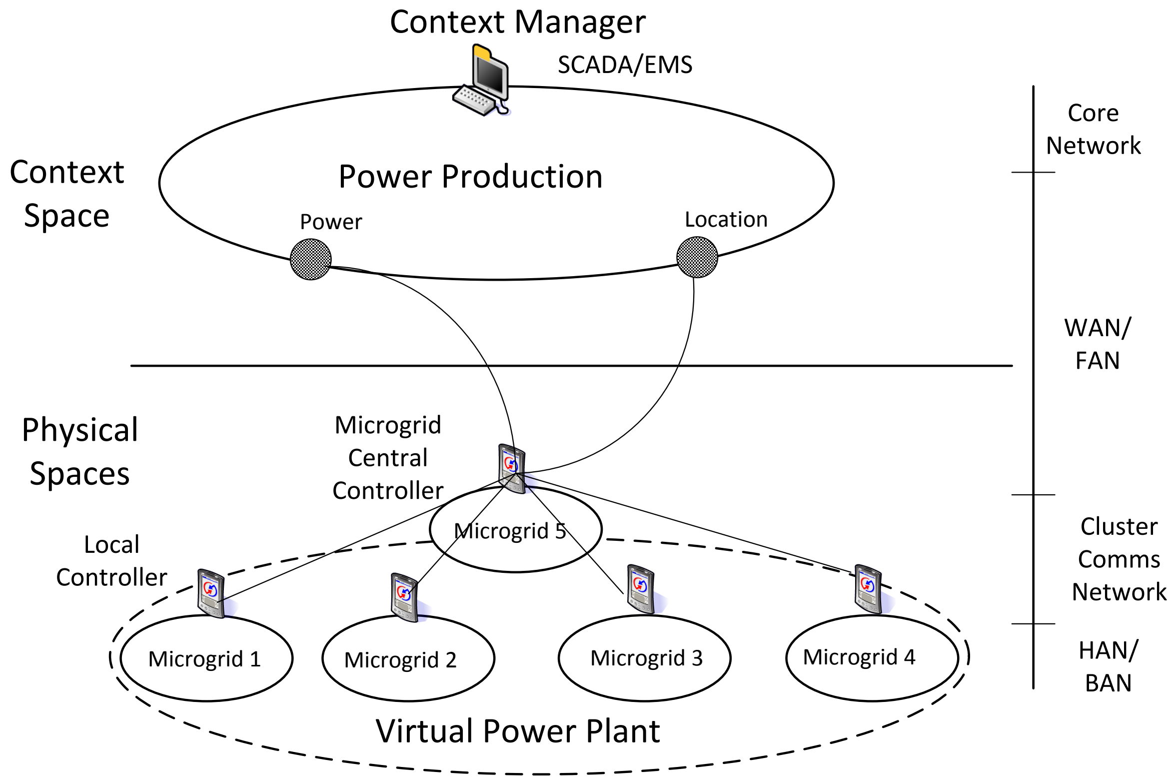

Figure 4: Microgrid physical spaces can be clustered into a VPP and mapped into a power production context space.

The challenges for consumer smart spaces include (a) the management of heterogeneous sensors, consumers and consumer domains, (b) the modelling of consumer behaviour based on sensor and other data to predict power supply and demand, (c) the control of appliances by consumers and providers (e.g. demand response). Smart spaces to represent domestic physical spaces have already been investigated in pervasive computing ([75], [76]). Therefore, adaptation of pervasive computing applications for smart grid domestic spaces may only require minimal extensions to existing models. The physical space (real or virtual) would use a single domain context-aware model like SOCAM, the Coalition PSG or PocketMon (HiCon) that can interact with a higher domain context space model. The context space would be based on the higher level Coalition or HiperMon platform. However, the middleware must incorporate dynamic context mapping that is not only suited to the end user in a domestic space but also can map to any dynamic environment that the user may migrate into.

6.2. *Microgrid Smart Spaces*

Microgrids present an interesting challenge as they exist in both the consumer space and the provider space. An individual microgrid can be its own physical space. As a consumer, it maps into the consumption context space while as a producer it maps into the power provider context space. The clustering of microgrids into *Virtual Power Plants* (*VPP*) requires a two-level physical space with a designated gateway acting as a *Microgrid Centralised Controller* (*MCC*), accepting requests and providing context attributes for the whole cluster. The hierarchical nature of the physical space would be reflected in the corresponding overlay communications network where the constituent HANs and BANs form a microgrid cluster network. The VPP physical space would still map into the power production context space, as shown in Figure 4, unless there were sufficient VPPs to warrant a separate context space. The main challenges for a cluster control system include balancing production and consumption, meeting any export forecasts and managing virtual storage (e.g. electric cars). Context-awareness can be implemented in the smart physical/context

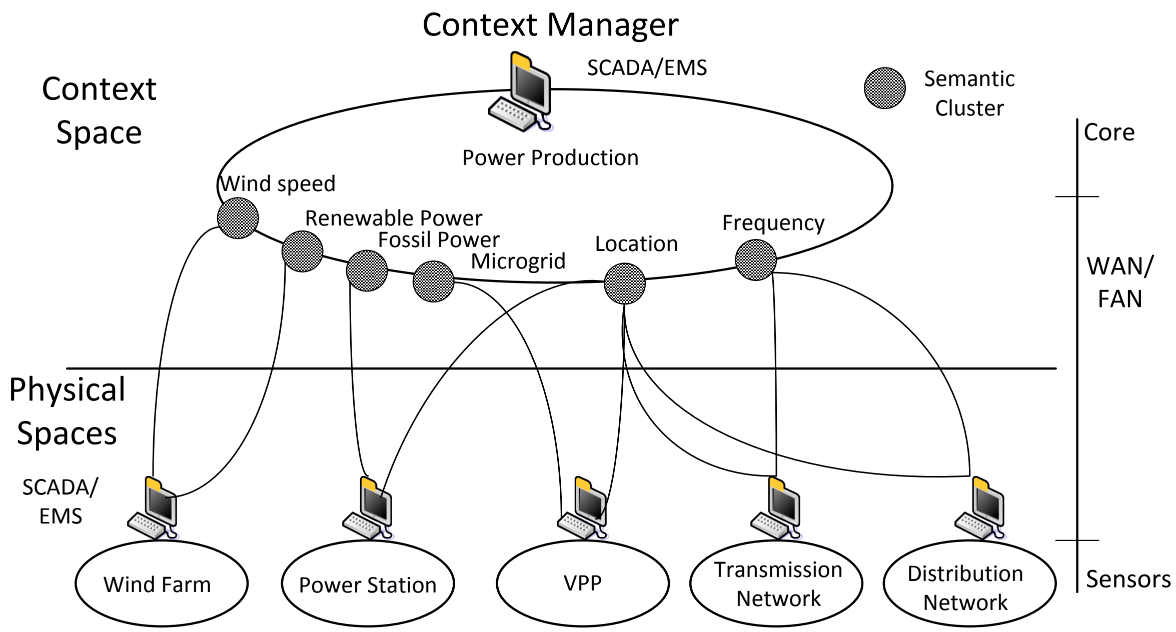

Figure 5: Power production and transmission virtual physical spaces are mapped into a power production context space.

space using a model like Coalition or PocketMon/HiperMon (HiCon) that can replicate single microgrids on the one hand and a cluster control system on the other.

6.3. Power Provider Smart Space

The power provider smart space will also contain physical spaces and context spaces. The power supply side (including renewables and interconnections) might best be modelled as *virtual physical spaces* (e.g. wind farm, solar farm) with the associated management systems (SCADA/EMS) acting as context-aware gateways. The corresponding *power production context space* would contain semantic clusters representing values like power output, voltage levels and meteorological data. The transmission and distribution networks can be similarly modelled firstly as virtual physical spaces and then mapped as semantic clusters for different types of sensor information into the power production context space.

A major challenge for power provider physical spaces is the handling of dynamic sensor information that is distributed throughout the infrastructure. Mitigating context imperfection (e.g. faulty or incomplete data) using data fusion has been addressed in pervasive computing systems but these solutions have only catered for small scale networks. At the same time, a power provider may incorporate large-scale wind farms, tidal power or solar power infrastructures. Each of these infrastructures may exist in very harsh environments that will require different types of data fusion approaches.

The overall power production context space would provide detailed information on power production and network status as shown schematically in Figure 5. Microgrid output will also dynamically change depending on consumption levels by the end users. There are existing context-awareness models (e.g. SOCAM) that could be extended for virtual physical spaces such as individual wind farms or microgrid clusters. These would then interwork with a higher

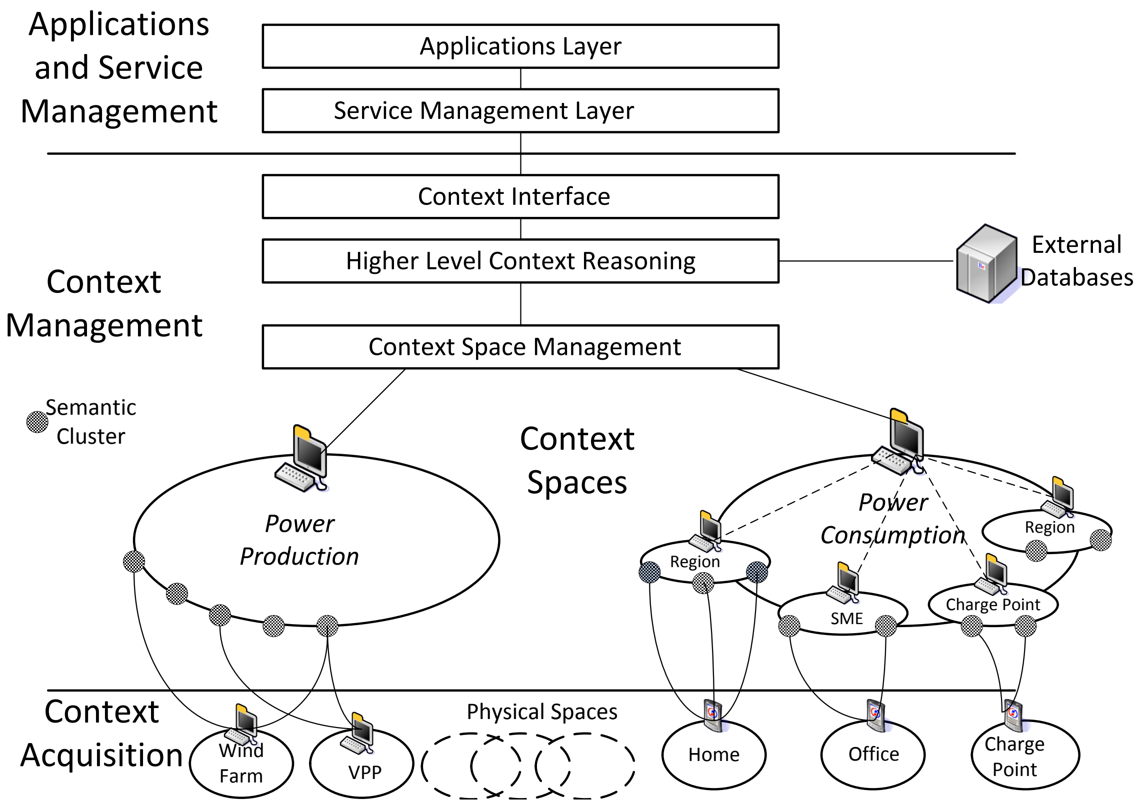

Figure 6: Integration of power production and power consumption context spaces using higher-level context-aware middleware.

layer of computation (e.g. Coalition or HiCon) to create a complete power production context space managed by a context-aware SCADA/EMS system.

6.4. The Complete Smart Grid Space

The power production context space would be peered with the power consumption context space providing all the context information for the complete smart grid. This structure is shown in Figure 6. The exact mapping of physical spaces into semantic clusters and context spaces is a specific modelling exercise that would have to consider projected data volumes from each physical space, the number of different context attributes (semantic clusters) and the latency introduced by adding hierarchical layers. An optimisation model could help identify an initial set of context spaces and a corresponding hierarchy. This could be reconfigured at any stage if growth in demand warranted it. As illustrated in Figure 6, the individual context spaces would form part of an overall context data management layer. This layer would perform context space management (configuring and managing context spaces), provide higher level context reasoning and process queries from a query interface. At this point inputs from external databases would also be added to provide information such as interconnected power levels, wholesale prices, customer tariffing, customer profiles and weather forecasts. Commercial or regulatory policies can also be incorporated at this level. This integration and aggregation of multiple context models from each of the context-spaces is an additional motivation for applying unifying canonical information models as recommended by NIST (as described in §3.6).

Challenges and guidelines for building smart spaces in the smart grid are summarised in Table 5. The challenges are those that will be encountered as a matter of course in different areas (smart spaces) of the smart grid. The guidelines show how context-awareness can be applied to meet these challenges using examples from existing context-aware models.

Table 5: Smart Grid Context-aware Platform Challenges and Guidelines

Smart Physical/Context Space	*Challenges*	*Guidelines*
Consumer Spaces	Manage heterogeneity of sensors and domains. Predict demand and manage supply based on consumer behaviour. Allow power provider control of appliances for demand response.	Embed context reasoning in Home Gateways, Building Gateways and other local management points using middleware like SOCAM, PSG or PocketMon. Manage the context space at the MDMS using the higher level reasoning of Coalition or HiperMon.
Microgrid and Microgrid cluster (VPP)	Manage the import and export of power based on different context and consumer profiles, variable tariffs and auction price points. Combine a cluster of microgrids into a virtual power plant. Optimise cluster operation to meet agreed export forecasts. Manage the use of electric cars as a storage system.	Provide a cluster control system based on a hierarchical middleware model like Coalition or HiperMon that would interact with (a) individual microgrids in a peer-to-peer fashion and (b) the power provider control system.
Power Provider Spaces	Manage and forecast distributed variable power production. Mitigate power surges and deficits through demand response. Detect and rectify network failures through situation response. Process sensor data in harsh environments.	Incorporate context reasoning in a local SCADA system (e.g. PSG). Use middleware like Coalition or HiperMon (HiCon) to process context data from production units and transmission networks in a higher level SCADA.
Full Smart Grid Context Space	Balance production and consumption across the grid. Forecast and schedule supply based on projected demand. Integrate information from external databases. Implement regulatory and commercial policies.	Use a context reasoning model like Coalition or HiCon to process context information from all context spaces and integrate it with external sources.

7. Conclusions

A smart power grid will not exist in isolation. Sensor networks, automated reasoning and context-awareness will be implemented in areas such as healthcare, transportation, utilities and other sectors of industry. Apart from the scenarios described earlier in §4.2 we can project ahead to other areas where context awareness can enhance the operation of a smart grid and provide for interworking with other smart spaces.

The balance of renewable power versus non-renewables can be computed at any given time by a power provider through a context-aware smart grid. A power company may also have policies in place (or imposed regulations) about maximising the use of renewable energy or minimising the importation from other companies. These policies can be incorporated into the forecasting and scheduling process. This will assist in meeting targets for the use of renewables or reducing CO_2 emissions. Power companies may therefore be able to benefit from incentives to maximise the use of renewable power and avoid penalties for excessive CO_2 emissions.

Smart power grids will become a part of much larger smart energy grids (gas/electricity) or smart utility grids (gas/electricity/water). Furthermore, smart buildings, smart transportation, smart street lighting and smart suburbs will all be components of future *smart cities*. Different types of information (commercial, technical, financial) will have to flow between these players for the seamless provision and billing of services. The context-aware model requires the exchange of agreed database information as part of service building. In turn, the majority of the information generated by a power provider may be of interest to other parties such as other utilities (gas, water), city authorities, government agencies, planning authorities and research institutes. Consumption patterns can be a good indicator of economic activity and provide valuable input for regional or national development plans.

The smart grid is still at an early stage of development. The rollout of smart meters for example varies widely from region to region while the deployment of sensor networks in the home and in the power network has yet to reach meaningful volumes. Nevertheless, there is a range of economic, political and environmental drivers at work that will inevitably force the move to greater intelligence in power grids. Hardware such as sensors and smart meters is just one aspect of this. Developing an overlay communications network and software systems for end-to-end smart grid management and services will be another major part. The ultimate goal is a self-aware network that can incorporate a multiplicity of power sources and deliver a wide range of consumer and power provider services.

The wide use of sensor networks and the need to provide a rich variety of time-aware and location-aware services points to a need for context-awareness for both producers and consumers. Consequently, we believe that scalable, interoperable context-aware middleware platforms should be developed to meet the needs of the smart grid. These platforms should be based on semantic data models that are specifically developed for the smart grid (e.g. CIM) and should use hybrid context reasoning methods based on fact, spatial and ontology based models. Large scale platforms may require a distributed architecture as a centralised approach would be considered too vulnerable. Furthermore, a distributed architecture would provide for some localised processing and autonomic control. The volume of data generated by a smart grid will necessitate the development of imaginative methods for prioritising data storage and retrieval if all service requirements are to be met. We believe that the use of context spaces, semantic clusters and a hierarchical processing structure is a realistic method of providing for scalability and the streamlining of data handling as well as delivering advanced services. The specification and hierarchy of suitable clusters and the definition of appropriate ontologies for context representations in different smart grid scenarios will be important areas of further research.

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Vitae

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