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Middleware-based Energy Resource Management in Smart Grid

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DECLARATION

I, Jianchao Zhang, hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university of institution of higher learning.

Signature　　　　　　　　　　　　　　Date

ABSTRACT

The Smart Grid incorporates advanced information and communication technologies (ICT) in power systems, and is characterised by high penetration of distributed energy resources (DER). Whether it is the nation-wide power grid or a single residential building, the energy management involves different types of resources that often depend on and influence each other. The concept of virtual power plant (VPP) has been proposed in literature to represent the aggregation of energy resources in the electricity market, and distributed decision-making (DDM) plays a vital role in VPP due to its complex nature.

Following an extensive literature review, it emerges that there is research opportunity in utilising middleware technologies for energy resources management in Smart Grid. Therefore, the research presented in this thesis is to design and develop middleware-based methodologies/approaches for effective and optimal management of energy and energy-related resources. This research provides insights into how buildings can be readied for the Smart Grid in the aspect of resource management, and how energy resources should be scheduled in VPPs composed of third-party buildings. Prototypes and evaluations for the research are presented as well.

This thesis is structured into seven chapters, with the first three chapters providing an introduction, background and literature review for this research. Chapter 4 investigates energy-related domain Resources Management and how Building Information Modelling (BIM) and Software-Defined Networking (SDN) can contribute to the development of

Smart Grid-Ready Buildings (SGRBs). Firstly, BIM is extended for the design phase to provide Material/Device profiling and information exchange interface for various smart objects. Next, a three-layer verification framework is proposed to assist BIM users in identifying possible defects in their SGRB design. For the post-construction phase, a facility management tool is designed to provide advanced energy management of SGRBs where smart objects as well as distributed energy resources (DERs) are deployed. Finally, the synergies between SDN and Smart Grid is presented, along with use cases of utilising SDN and BIM for SGRBs in VPP.

Chapter 5 proposes a framework for managing different resource types of relevance to energy management for VPP in decentralised manner. The framework views VPP as a hierarchical structure and abstracts energy consumption/generation as contractual resources, i.e. contractual offerings to curtail load/supply energy, from third party VPP participants for DDM. The proposed resource models and event-based approach are presented for decision making. The proposed multi-agent system and ontology implementation of the framework are discussed. The effectiveness of the proposed framework is then demonstrated through an application to a simulated campus VPP with real-world energy data.

In Chapter 6, a novel two-step game theoretic approach to energy scheduling in VPPs composed of third-party owned residential/commercial houses/buildings with prosumer resources, is proposed. The two steps include day-ahead planning and very short term scheduling to address real-time market/prosumption conditions through integrating finite and infinite game models. A new prosumer utility function is introduced, which models prosumer through three sub-utilities: consumption willingness, production willingness and consumption-production constraint. To practically evaluate the proposed designs, their multi-agent system (MAS) implementations and simulations are presented using real-world energy data.

Chapter 7 concludes the thesis.

ACKNOWLEDGMENTS

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Finally, I would like to thank my family. My wife Jie and my son Zongyue, who stand by me through all the hard times, my little son Zongyou, who was born during the final amendment of this thesis, and my parents who tolerate all my faults as always. Thank you all for your support, for your understanding, and for your love.

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GLOSSARY

AMI	: Advanced Metering Infrastructure
BIM	: Building Information Modelling
CIM	: Common Information Model
DER	: Distributed Energy Resource
DG	: Distributed Generation
EV	: Electric Vehicle
ICT	: Information and Communication Technology
MAS	: Multi Agent System
MG	: Microgrid
OWL	: Web Ontology Language
PMU	: Phasor Measurement Unit
PV	: Photovoltaic
RES	: Renewable Energy Sources
UML	: Unified Modelling Language
VPP	: Virtual Power Plant
µCHP	: Micro Carbon Heat Produce

CHAPTER I: Introduction

In recent years, the electrical power grids around the world have gained unprecedented momentum to advance towards a “smart” era. The term Smart Grid [1], which has been proposed as an evolution of current electricity power systems with advanced information-communication technologies (ICT), is sometimes also referred to as “Internet of Energy” [2]. This is because the Smart Grid is large-scale, heterogeneous and distributed in nature. Furthermore, unlike in the traditional electricity system where energy can only flow in one direction from the power plants to end-consumers, Smart Grid is designed to have bi-directional energy flow, i.e. two-way energy supply which makes entities in the system able to both supply and consume energy. In Smart Grid, a diverse and large number of devices, appliances, and energy sources distributed throughout the electricity system will be interconnected and communicating information for metering, monitoring and control, as shown in Figure 1.1.

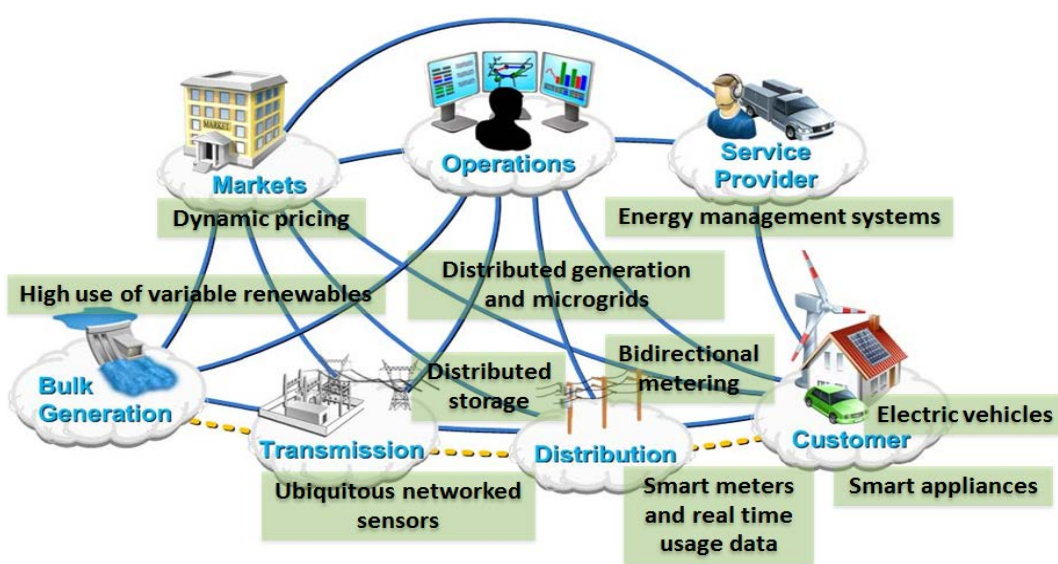


Figure 1.1 Smart Grid Conceptual Model

One of the aims of the Smart Grid is to enable smarter energy usage through the integration of distributed energy resources (DERs), which in recent years have increasingly penetrated the electricity power system through their massive installations on either power company or end-consumer sites. The term DER commonly refers to distributed generation (DG) devices of electricity, distributed energy storage and controllable energy loads [3]. Renewable energy sources (RES) such as solar panel and wind turbine, are types of DG devices and therefore DERs.

With the application of sophisticated ICT, new forms of DER control and electricity market interfaces have emerged, which however also increase the complexity of interaction required to facilitate de-centralised system management across the power grid. To effectively integrate DERs and have the power systems evolve towards the "Internet of Energy", the concept of Virtual Power Plant (VPP) has been proposed by researchers to represent the aggregation of energy sources in the electricity market [4].

As more and more buildings, either residential or commercial, are installed with on-site RES or energy storage systems, the role of buildings in the power system has changed from pure energy consumer to both energy producer and consumer, or better known as "prosumer" [5]. The energy resources of buildings in close proximity can be aggregated as a VPP, the operational details of which are hidden from the main grid, which sees only one power plant in the energy flow. It is believed that VPP is the evolution pathway to Smart Grid, and thus it has attracted much research around the globe [4].

1.1 Motivation and Scope

There is a large variety of resources (e.g. energy resources such as DERs and prosumers, ICT resources such as computing platforms and network infrastructure) in Smart Grid. However, to date there is no successful mechanism to control and coordinate these resources at distribution level. Some researchers also observe that the current Distribution Management System (DMS) of the utility operator does not fully take DER integration support into consideration [6]. Furthermore, DERs and prosumers are also expected to contribute to general power reliability and stability by actively participating in the energy market (through VPP), and this requires proper modelling of the energy resources and their scheduling as well as a viable VPP architecture/framework to facilitate solutions for resource management based on such models.

As buildings have become prosumers and participants of VPP, the resource management problem in VPP involves different resources from different domains, e.g. power system and ICT domains, requiring complex provisioning and planning by collaborating between different resource management systems that are often owned by different customers. This demands a resource management approach that is more agile and flexible than existing ones, and which explicitly considers the interactions between systems in different domains. Specifically, the following questions have arisen when managing resources in a VPP composed of third-party buildings not owned by the VPP operator:

- For a VPP constituted of buildings in which smart objects such as networked sensors and actuators are installed for energy management/provisioning and making the buildings “smart”, domain resources other than power system resources, such as ICT resources and spatial resources, are coming to play an important role in the scheduling of energy by energy management systems (EMS). This is because they are either supporting their data operations (e.g. data collection/processing/storage) or serving as the knowledge base for energy forecast/control. The questions arise on how these resources in different domains should be managed in the context of VPP? How should they be managed in a building's post-construction phase? Is there a solution that seamlessly integrates DERs into the buildings' life cycle with relevant ICT/spatial resources and makes them ready for Smart Grid operations such as energy generation forecast, load scheduling, storing and feeding energy back to the grid?

- In a VPP, since each participant (building) has to consume energy to achieve some objectives, how should the VPP maintain a balance between profiting from energy trading and meeting participants' consumption needs? Furthermore, how should these prosumers' consumption/generation be scheduled in order to maximise their payoff (e.g. revenue and comfort) under real time changes in both generation and consumption patterns?

- To enable effective co-operation and decision-making between VPP participants, how should different energy related resources be modelled, organised and managed, considering their different ownerships? Is it possible to design a universal framework for resource management problems in VPP? What methodology should such a framework utilize for real world energy resource scheduling problems?

This research seeks to address and answer the above questions, and to provide insights into the application of energy management systems for VPP in Smart Grid. Middleware approach is adopted, as it offers the ability to provide abstraction and interoperability for distributed decision making, while providing a component-based paradigm for flexible development of distributed applications. Fault tolerance and recovery of the middleware system is beyond the scope of this research.

1.2 Contributions

There are three main contributions from this thesis, which are listed as follow:

- **Management of energy-related domain resources for VPP in Smart Grid.** There is currently a knowledge gap in cross-domain management of energy-related resources for VPP in Smart Grid, which include not only power system resources, but also ICT and spatial resources. To address this gap, a novel methodology is proposed for integration of Building Information Modelling (BIM) and Software-defined Networking (SDN) for DERs in VPP constituted of smart buildings. This research investigates how BIM can contribute to the development and management of smart buildings in the Smart Grid era. Since BIM is designed to host information of the building throughout its life cycle, our investigation has covered phases from architecture design to facility management. Firstly, BIM is extended for the design phase to provide Material/Device profiling and information exchange interface for various smart objects. Next, a three-layer verification framework is proposed to assist BIM users in identifying possible defects in their smart building designs. For the post-construction phase, a facility management tool is designed to provide advanced energy management of Smart Grid connected smart buildings where smart objects as well as DERs are deployed. Furthermore, for the management of ICT resources in VPP to support Smart Grid operations, SDN technology is explored together with BIM through use-case studies for supporting virtualisation in VPP, thereby readying the building participants in VPP for the Smart Grid.

- **Event-based resource management framework for distributed decision-making for decentralized VPP in Smart Grid**. There has been very limited or no research on distributed decision-making for resource management with buildings as VPP participants. To address this gap, this research presents novel resource models, concepts of events and corresponding event processing, based on which an event-based resource management framework is proposed to support distributed decision making in the VPP. By viewing the VPP as a hierarchical structure and abstracting energy consumption/generation as contractual resources, i.e. contractual offerings to curtail load/supply energy, from third party VPP participants, the proposed framework offers flexibility and adaptability to cross-domain system designs, which in turn accelerates the development of energy management applications. Ontology and multi-agent system (MAS) implementations are presented for the proposed framework.

- **Game theory based energy resource scheduling for VPP in Smart Grid**. To-date, game theory based resource scheduling research for VPP have mainly focused on consumption behaviours of VPP participants. There is neither yet a sound prosumer game model, nor a game-based approach to real-time resource scheduling for VPP. To address this gap, a novel two-step game theoretic approach to prosumer resources scheduling is proposed. This approach seeks to make a balance between monetary profiting from energy trading and meeting energy consumption needs of the VPP participants by evaluating their payoff with their willingness to consume/produce energy, and to address real-time uncertainties of VPP energy resource scheduling by dividing the problem into day-ahead planning and very short term scheduling. The proposed methodology can be applied to any buildings with on-site generation to achieve both short-term (day-ahead) and real time (within half hour) scheduling. In addition, a prosumer utility function is proposed, which models the prosumer through three sub-utilities: consumption willingness, production willingness and consumption-production constraint. The proposed utility function differs from current player utility functions, in that the latter are typically based on appliance list, environmental conditions, or modelling prosumer behaviour using only consumption preferences. Finally, through integrating finite and infinite game models with a consistent prosumer utility function, the proposed approach addresses the challenges of real-time resource scheduling in VPP under dynamic conditions, such as consumption/generation changes in short notice, e.g. at less than half hour.

The following are publications generated during this research:

Journals:

Zhang, J., Seet, B. C., & Lie, T. T. An Event-Based Resource Management Framework for Distributed Decision-Making in Decentralized Virtual Power Plants. *Energies*, 9(8), 595, 2016. doi:10.3390/en9080595

Zhang, J., Seet, B. C., & Lie, T. T. Building Information Modelling for Smart Built Environments. *Buildings*, 5(1), pp. 100-115, 2015. doi:10.3390/buildings5010100

Zhang, J., Seet, B. C., & Lie, T. T. Game Theoretic Real-Time Energy Scheduling for Virtual Power Plant with Prosumer Resources (submitted to a journal).

Conferences:

Zhang, J., Seet, B. C., Lie, T. T., & Foh, C. H. Opportunities for Software-Defined Networking in Smart Grid. In Proceedings of the 9th International Conference on Information, Communications and Signal Processing (ICICS), Tainan, Taiwan, 10-13 December 2013.

Zhang, J., Seet, B. C., & Lie, T. T. BIM-Based Energy Management for Smart Built Environments. In Proceedings of the Building a Better New Zealand Conference, Auckland, New Zealand, 3-5 September 2014.

1.3 Thesis Structure

The rest of this thesis is organised as below:

Chapter 2 gives an overview on various aspects of Smart Grid, middleware, resource management, BIM and game theory, which form the background of this research.

Chapter 3 presents a literature review of related works, including topics on existing middleware and standards in Smart Grid, VPP development and scheduling, smart buildings, and game theory application in Smart Grid.

Chapter 4 proposes a methodology of integrating BIM and SDN in smart building design and energy management, with the aim of making buildings ready for Smart Grid. This chapter provides insights into how DERs can be integrated into the building life cycle, and presents a middleware prototype as proof of concept. In addition, the opportunity for SDN in Smart Grid is explored and use cases are presented.

Chapter 5 proposes a framework, which views VPP as a hierarchical structure and abstracts energy consumption/generation from third party VPP participants for managing different resource types of relevance to energy management in decentralized VPP. Under the proposed framework, resource models and an event-based approach for distributed decision-making on resource selection are presented. The MAS and ontology implementation of the framework are also presented. As evaluation, an analysis is conducted on a simulated campus VPP with real building energy data.

Chapter 6 proposes a two-step energy resource scheduling for VPP composed of both residential and commercial buildings based on game theory. The energy resource scheduling is modelled with prosumer resources as players. The two steps include day-ahead planning and very short term scheduling to address market and real time conditions.

A prosumer utility function is introduced, which expresses the willingness to consume energy in a prosumer objective function. A MAS implementation approach on the design and simulation results are presented as well.

Chapter 7 concludes the thesis and discusses some possible directions for future research.

CHAPTER II: Background

In this chapter, the background concepts of technologies related to this research, namely Smart Grid, middleware and utility/game theory are presented.

2.1 Smart Grid Technologies

Smart Grid has been proposed as an evolution of current electricity power system by incorporating the most advanced information communication technologies (ICT) [1]. ICT resources, such as communication network devices, data storage servers and computation processors, serve to support energy related data transmission, storage and/or processing. Unlike in the traditional electricity system where energy can only flow in one direction from the power plants to end-consumers, Smart Grid is designed to have bi-directional energy flow, i.e. two-way energy supply which makes entities in the system able to both supply and consume energy.

In this section, three main building blocks of Smart Grid are introduced, namely: advanced metering infrastructure, Microgrid and virtual power plant, demand side management and demand response. In addition, the operations of the New Zealand electricity market for Smart Grid are presented.

2.1.1 Advanced Metering Infrastructure

There is much ongoing work to improve the metering reading of the electric distribution system. In recent years, Automated Metering Reading (AMR) has provided the power company with the capacity to read the customer's consumption records and status remotely [7]. However, AMR’s capability is far from being able to achieve load controlling due to its one-way communication. Consequently, Advanced Metering Infrastructure (AMI), which provides a two-way automated metering infrastructure, has been advocated by power companies around the world. Smart meters, manufactured according to AMI standards to provide two-way communication and appliance control capabilities, have been deployed on the customer side. These meters are also considered as an essential component of smart buildings/homes, for they are crucial devices of energy management.

2.1.2 Microgrid and Virtual Power Plant

To address distributed energy resource (DER) integration requirements in Smart Grid, the concepts of Microgrid (MG) and Virtual Power Plant (VPP) have been proposed. Lasseter [8] defines a Microgrid as a cluster of local DERs and loads operating as a single controllable system that responds to central control signals and provides both power and heat to its local area. Most DERs installed in a MG are not able to be directly connected to the electrical network due to the characteristics of the energy they generated. Consequently, power electronic interfaces (DC/AC or AC/DC/AC) are an absolute necessity. Therefore, one of the primary concerns in MG operation is the inverter control. The MG is centrally managed by a MG central controller (MGCC) installed at the medium voltage/low voltage (MV/LV) substation. The MGCC is responsible for functionalities such as economic management and power control, and is the parent of the hierarchical control systems inside MG [8]. Key global research initiatives on MG include “MICROGRIDS” of the European Research Project Cluster “Integration of RES+DG” [9], Japanese NEDO Aomori, Aichi and Kyoto projects [10], and the Korean

Jeju project [11]. These projects mainly aim at integrating DERs from the energy prospective and focus on power inversion and control.

On the other hand, the concept of VPP refers to a logical aggregation of local and non-local DERs and presents them to the rest of the energy system as a single technical and commercial entity by clustering the DERs according to their geographical, technological and/or commercial characteristics [12]. VPP provides individual DERs a universal logical gateway to participate in the energy system and market operation. Research has shown that through aggregation and clustering into a VPP, distributed energy resources can benefit from the aggregated market intelligence, not to mention the increased overall power system efficiency [13–16]. In fact, the VPP concept has been extended to the aggregation of power loads as well, giving rise to the concept of Virtual Power Load (VPL), which has been popular in aggregating controllable loads such as EVs. In [17], a generic framework for VPP design is proposed. The Danish EDISON project in [18] investigated the possibilities of clustering EVs on an island into an EV-VPP and implementing the VPP in real power system.

The control and aggregation of DERs in MG and VPP have attracted much attention within the research community. To effectively achieve the aggregation/clustering modelling function of the middleware, this thesis focuses on the VPP concept for designing the technique needed to support DER integration and management, as well as the resource scheduling algorithm.

2.1.3 Demand Side Management and Demand Response

Demand side management (DSM) is a portfolio of measures to improve the energy system at the consumer side. It ranges from improving energy efficiency by using better building materials, to introducing smart energy tariffs with incentives for certain consumption patterns, and sophisticated real-time control of distributed energy resources [19]. It has been widely accepted that demand response (DR), one type of DSM which signals electricity customers to perform consumption/generation adjustment, will play an important role in reliable and economic operation in Smart Grid [20]. Demand response programs are designed to increase the flexibility and reliability of the power system, and reduce customer load at peak periods (peak-shaving). As encouragement to participate in DR programs, customers are normally financially rewarded for curtailing their electricity usage at peak hours, and/or shifting their energy consumption to non-peak hours.

Demand response programs can be classified into three types according to the party which initiates the demand reduction action [21]:

- Incentive-based DR programs: demand response signals are sent from the power company to the end customers. Directly controllable or interruptible loads (by the power company) can be utilized to reduce demand upon receiving such signals.

- Rate-based DR programs: the price of electricity is changed at predefined time periods, or dynamically based on various times of the day/week/month/year. The customers would pay higher electricity price at peak hours.

- Demand reduction bids: bids from customers to reduce their energy consumption are sent to the power company, which chooses acceptable bids and sends back corresponding agreements. Customers whose bids are accepted undertake actions according to their bids.

2.1.4 New Zealand Electricity Market

New Zealand has put much effort into Smart Grid development, e.g. by implementations of real time pricing and massive deployment of smart meters. In this sub-section, the operations of the New Zealand electricity market are introduced.

In New Zealand, electricity is traded at a wholesale level in a spot market [22]. Generators submit offers, each of which covers a future half-hour period (called a trading period) and is an offer to generate a specified quantity of energy at that time in return for a nominated price. The national system operator ranks submitted offers in order of price, and selects the lowest-cost combination of offers from the generators to satisfy demand.

The highest-priced bid offered by a generator required to meet demand for a given half-hour sets the spot price for that trading period. Electricity spot prices can vary significantly across trading periods, reflecting factors such as changing demand (e.g. lower prices in summer when energy demand is subdued) and supply (e.g. higher prices when water level in hydro lakes and inflows are below average).

2.2 Middleware Technologies

Middleware is computer software that provides services to software applications beyond those available from the operating system. It can be described as "software glue" [23]. Due to its capability of hiding lower level details and providing a unified interface to upper level applications, middleware technologies have become a crucial component for many large-scale software applications. Examples of modern middleware are enterprise service bus (ESB) and cloud-based publish-subscribe messaging platforms. In cyber physical systems (CPS), e.g. Smart Grid, physical and software components are deeply intertwined, and middleware technologies plays an important role as well. In this section, two middleware technologies related to this research, namely ontology and multi-agent system, are introduced. An introduction to software-defined networking (SDN) is also presented at the end of this section. Though SDN is not a technology of middleware, its control plane component is commonly integrated into middleware to provide networking interface for software applications.

2.2.1 Ontology

First defined by Aristotle, ontologies are formal models on how we perceive a domain of interest and provide a precise, logical account of the intended meaning of terms, data structures and other elements modelling the real world [24]. Ontologies can help in the representation of the content of a Web resource in a formal manner, so as to be used by an automated computer agent, crawler, search engine or other Web services. The importance of ontologies in current artificial intelligence (AI) research is also demonstrated by the interest shown by both the research and enterprise community in solving various problems related to ontologies and ontology manipulation [25].

In information and computer science, ontologies are commonly implemented using Resource Description Framework (RDF) [26] and Web Ontology Language (OWL) [27]. RDF and the related RDF Schema (RDFS) are the format for graph data models by defining a RDF statement called RDF triple consisting of a subject, predicate and object. An RDF triple example is shown in Figure 2.1.

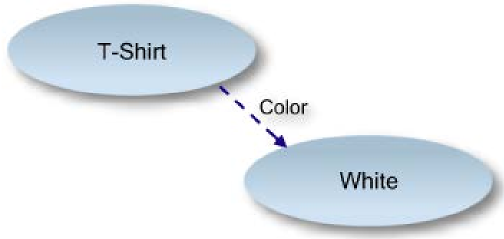


Figure 2.1 RDF Triple: Subject ‘T-shirt’, Predicate ‘Colour’, Object ‘White’.

Based on RDF, OWL is a semantic Web language designed to represent rich and complex knowledge about things, groups of things, and relations between things [27]. It extends RDF to allow machines to process and perform useful reasoning on resource descriptions. An example of an OWL document is shown in Figure 2.2.

```
<!DOCTYPE rdf:RDF [
   <!ENTITY owl "http://www.w3.org/2002/07/owl#">]>
<rdf:RDF xmlns:owl ="http://www.w3.org/2002/07/owl#"
      xmlns:rdf ="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
      xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#">
<owl:Ontology rdf:about="">
   <rdfs:label>My Ontology</rdfs:label>
   <rdfs:comment>An example ontology</rdfs:comment>
</owl:Ontology>
<owl:Class rdf:ID=”Person” />
<owl:Class rdf:ID=”Man” />
   <rdfs:subClassOf rdf:resource=”#Person” />
</owl:Class>
<owl:ObjectProperty rdf:ID=”hasChild” />
<owl:ObjectProperty rdf:ID=”hasDaughter”>
   <rdfs:subPropertyOf rdf:resource=”#hasChild” />
</owl:ObjectProperty>
<owl:DatatypeProperty rdf:ID=”age” />
<owl:ObjectProperty rdf:ID=”isParentOf”>
   <owl:inverseOf rdf:resource=”#isChildOf” />
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID=”isTallerThan”>
   <rdf:type rdf:resource=”&owl;TransitiveProperty” />
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID=”isFriendOf”>
   <rdf:type rdf:resource=”&owl;SymmetricProperty” />
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID=”hasSSN”>
   <rdf:type rdf:resource=”&owl;FunctionalProperty” />
   <rdf:type rdf:resource=”&owl;InverseFunctionalProperty” />
</owl:ObjectProperty>
</rdf:RDF>
```

Figure 2.2 Example OWL Document

2.2.2 Multi-Agent Systems

Multi-Agent System (MAS) is an implementation of distributed decision making (DDM) methodology that deals with behaviour management in collections of several independent entities or agents [28]. MAS provides both principles for construction of complex systems involving multiple agents and mechanisms for coordination of independent agents' behaviours, where agents are considered as entities in the system that behaves individually with their own behaviour goals/objectives. MAS is particularly useful for designing applications if there are different people or organisations with different goals/objectives and proprietary/private information.

The Foundation for Intelligent Physical Agents (FIPA) [29] is an organisation for developing and setting computer software standards for MAS, heterogeneous and interacting agents. The most widely adopted standards are the Agent Management and Agent Communication Language (FIPA-ACL) specifications.

2.2.3 Software-Defined Networking

In recent years, the paradigm of Software Defined Networking (SDN) has attracted much attention. It proposes the concept of a new networking architecture which abstracts the control functionalities from the packet forwarding hardware (data plane) to an external software controller (control plane). This is extremely convenient for large data centres to cope with virtual machine networking in which virtual machines are created dynamically and move between different physical machines. Due to the controller being implemented as software and its programmable interfaces with individual networking devices being exposed to other software applications, any network applications and services based on such an architecture can be more agile, as illustrated in Figure 2.3.

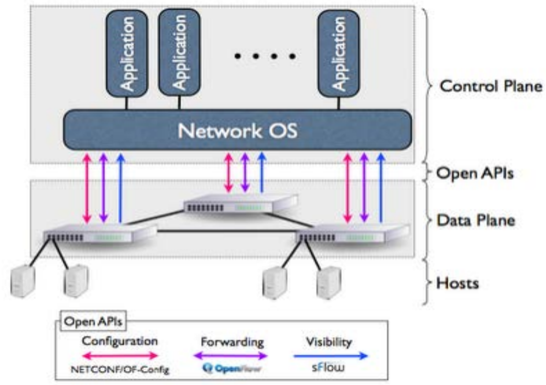


Figure 2.3 SDN Conceptual Model

Furthermore, application systems are enabled to be network-aware, which means that they are aware of the properties, requirements, and state of the network environment, and can quickly adapt to changes in the network context [30]. Therefore, in this thesis, SDN is perceived to have tremendous potential for the utilisation of ICT resources in Smart Grid.

2.3 Utility and Game Theories

As the basis for the proposed resource scheduling algorithms, utility theory and game theory play an important part in this research. In this sub-section, related background knowledge on utility and game theories is introduced.

2.3.1 Utility Theory

In economics, *utility* is a measure of preferences over some set of goods and services [31]. The concept is an important underpinning of rational choice theory in economics and game theory, because it represents satisfaction experienced by the consumer of a good, which satisfies human wants. Utility is considered to be reflected in people's willingness to pay different amounts for different goods. In game theory, utility also refers to the payoff for player.

The term *marginal utility* of a good or service is the change in utility resulting from an increase or decrease in consumption of that good or service. The concept that marginal utilities diminish across the consumption ranges relevant to decision-making is called *the law of diminishing marginal utility*. It means that the first unit of consumption of a good or service yields more utility than the second unit of consumption, and the utility continues to decrease with further units of consumption.

Another term *risk aversion* refers to the behaviour of humans (especially consumers and investors), when exposed to uncertainty, in an attempt to reduce that uncertainty. It is the reluctance of a person to accept a bargain with an uncertain payoff rather than another bargain with a more certain, but possibly lower, expected payoff. Say a consumer has a utility function $u(x)$ where x represents the monetary or goods value that he might receive in money or goods, and he possesses risk aversion if and only if the utility function is concave.

2.3.2 Game Theory

Game theory [32] is the formal study of decision-making where several players must make choices that potentially affect the interests of other players. Most research on game theory focuses on how groups of people interact.

There are two main branches of game theory: *cooperative* and *non-cooperative* game theory. *Non-cooperative* game theory deals largely with how intelligent individuals interact with one another in an effort to achieve their own goals. *Cooperative* game is a game where groups of players (coalitions) may enforce cooperative behaviour; hence the game is a competition between coalitions of players, rather than between individual players.

A strategy is one of the given possible actions of a player. A payoff is a number, also called utility, which reflects the desirability of an outcome to a player who exerts a certain strategy. A Nash equilibrium, also known as strategic equilibrium, is a list of strategies, one for each player, where no player can gain further payoff by unilaterally changing his strategy.

2.4 Chapter Summary

In this chapter, various technologies related to this thesis, namely Smart Grid, middleware, utility and game theories, are introduced. Microgrid and Virtual Power Plant are key technologies for DER integration and middleware technology has the potential to contribute to Smart Grid software development. In the next chapter, a detailed state-of-art review will be presented.

CHAPTER III: Literature Review

In Chapter 2, the background concepts of relevant technologies were presented. This chapter presents a detailed review of the state-of-art research relevant to the thesis topic, namely: resource modelling, middleware technologies, and resource scheduling algorithms.

3.1 Resource Modelling

As the basis for resource management, resource modelling provides the resource characteristic abstraction which can be further applied in relevant knowledge and mathematical analysis for resource management systems (RMS). Since in Smart Grid there are non-power system resources, which have been studied in other research areas, such as ICT resources in cloud computing, this section introduces various resource modelling techniques that are relevant but not limited to Smart Grid.

3.1.1 Resource Modelling in Cloud Computing and IoT

Information modelling is an essential process for resource management in Cloud Computing and the Internet of Things (IoT). The Semantic Sensor Network (SSN) Ontology [32] produced by the Semantic Sensor Networks Incubator Group (SSN-XG) is one of the most widely used information modelling techniques in IoT. The SSN is derived from Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) [33] and is based on Ontology Web Language (OWL). It describes the capabilities of sensors, their act of sensing and observations of result. In SSN, events are defined to represent resource state transition and are classified into two types: action and process.

SSN aims to provide universal modelling and thus may lack some functionality specific to different applications, but due to the extensibility of OWL, SSN can be easily extended to achieve those functionalities. The authors of [34] propose to extend SSN with querying historical data within the semantic sensor domain. A query language called QueryML is developed, which is claimed to gracefully handle query challenge within sensor domain.

On the other hand, in cloud computing, ICT resources have also been modelled using application-specific domain knowledge. In [35], the authors proposed multi-dimensional resource modelling for the allocation scheme in cloud computing, in which application-specific knowledge such as processing, computation and communication requirements of the client are considered in order to meet the service level agreements (SLA). In [36], the authors incorporate a user model into their ICT resource framework for storage allocation, modelling their ICT resources based on application-specific domain knowledge of both user and hardware information.

3.1.2 Power System Resource Modelling Standards

The International Electrotechnical Commission (IEC) Technical Committee 57 (TC57) [37] provides a reference architecture for electric power systems. The main data semantics and system models are standardized by the IEC 61850 and IEC 61970/61968 suites. Figure 3.1 shows the modelling domains of these standards.

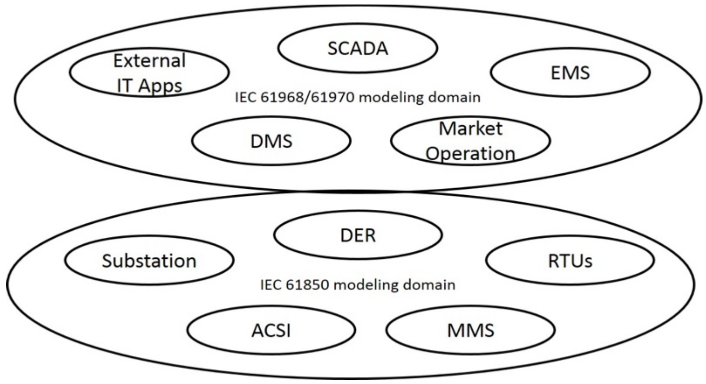


Figure 3.1 IEC Standards Modelling Domains

Data semantics provided by IEC 61850 are closely related to the functionality of devices in the subsystems of the power grid operator, such as substations, wind power plants, hydro power plants, and DERs [37]. Based on object-oriented modelling, IEC 61850 defines the abstract device and information model for common information found in real devices and available to be exchanged in power system automation [38]. The device data are classified into runtime exchange data and device configuration data, and information in real devices is mapped to Logical Devices (LDs) and Logical Nodes (LNs). LDs are virtual representations of devices intended for supervision, protection or control, while LNs are representations for various device functionalities and are crucial part of IEC 61850 data semantics [38].

IEC 61970 was developed for exchanging information about the electrical grid and application programming interfaces (API) for energy management systems commonly used in control centres, while IEC 61968 further describes the details of the distribution system in IEC 61970 [39]. Collectively, the IEC 61970/61968 standards constitute part of the IEC Common Information Model (CIM) for modelling the power system semantics [40]. Figure 3.2 shows an example modelling hierarchy of power breakers/switches in CIM.

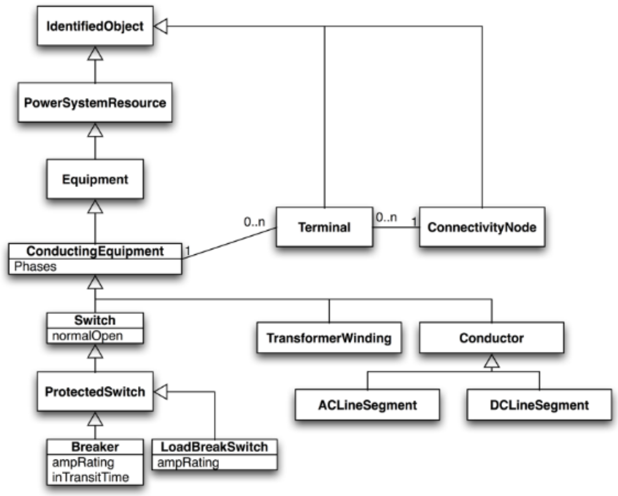


Figure 3.2 Example Modelling Hierarchy in CIM

CIM is based on Unified Modelling Language (UML), and it specifies object-oriented semantics and structure, using data classes, attributes and object relations to represent power system entities and their status/relation. CIM forms the underlying model which describes real world objects and information entities in power systems [40], and is used for power companies' applications and operational systems such as energy management system (EMS) or Supervisory Control and Data Acquisition (SCADA) systems.

For seamless integration of different applications, CIM is often mapped to Resource Description Framework (RDF) or OWL for exchange of information. RDF Schema (RDFS) provides a data-modelling vocabulary for RDF data, and the class generalization in CIM can be mapped to the subClassOf property in RDFS. On the other hand, to define the ontology and relationship between components of power systems, some tools, e.g. CIMTool [41], also use OWL to process CIM.

However, since IEC 61850 and CIM have been developed separately by different workgroups, any mismatches between the models may hinder interoperability between the devices, systems, and applications. Authors of [42] suggested an ontology approach for the integration of the protocol sets.

3.1.3 Resource Modelling in Smart Grid

In recent years, resource information modelling has also attracted much attention from Smart Grid researchers. In the context of the European Commission's Standardization Mandate M/490, the Smart Grid Architecture Model (SGAM) has been developed to provide a holistic view on Smart Grid systems [43].

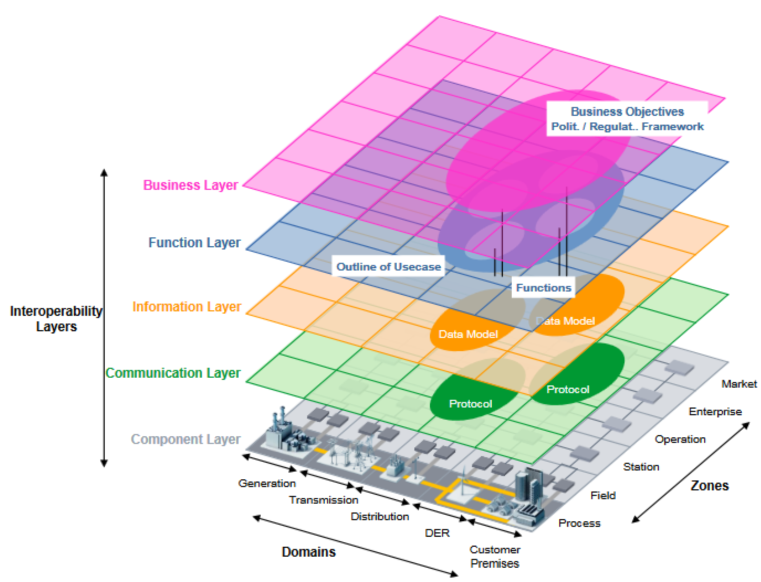


Figure 3.3 Smart Grid Architecture Model

As depicted in Figure 3.3, the SGAM is a three dimensional model based on the National Institute of Standards and Technology (NIST) Domain Model [44], the automation pyramid (zone definition in Figure 3.3) and the GridWise Architecture Council (GWAC) Interoperability Stack [45]. The domains-axis of the SGAM decomposes a Smart Grid system based on the NIST Domain Model, whereas the zones-axis depicts the automation functionality of the automation pyramid. Thus, every element within the model can be identified according to its position within the electricity grid and its role in terms of automation. To provide interoperability between particular elements, a number of interoperability layers derived from the GWAC Interoperability Stack are introduced in SGAM.

In [46], the authors propose an ontology for Microgrid (MG) management named OntoMG, which is claimed to address the interoperability between different energy management systems within the MG, and the need to model all aspects of energy for multiple management objectives such as reliability and balancing in MG. OntoMG is based on CIM and a “Microgrid” class was created as a subclass of “EnergyUnit” to model MGs that are connected to the main grid or operate in island mode. The “Microgrid” class has three branches: distributed energy source branch, energy storage branch and energy load branch. Five aspects—identification, economy, operation, ecology and mobility—are modelled for devices in MG.

In [47], an ontology for modelling prosumer details down to appliance level is proposed. The authors present the classification of the MG components using several predefined use cases. Five power consumption patterns are identified, namely: commercial (such as shops), business (such as office buildings), residential, non-residential and industrial premises. For energy sources classification, two categories are introduced: renewable and non-renewable energy sources. Three categories are identified for energy storage systems: energy management, power quality and bridging power. Finally, the term component connectivity is introduced to focus on enabling the exact connectivity relationships between the producers and the consumers. Besides components classification, a class "events" has been added for the Complex Event Processing (CEP) with MG events classified into appliance, weather, storage and generator events.

3.1.4 Discussion and Analysis

In this sub-section, a comparison is made between the various resource modelling approaches presented above. These approaches are examined with four features relevant to energy resource management, namely: power system device level information modelling, energy-related domain resources integration, customer (VPP participants) energy trading information modelling, and event classification and processing, as shown in Table 3.1.

For SSN [32], it is a generic resource model for WSN and thus it cannot be directly applied in power system as it lacks the power system domain and electricity customers' energy trading information. It has generic ICT/spatial resource modelling methodologies but needs much extension in Smart Grid, e.g. for DER integration. Event classification in SSN is too general to be usefully applied to Smart Grid.

Other resource modelling approaches in Cloud computing and IoT focus [34-36] on ICT domain, and lack knowledge of other features that are required by the Smart Grid.

Features / Approaches	Power system detail information modelling	Energy-related domain resources integration	Customer energy trading information modelling	Event classification and processing
SSN [32]	N/A	Partial	N/A	Partial
IEC suites [37]	Yes	N/A	N/A	N/A
SGAM [43]	Yes	Partial	N/A	Partial
OntoMG [46]	Yes	N/A	Partial	N/A
Prosumer [47]	Yes	Partial	N/A	Partial

Table 3.1 Resource Modelling Approaches Comparison

The IEC modelling standard suites [37] primarily focus on the power grid operator's network, and do not encompass other information (e.g. building spatial information) necessary for modelling resources in buildings, which can be also active Smart Grid participants. Furthermore, since CIM and IEC 61850 have been separately developed by different workgroups, any mismatches between the models may hinder interoperability between the devices, systems, and applications. It is fully fledged in power system device information modelling, and is usually integrated as a modelling component by other approaches, e.g. OntoMG in [46]. However, it does not provide modelling of other features such as customer trading information.

The SGAM [43] also focuses on the power grid operator's network. Since it is a generic architecture for Smart Grid, it considers ICT resource by supplying a data services synergy model but does not cover more details on the customer side such as spatial information. Furthermore, its market operations model is focused on the main grid market for generation plants and large consumer node, and lacks information on VPP participants. The event processing in SGAM also considers the main grid operation to facilitate event-driven functions in supervisory control and data acquisition (SCADA).

OntoMG [46] is based on CIM, and extends it to device level information modelling for Microgrid (MG). It has partially modelled customer energy trading information by considering the cost for operating devices but does not evaluate customers' costs/revenues from energy trading in the power market. OntoMG provides neither a clear study on energy-related domain resources nor events in Smart Grid.

Prosumer-oriented ontology [47] mainly focuses on covering all useful information for prosumers but it lacks the capacity for resource abstraction that is crucial to VPPs, which are aggregating third party energy resources. For a VPP that aggregates multiple buildings, it is not always possible to obtain every detail at the customer site and exert direct control on their consumption/generation patterns. Although it classifies events, it does not have a solution for event processing. In addition, the customer energy-trading information modelling is limited to providing service ontology for trading contracts, which does not fully consider customers' costs/revenues from energy trading in the power market.

In summary, the gaps and issues identified in the current state-of-art resource modelling in Smart Grid are:

- There is not yet a sound consideration for energy-related resource management to effectively integrate DERs into customer level in Virtual Power Plant. As buildings are becoming active participating VPP, different domain resources related to energy, e.g. spatial and ICT resources, must be taken into account when planning/scheduling energy.

- There is no resource modelling designed from ground up for customer energy trading information modelling. The customer information modelled in current approaches such as OntoMG only provide economic cost information for DERs. The detailed customers' (VPP participants) costs/revenues from energy trading in power market are not considered, neither is the abstraction of energy resource offered by the customer to VPP.

- The concept of events is still not clear and questions as to how events should be processed between entities in VPP have not been answered. In VPP context, one major challenge is tackling real time uncertainties introduced by DERs and customer behaviour, in which the concept of event and event processing play significant roles. However, current resource modelling approaches do not take full consideration of this issue.

3.2 Middleware Technologies in Smart Grid

As this research focuses on energy resource management based on middleware approach, in this section various state-of-art middleware technologies in Smart Grid are examined.

In Internet of Things (IoT), a massive number of networked sensor devices are deployed in large scale environment, which spontaneously generate and disseminate countless events and data across heterogeneous communication networks and platforms. Middleware technology is of crucial importance in developing IoT applications for it ensures the interoperability between heterogeneous components.

As Smart Grid is also being referred to as "Internet of Energy" [1], in this context, the underlying communication environment shares much in common with IoT, but there are Smart Grid specific issues, and middleware development faces unique challenges, e.g. data transmission over power lines and energy market operations. The middleware design for Smart Grid is still an open research issue, and current Smart Grid middleware are categorized in the following sub-sections:

3.2.1 Middleware for Energy Trading

One main functionality of Smart Grid is to operate the energy market, which is composed of different roles such as energy bidders and offerers. A major part of middleware research in Smart Grid has been intensively connected with market operation, which is quite different from those in IoT. In particular, multi-agent middleware, which uses agent technology to represent roles in the energy market and provide decision-making support to implement distributed decision-making (DDM), has attracted much attention. Some of the significant related works are discussed here.

In [48], an application of the multi-agent system (MAS) for DER management in MicroGrid is proposed. Software agents are created and decisions are made on behalf of generators and loads to perform distributed control. The middleware is tested in a simulated market using a contract-net protocol. This multi-agent approach is claimed to be an effective strategy to realise the benefits of distributed energy systems.

The GridAgents framework, developed for the Australian CSIRO testbed [49], explores a variety of alternatives to market-based control. In particular, a method that uses genetic optimisation technique to optimise agent plans has been studied. A cap on energy use for a given period is set for a group of agents, which accordingly rearrange plans to minimise cost and achieve local energy efficiency goals [50].

In [51], the suitability of applying adaptive clustering of DER is investigated. Different from other agent frameworks that focus on using agents to represent roles in energy market, the authors propose an optimised management scheme of clustering resource agents with energy consumption/generation planning and a coordination algorithm.

Baladrón et al. [52] propose a multi-agent system model for VPP management and forecasting. The system includes agents embedded with artificial neural networks to forecast users' energy demand.

In [53], the authors define agents responsible for load, generation and storage management, and propose an agent profit maximization model, which is applied to an electric vehicle management system based on IEEE 37-bus distribution grid.

In [54] an architecture for the provisioning of demand response services from aggregated small residential consumers is presented, along with its MAS implementation.

The authors of [55] propose a MAS model for VPP, in which generation/consumption control is achieved by implementing roles and tasks for the producer/consumer whose behaviour was specified by use cases. Energy user demand forecast was also introduced by integrating artificial neural networks into each agent. However, real time scheduling was not studied.

3.2.2 Middleware for Massive Data Dissemination

In order to construct a communication infrastructure for large-scale and reliable data dissemination, several middleware solutions have been proposed. GridStat [56] is proposed as a middleware framework which divides the data transferring architecture into management plane and data plane. The management plane allocates resources and adapts the network in reaction to changing power system configurations or communication network failures. The data plane utilises a publisher-subscriber (pub-sub) mechanism, in which data producers publish their data to brokers in the management plane, and the brokers in turn are responsible for delivering the published data to data consumers who have subscribed to them in a way that satisfies their quality-of-service (QoS) requirements.

GridDataBus (GDB) [57] is a PMU data sharing middleware architecture similarly based on the pub-sub paradigm and an overlay network. Publishers (PMU devices) and subscribers (various power applications) are grouped based on topics such as data type, location, and time; and data is delivered over networks that might be owned by different organisations.

Kim et al. [58] present a secure and decentralised data-centric information infrastructure for Smart Grid, which tackles issues such as distributed data sources, latency-aware data transactions, security and real-time event updates. The proposed infrastructure is extendable by adding self-healing and self-configurability capabilities. Decentralisation is also investigated in order to solve scalability and bottleneck issues. Other implementation issues such as naming and routing have also been treated using domain management based on IP address.

A recent application of SDN for data dissemination is a publish-subscribe (pub-sub) middleware [59] implemented based on the OpenFlow technology. The idea is that by operating the pub/sub middleware as an internal component of the SDN controller, i.e. control handler, it can have a global view of the publishers and subscribers, including their locations in the network. All pub/sub relevant control traffic will be sent to the control handler of the middleware by OpenFlow switches. When a new subscription is received by the control handler, routing optimisation will be executed and the data path between publishers and subscribers will be set up by updating data plane flow rules to enable various communication paradigms on demand, e.g. group communication. This pub/sub mechanism processes data and subscriptions in the network layer, which is quite different from traditional ones based on application layer. It was found that implementing OpenFlow-based pub/sub enables a more efficient data dissemination at line-rate speed than application layer based approaches by minimising switching delays and forwarding data streams using dedicated network layer hardware.

3.2.3 Middleware for Semantic Processing

Another major challenge of middleware in Smart Grid is the proprietary management systems that power companies have already deployed for years, and any newly emerging middleware will have to be flexible and adaptable to interact with such legacy systems instead of brutally replacing them all. This sub-section introduces research efforts to address semantic information challenges based on resource modelling approaches.

As aforementioned, the standardisation bodies are pushing forward communication standards for Smart Grid, such as IEC protocol suites that use semantic modelling. The IEC protocol suites are mapped in current electric utility application using Manufacturing Message Specification (MMS), Generic Object Oriented Substation Events (GOOSE) and Sampled Measured Values (SMV). However, these mappings cannot fully adapt to new Smart Grid components and evolving standards such as IEC 61850-7-420 standards for DER [37].

Sucic et al. [60] present an integration between IEC 61850 standard and Devices Profile for Web Services (DPWS). The DPWS mapping is deemed to be a notable middleware architecture in which device management functionalities can be migrated from the SOA architecture. The entire system is standard compliant and event driven for semantic-enabled Smart Grid Automation. In [61], the authors take a step further to present a DPWS and IEC 61850 integration that is applied to DERs. Simulations are run as EVs leave/join a Microgrid and the latency of WS-Discovery and scalability are analysed.

3.2.4 Middleware for Home/Building Energy Management System (HEMS/BEMS)

There exists research on energy management systems for homes and buildings, but not all have considered Smart Grid requirements. Often a unifying middleware layer is hard to be spotted in such systems, which mostly use generalised Enterprise Service Bus (ESB) for implementing the interaction between software components.

Byun et al. [62] propose an energy distribution and management system (SEDMS) with context-awareness based on user patterns and load forecasting. It uses a light-weight adaptive middleware, which is comprised of an interface layer, knowledge management layer, and service management layer. The interface layer is responsible for connecting different devices and gathering energy/user information. The knowledge management layer generates and stores patterns/contexts; while the service management layer analyses the context/patterns and provides services such as prediction and decision.

In this research, the design and management of smart buildings are perceived to generally focus on two aspects: service and sensing. The service refers to that provided by smart buildings to support users in their daily lives. The authors in [63] discuss the service life cycle and design principles for a management framework to effectively manage autonomous and adaptive services in smart spaces. In [64], a Smart Shadow System is proposed to provide home users with real-world services – defined as services that affect the real world by altering the user's environmental factors such as ambient temperature, humidity and lighting, and to dynamically detect and resolve service conflicts.

On the other hand, some design approaches consider sensing as one essential component of smart buildings. The authors in [65] utilise a logic-based modelling language, namely timed communication object Z (TCOZ) to describe constraints on the sensor imposed by its environmental conditions or relations with other sensors, and its sensing pattern such as periodic or conditional sensing. The sensor-based model is then applied to the design of smart spaces. In [66], ECA (event, condition, action) rules are introduced for describing home-based sensor driven services, which can often cause a chain reaction, i.e. one service may generate an outcome that automatically triggers another service. Therefore, a method is proposed to detect such service chains and the possible conflicts among these services.

In recent years, Building Information modelling (BIM) has attracted much attention, and researchers have explored how smart buildings design and post-construction management could benefit from harnessing BIM information and capabilities. In [67], an indoor wireless sensor network (WSN) is designed with BIM data that provides a detailed description of the building environment, which is required for accurate predictions of signal propagation and therefore link quality between sensor nodes in the building. In [68], a three-dimension smart space design framework is proposed in which space (e.g. furniture, walls, floors, etc.) is viewed as one dimension, along with technologies (for ubiquitous computing) and living (e.g. safety, health and sustainability requirements) as the other two dimensions. Bhatt et al. [69] propose an ontology-based spatial-terminological inference approach to validate work-in-progress designs of smart environments. The approach checks the design for compliance with spatial and functional constraints of environment entities based on available architecture data in IFC format.

While not specifically for smart buildings, it is also shown in [70] that BIM can benefit post-construction facility management such as locating components, checking maintainability and creating digital assets through its powerful visualization, analysis and control capabilities. There are a number of existing works on integrating BIM with real-time information. For example, the Autodesk research group integrated BIM with sensors and meters to provide 3D visualization of building performance and life-cycle operation [71]. The Virtual Real-time Information System (VRIS) combines the Onuma cloud-based BIM tool [72] with a real-time sensor engine called Virtual Real-time Operating Centre (vROC) to provide building management functions [73]. However, when it comes to energy management, to the best of our knowledge, there are no existing BIM-based solutions in smart buildings which are Smart Grid ready.

3.2.5 Discussion and Analysis

This sub-section discusses different middleware approaches in Smart Grid. Based on the above literature review, the characteristics of surveyed middleware are summarised and compared in Table 3.2.

Features / Middleware	Energy-related domain resources integration	Resource model utilisation	Energy-related decision making	Complex event processing
GridAgents [49]	N/A	Yes	Yes	N/A
GridDataBus [57]	Partial	N/A	N/A	Partial
DPMS-IEC61850 [60]	N/A	Yes	N/A	N/A
SEDMS [62]	N/A	Yes	Partial	Partial
VRIS [73]	Partial	Yes	Partial	N/A

Table 3.2 Comparison of Middleware Approaches

Middleware for energy trading and the methodology of representing the system using agents such as GridAgents [49], afford the ability for EMS applications to be power system context-aware, and reduce the complexity of implementing scheduling algorithms. However, they are limited to energy trading strategies in the application layer, and require further extensions to cover underlying resource management and event processing issues.

For data dissemination middleware such as GridDataBus [57], while they might differ in their design objectives or technical implementation, in order to achieve efficient data transmission and scalability in a distributed environment, the use of current publish-subscribe (pub-sub) techniques for data exchange on application layer is commonly adopted. There is also the treatment of metering data as the only data source. For example, GridDataBus only operates on data from meters/PMUs, and does not consider DER challenges such as DER aggregation in their research scope. ICT resources are the main concern for such middleware, and they lack the capability of management for DERs as well as energy for ICT resources.

The semantic middleware are successful endeavours that afford Smart Grid applications the awareness of the meaning of the data content, especially by utilising the resource modelling approaches mentioned in section 3.2.1. However, the semantic analysis provided by the semantic middleware is also restricted to the resource modelling approach it is based on. For example, the work in [60] is limited to the scope of IEC61850 discussed in section 3.2.4. Resource-related operations are based on parsing resource model information, e.g. XML formatted web service response. Decision making for resource scheduling and event processing are not considered in such middleware.

Although the middleware design for HEMS/BEMS often explores the ontology utilisation as resource information modelling in Smart Grid context, there are still gaps to be addressed. For example, SEDMS [62] and VRIS [73] are more of systems to provide context-awareness for load-forecasting and energy scheduling/planning on the building level. However, they do not yet give consideration to DERs integration and buildings as VPP participants.

In summary, the gaps and issues identified in the current state-of-art middleware technologies in Smart Grid are:

- There is no middleware designed from ground up for energy resource management in VPP. Prior to this research, Smart Grid middleware was perceived more of an afterthought than a defined and integral component for VPP energy management [74]. The researchers have mostly focused on delivering targeted solutions to address some specific issues of the Smart Grid, and the resulting underlying integration components are labelled as middleware.
- Energy trading middleware are the most relevant developments for energy resource management, and agent technology, i.e. MAS, is most commonly used for VPP aggregation. Yet current approaches fail to provide an infrastructural framework for DER integration. There is not any consideration for energy-related domain resources integration or an in-depth study of event processing mechanism between buildings in VPP.

3.3 Resource Scheduling Algorithms in Smart Grid

As an important constituent of resource management, the resource scheduling algorithms play a crucial role in optimising the output of resource management operation in various domains. To support the decision making for RMS in Smart Grid, researchers have proposed different scheduling algorithms for energy resources, the state-of-art of which will be examined in this section. For the ease of modelling process and intuitive deployment in MAS, the approach based on game theory has been relatively more popular in Smart Grid. Therefore, this section has been divided into non-game theory and game theory approaches. Note that since optimisation is the objective of resource scheduling, algorithms utilised for "optimisation" in some related works are also considered as resource scheduling algorithms in this section.

3.3.1 Non-Game Theory Resource Scheduling Algorithms

In Smart Grid, different resource scheduling algorithms have been studied, which model different objectives of different entities (DERs owned by different parties, and the main grid). The authors of [75] propose a multi-objective resource scheduling model which combines the minimisation of operation cost and the minimisation of voltage magnitude difference for day-ahead power distribution in VPP. Two forecast functions F_1 and F_2 are presented, wherein F_1 is the next day operation cost for VPP operator and F_2 is the voltage magnitude difference in the distribution network. The multi-objective function F is formulated as follows, with NF as normalising factor:

$$\min F = \alpha \times F_1 + \beta \times F_2 \times NF, \quad \alpha + \beta = 1;\ \alpha, \beta \epsilon [0,1]$$

The above weighted sum method transformed two objective functions into a single function. The best compromise solution was chosen based on fuzzy set theory and the mathematical formulation of the proposition was implemented using mixed-integer non-linear programming (MINLP) in general algebraic modelling system (GAMS).

The authors also present the use case study to apply the proposed algorithm to a VPP that manages DERs in a 33-bus distribution network. From the simulation results, the authors claim that their approach was able to effectively increase the voltage profile in all buses with minimum additional cost.

The authors of [76] propose the global best artificial bee colony algorithm (GABC) to solve the problem of generation scheduling in Smart Grid. Direct cost, overestimation and underestimation costs of uncertain wind power generation were combined into the generation scheduling objective function. The impact of demand response on generation was taken into account, in which customers' energy demand is modelled by an exponential function, assuming customers were offered incentive values by the system operator in demand response programmes. The overall objective of the model in [76] is to minimise the total cost (generation cost and demand response cost) while satisfying generation constraints over the scheduled horizon (period). An implementation of GABC was proposed for solving the formulated problem and the authors claim GABC to be efficient in giving a near-optimal response and minimum total cost.

In [77] a probabilistic price-based generation resource scheduling approach using Hong's two-point estimate method (HTPEM) is employed to model the uncertainty in market price and generation sources, for optimal bidding of a VPP in a day-ahead electricity market. The overall objective function is for a VPP to maximise its profit by revenue (from energy trading between consumers and main grid) minus cost (generation cost). Stochastic DG generation is handled through increasing the required reserved energy. HTPEM was implemented to find the solution for the objective function under constraints such as capacity of interconnections and bus voltage limits, and the algorithm was examined in three use cases, each with a different setting for DG generation uncertainty.

In [78] the authors study the scheduling problem for vehicle-to-grid operations and propose an event-triggered scheduling with stochastic PEV connection. In this work, each day was viewed as a basic period and divided into 96 15-minutes slots. Information about the connection time slots and demanded energy amount are assumed to be gathered whenever a PEV is connected. The objective function of the scheduling problem is to minimise the power load variance for a period (day). The authors claim that their proposed scheduling can dramatically reduce the variance of total load power curves.

3.3.2 Game Theory Resource Scheduling Algorithms

Game theory is perceived to constitute a robust framework and a key analytical tool in Smart Grid for addressing the requirements of distributed operation, heterogeneous operating environment and low complexity of distributed scheduling algorithms that efficiently represents competitive, e.g. between energy sellers, or collaborative scenarios, e.g. between energy seller and buyer [79]. Particularly in VPP, since all participants have their own objectives with regard to energy trading, and therefore can be intuitively treated as players interacting with each other in game theory. In this sub-section, applications of game theory by researchers in Smart Grid are introduced.

There exist works that study the electricity market where bidders/sellers are considered as intelligent players performing “smart” actions through game theoretic-based models. For example, the authors of [80] propose a non-cooperative game-theoretic algorithm to settle the deregulated retail electricity market price. Three types of energy resources (referred to as energy cells by the authors) are considered for residential customers: distributed generation, dispatchable load (which can be ramped up or shut down in a relatively short amount of time) and non-dispatchable load. For distributed generation, the objective is to maximise profit by selling energy to the main grid or neighbouring customers; for dispatchable loads, the objective is to minimise the operating cost; for non-dispatchable loads, they are not flexible and only try to maintain a consumption value above threshold. The three types of energy resources and the utility grid compete in a non-cooperative n-person game, each represented by one type of player. By finding the Nash Equilibrium, it was shown to be capable of settling the deregulated electricity market price under both local and global constraints.

In [81], a cooperative game model is applied to model the economic incentives of Microgrids that are electricity market participants. Different coalitions of electric utility, private investors and customers were studied for their achievement (of profits/system reliability) with respective values of profits (by utility and investors) or energy surplus (by customers). The authors claim their research shows how the cooperative game framework can be useful to regulators and policy makers for identifying the beneficiaries of Microgrid promotion policies, and for correcting the market failures in utility pricing that can distort incentives for Microgrid investment. Game theory has also been applied to the study of electricity market bid/offer settling mechanism in [82]. Each of the energy resources has the objective to maximise its own profit, and distribution locational marginal price (DLMP) was adopted to study a mechanism where each location had a different profit per energy unit sold.

Another application of game theory is on scheduling resources inside energy aggregations, e.g. VPP. The authors of [83] adopt an instantaneous polynomial pricing scheme and propose a game model where each customer as a player competes to minimize its individual energy cost. The customer’s energy consumption was modelled as vector of consumption volume over a set of time slots and a distributed iterative proximal-point algorithm was proposed to find the Nash Equilibrium. The authors claim the developed algorithms can quickly converge to the Nash Equilibrium of the formulated game and convince the consumers to shift their on-peak consumption. Similarly in [84], the authors propose a game theory based approach for residential distribution economic operations, where both the distribution company and energy resources in residential houses have their own objective function models to maximise revenue or minimise cost.

The authors of [85] propose a game theoretic DSM scheme named GTES, which employs an exponential utility function for each customer to maximise its gained utility (revenue) minus energy cost. A logarithmic price function was designed for the main grid to adjust the energy price in order to control energy consumption of customers. MATLAB was used to construct the simulation environment and the algorithm performance was compared to several other game theoretic approaches.

Because the electricity power aggregator often takes the dominant role in electricity trading, solutions have been proposed to use the Stackelberg game (a model of imperfect competition based on a non-cooperative game) approach to coordinate energy operations for different roles, e.g. energy sellers and buyers, in the power system. For example, the authors of [86] propose a Stackelberg game model for residential buildings and the facility controller, in which residential buildings are assumed to have no storage and adapt their consumption to maximise their revenue from exporting energy, while the facility controller is assumed to have no generation and acts to minimise the cost of purchasing energy from residential units and the main grid. In [87], the electricity trading is modelled as a Stackelberg game as well, with one power company and multiple users. Iteratively, the utility and users achieved equilibrium where peak demands were flattened and supply-demand mismatch reduced.

3.3.3 Discussion and Analysis

This sub-section discusses different approaches for resource scheduling in Smart Grid.

It is debatable whether or not to apply game theory when designing resource scheduling algorithms. As game theoretic problems can be transformed and solved by other approaches such as integer linear programming, there is no certainty that game theory based approaches can yield better result than others. However, one definite advantage of game theory based approaches in Smart Grid is the low complexity of distributed algorithms in competitive (such as competing for individual profit) or collaborative (such as cooperating for power system reliability) scenarios.

Table 3.3 shows the comparison between several key approaches, with those based on game theory preceded with “GT”.

For most research on resource scheduling within a group of energy suppliers/users as introduced in section 3.4.1 and 3.4.2, the focus is on short-term, e.g. day ahead, demand side management (DSM); it considered only residential houses as customers/users, and assumed constraints such as users have no means of storing energy. However, these works are not suitable when VPP users include commercial buildings because the VPP operator does not often have direct control of the appliances in such buildings. Besides, some of the commercial building participants in a VPP might prefer not to share information with others in the same VPP due to security issues. In such cases, information exchange between VPP participants should be reconsidered. On the other hand, the energy consumption of such users produces a certain utility such as customer comfort or satisfaction of business need, and their willingness to consume energy cannot be neglected. However, most works, as shown in table 3.3, have failed to consider such willingness.

Features / Scheduling Algorithm	Consider prosumer aggregation	Consider customer consumption needs	Support decision making with real time uncertainties
Multi-Objective [75]	Partial	N/A	N/A
Probalistic Price-based [77]	Partial	N/A	Partial
GT Cooperative [81]	N/A	N/A	Partial
GT Auto DSM [83]	N/A	N/A	Partial
GT GTES [85]	N/A	Yes	Partial
GT Stackelberg [86]	Partial	Partial	Partial

Table 3.3 Comparison of Resource Scheduling Approaches

In summary, the gaps and issues identified in the current state-of-art resource scheduling algorithms in Smart Grid are:

- Prosumers’ role in aggregating energy consumers and producers have not been fully considered. Existing research mostly studied pure consumers who are in proximity of Microgrid/VPP operator owned DG devices. However, the case of customer-owned distributed generation must be taken into account, especially when studying VPP composed of third party buildings.

- The customers’ need (willingness) to consume energy is neglected in most cases. The customers, especially buildings, are willing to consume energy to satisfy their living requirement as well as generating additional utility such as entertainment in residential houses and producing economic income by serving clients in data centres. When modelling prosumers, such factors should be taken into account.

- In resource scheduling, the current focus is mainly on short term, e.g. day-ahead scheduling. There is no consideration for very short term scheduling, e.g. in half hour, except in [51] for vehicle-to-grid operation.

3.4 Chapter Summary

From the review of the recent literature, it is observed that considerable research has been conducted on the relevant aspects of resource modelling, middleware technologies and resource scheduling algorithms. However, there is not yet a sound solution in any of these areas in the context of Smart Grid. To achieve the goal of effectively managing energy resources, particularly for VPP composed of third-party buildings in Smart Grid, this thesis has undertaken research on the methods of: energy-related domain resources management, event-based energy resource management and game theoretic energy resource scheduling, which are presented in the next three chapters.

CHAPTER IV: Energy-related Domain Resources Management for Smart-Grid-Ready Building

4.1 Introduction

For a VPP constituted of buildings in which smart objects such as networked sensors and actuators are installed for energy management/provisioning and making buildings "smart", domain resources other than power system resources—such as ICT resources and spatial resources—are coming to play an important role in the scheduling of energy by energy management systems (EMS). This is because they are either supporting their data operations (e.g. data collection/processing/storage) or serving as the knowledge base for energy forecast/control. In this chapter, methodologies for managing energy-related domain resources, i.e. spatial and ICT resources, are proposed to render buildings ready for Smart Grid.

4.1.1 BIM and Smart-Grid-Ready Building (SGRB)

Building Information Modelling (BIM) was introduced to the field of Architecture, Engineering and Construction (AEC) in the mid-1990s [88]. BIM is a methodology enabled by a set of software tools and processes for facilitating the creation and use of a digital representation of the physical and functional characteristics of a facility [89]. In terms of software, BIM introduces exchangeable information formats, i.e. International Foundation Classes (IFC), for modelling and visualizing building entities in 3D. In terms of processes, BIM facilitates the conveyance of building information from design phase throughout the building life cycle, supporting cost management, construction management, and facility management [90].

Thus, research on BIM as a methodology has been focused on the following two areas: i) Development of software tools and techniques for creating and evaluating new BIM artefacts that arise as building designs and technologies evolve; and ii) Application and usage of BIM processes across the life-cycle of a building from pre-construction design to post-construction facility management.

Recent rapid advances in Information and Communication Technologies (ICT) have led to their pervasive use across industry sectors, including building construction. An upcoming and important aspect of ICT use which we anticipate to take a central stage is the construction and management of emerging Smart Buildings (SBs). Here, ‘smart building’ refers to a built environment which has been embedded with smart objects such as sensors and actuators with computing and communication capabilities, making the environment sufficiently 'smart' to interact intelligently with and support their human users in their day-to-day activities [91]. With the Smart Grid evolution, the Smart Buildings research faces the problem of how to make them ready for Smart Grid, e.g. enhanced energy management through smart objects and energy trading as virtual power plant (VPP) participants. In this thesis, such Smart Buildings are referred to as Smart-Grid-Ready Buildings (SGRBs).

In an SGRB, the human users refer not only to the building occupants, but also to the building’s owners/managers. The former is typically concerned with how a smart building could improve personal safety, comfort and productivity, while the latter are more concerned with how a smart building could better support their operation and management of the building. In addition, as buildings are a major source of energy consumption – accounting for 40% of primary energy consumption in most countries [92] – SGRB will be expected to harness its new technological capabilities to achieve an unprecedented level of energy efficiency.

Therefore, constructing SGRBs can have a set of requirements and procedures not defined or typically considered in traditional construction settings. Although there has been research conducted on various aspects of SGRBs, very little attention has been focused on the role and application of BIM in pre- and post-construction processes of SGRBs. Motivated by Smart Buildings research, this chapter investigates how BIM can contribute to the pre-construction design and post-construction management phases of SGRBs.

4.1.2 SDN in Smart Grid

The development of Smart Grid will be based upon complex networking between a vast number of sensors deployed in the generation, transmission and distribution facilities, smart meters, DERs, supervisory control and data acquisition (SCADA) systems, back-office systems, as well as end-user devices and appliances located on residential and commercial premises which interact with the power grid [93]. To sustain the transmission of a massive amount of real-time data generated by these entities, the underlying communication infrastructure of the Smart Grid must be scalable, efficient and reliable.

With the advent of SDN, the interface between applications and networks will be greatly changed. Moreover, application systems in Smart Grid and SGRBs will have a higher degree of network awareness which enables more dynamic adaptations of the applications with the underlying communication network.

Motivated by a vision of future development, this chapter also examines the opportunities for SDN technology in Smart Grid are also examined. To the best of our knowledge, this is one of the first studies on the utilisation of SDN in Smart Grid. Previous research on SDN has focused on heterogeneous Internet [94] and cellular networks [95].

4.2 Utilising BIM in Smart Buildings

As aforementioned, a variety of smart objects will be ubiquitously and transparently installed in SGRB to perform actions such as sensing and control. These smart objects may interact with each other and with the environment and the environment users. The communication can be carried by either wireless (e.g. Zigbee, 802.11a/b/g/n) or wired (e.g. Ethernet, power line) information networks.

4.2.1 General Challenges

A number of questions arise when considering the life cycle of a smart built environment. Firstly is how the smart objects are embedded into the environment. From the aspect of sensors, the physical location and the surrounding settings can significantly affect their ability to carry out specific tasks, e.g. ambient light or occupancy sensing. From the aspect of information network, whether a wireless sensor network (WSN) or wired Ethernet is deployed, it should be designed to offer the smart objects an excellent level of communication.

Secondly is how the smart objects interact with the environment. The smart objects are situated in a specific surrounding to carry out their tasks and often require the input of space data such as building floor plans. Furthermore, in carrying out their tasks, the confluence of the actions by different smart objects may involve affecting a common set of environment factors, the impact of which should be studied and understood within a spatial context. Last but not least, when conducting a building performance analysis, such as an energy efficiency analysis of the SGRB, not only the information from sensors/meters is vital, but the building architectural/geometry data are also indispensable.

Thirdly is the maintenance of such smart objects in a building's post-construction phase. In building management, it is common for facility managers to complain about either incomplete or inaccurate (not up-to-date) documentation [96]. To maintain a Smart-Grid-Ready Building that is more complicated than traditional structures, more building design and construction data will need to be documented and conveyed to the facility managers. In the event that the company which designed and constructed the building is no longer in business, building management can continue to function properly provided that the documented information is both comprehensive and reliable.

4.2.2 Introducing BIM in Smart-Grid-Ready Buildings

BIM hosts the collaborative architectural information and provides the semantic knowledge of the building. With the emergence of smart built environment technology, BIM should be further developed to be capable of seamlessly integrating smart objects in building design, verifying the SGRB design and feeding smart objects with relevant building-related information.

Designing SGRB with BIM is both advantageous and convenient. Firstly, designers of SGRB can utilize the building knowledge of BIM for planning the layouts of sensors, tags, actuators and meters. The performance of smart objects can be verified against known constraints, and their layouts optimised for best functional performance. Secondly, BIM also serves as a data repository for the physical information of smart objects. For maintenance and asset tracking in the building post-construction phase, the hardware information of smart objects can be recorded, and their installation locations can be documented and visualized in 3D.

On the other hand, BIM provides a perfect ontology database for SGRB. Smart objects may be designed and manufactured by different vendors. The data they provide may vary in structure, and they may communicate using different protocols. Middleware is a popular approach to addressing such issues with heterogeneous smart objects [97]. With the introduction of BIM, each smart object can be profiled through its information exchange interface. Because BIM is standard-compliant, the middleware can extract data formats of smart objects and other building information for viewing as an ontology database.

4.2.3 Energy Management in Smart-Grid-Ready Buildings

Energy management is an important part of facility management. In SGRBs, energy management can be enhanced through smart objects such as temperature, occupancy and ambient light sensors that provide data for estimating the building's energy requirements, understanding the building's energy usage patterns, and decision-making by building control systems to achieve a balance between a building's energy efficiency and the comfort level of its occupants.

As awareness of energy efficiency grows within the building industry, the trend of deploying various sensors in the buildings will only become more common in energy management practice. Furthermore, with the introduction of Smart Grid, buildings have an active role in the power system, as they exchange electrical power information with the power grid via their smart meters [93]. Sub-metering systems are also important to achieve energy awareness for building management as they can provide high-resolution monitoring data down to individual appliance level.

Another significant aspect that challenges energy management today is the penetration of DERs such as photovoltaic (PV) panels and micro wind turbines. With on-site DERs, the role of building changes from pure energy consumer to both energy producer and consumer (or 'prosumer') [4]. Correspondingly, the role of SGRB is also extended to include the tasks of performing energy generation forecast, load scheduling, storing and feeding energy back to the grid. The monitoring and control of DERs is therefore vital for energy management in SGRBs.

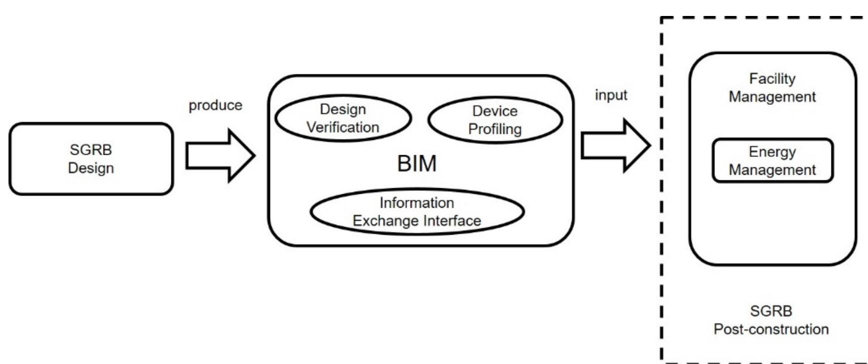


Figure 4.1 Role of BIM in Smart-Grid-Ready Buildings

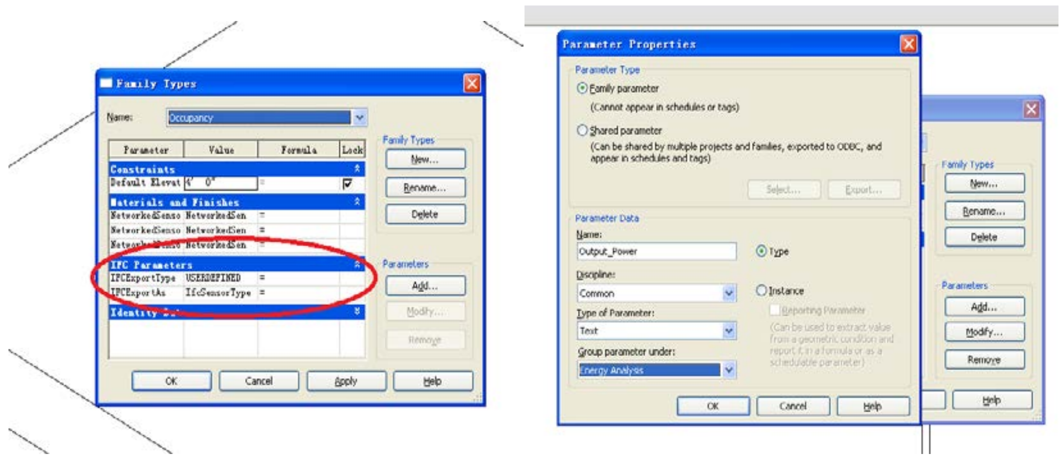
In essence, smart meters and DERs can be viewed as real-time information objects, which are a type of smart object that can be embedded into the BIM design of SGRB, and the energy management system can benefit from the profiling capability of BIM, as shown in Figure 4.1.

4.3 Designing Smart-Grid-Ready Buildings with BIM

As discussed in the previous section, BIM has the potential to support the entire life-cycle of the SGRB. Therefore, we started by investigating how existing BIM platforms can be further developed to better support the design of SGRB. To date, the most popular BIM software are the Revit suite from Autodesk and Archicad from Graphisoft. In this work, we have conducted our SGRB design in BIM with Revit, but similar work could be conducted in Archicad.

4.3.1 Embedding Smart Objects in BIM

The intention is to profile smart objects with Revit during the SGRB design phase. The produced BIM model with smart objects should be correctly exported as an International Foundation Class (IFC) file, so that other BIM tools can parse the information. We adopted three methods for the profiling: IFC shared parameter, family property parameter, and the mark tag. Reference [98] demonstrates how sensors can be modelled in Revit, and we took a similar approach which uses the IFC shared parameter field to indicate the sensor type in IFC, as shown in Figure 4.2(a). For actuators, new properties can be added to the building element that is being controlled by the actuator. Therefore, new BIM artefacts such as a smart window (e.g. capable of self-actuating to adjust its light transmission properties) can be created using the original window family with added actuator properties.



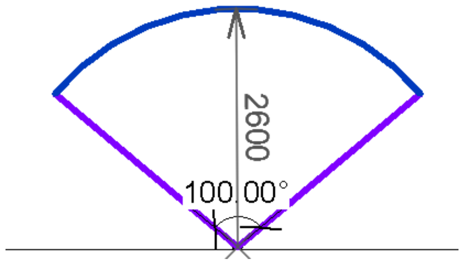
(a) (b)

Figure 4.2 (a) Extending BIM design using "IFC shared parameter". (b) Adding new parameter properties in Revit

The IFC shared parameter enables the new smart object family to be a compatible type in BIM, i.e. exportable and parsable in IFC format. However, to fully model an SGRB design, we have to provide additional information. For that purpose, we utilize the family property parameters for a type of smart objects and mark tag for an individual smart object.

A. Spatial Interaction Information

One of the most important factors to consider when designing SGRB is the spatial interactions between a smart object and its physical surroundings. For sensors, it has been referred to as the range space or the effective sensing space area [99], which is the foremost element to consider when planning their placement layout during the design of SGRB. Different sensors types may have different range space characteristics. For an infrared motion sensor, its range space may have a shape like a sector of a circle. For a temperature sensor, its range space may be spherical-like. For simplicity, we represent the range space of a sensor by a range radius and range angle, and its axis is determined by the surface to which it attaches, as shown in Figure 4.3.



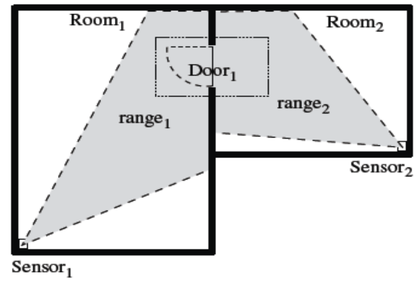


Figure 4.3 (a) Example of range space of a sensor with range radius of 2.6m and range angle of 100 degrees. (b) The door's operational space should be within the range space of the two monitoring sensors.

B. Informational Exchange Interface

For the information exchange interface which describes the data input/output behaviour of the smart object, family property parameters are added to the smart object family. Since this work focuses on energy management, we specify parameters in the energy analysis properties.

As illustrated in Figure 4.2(b), in order to enable the BIM file (in IFC format) to provide information exchange interface for the facility software, family property parameters are designed to be a mapping from IFC text to the device software programming interface, which can be a middleware or another BIM software. Three types of smart object data operation are defined:

- *Output*: interface from which external software can read the output (generated power, grid signal, or sensed data) of the device. Format in IFC file is: "Output_xxxxx".
- *Input*: interface from which external software can read the power generation or consumption status of the device. Format in IFC file is: "Input_xxxxx".

- *Control*: interface from which external software can control the operation of the device, tilting angle of the PV panel/wind turbine, power consumption of the BACnet compatible smart appliances, etc. Format in IFC file is: “Control_xxxxx”.

C. Identification and Service Mapping

Finally, to map a smart object from BIM to an individual real-world device, the mark tag in BIM is used. The BIM software which parses the produced BIM file reads the mark tag for the smart object and determines additional runtime information, e.g. the Internet Protocol (IP) address, of the device from a database. This tag is also used to map a smart object to a service descriptor file, which will be detailed in the next section.

Using Revit, we created an SGRB design which is modelled as a smart house with sensors, actuators, smart meters, photovoltaic (PV) panel and wind turbine. After completing the BIM design, a BIM file in IFC format is generated as shown in Figure 4.4.

```
……
#192496= IFCSENSORTYPE('3Ea9KIygfFOf3hy58KLU_a',#52,'Occupancy',$,$,$,(#192495),'211594','Occupancy',.USERDEFINED.);
……
#192534=IFCDISTRIBUTIONCONTROLELEMENT('3Ea9KIygfFOf3hy58KLU_B',#52,'Networked
Sensor:Occupancy:Occupancy:211621',$,'Occupancy',#192533,#192528,'211621',$);
#192535= IFCPROPERTYSINGLEVALUE('Mark',$,IFCLABEL('LivingRoomSensor'),$);
#192537= IFCPROPERTYSINGLEVALUE('Host',$,IFCLABEL('Basic Wall : Interior - Partition'),$);
……
#192540= IFCPROPERTYSINGLEVALUE('RangeRadius',$,IFCLENGTHMEASURE(2600.),$);
#192541= IFCPROPERTYSINGLEVALUE('Output_occupancy',$,IFCINTEGER(0),$);
#192542= IFCPROPERTYSINGLEVALUE('RangeAngle',$,IFCPLANEANGLEMEASURE(99.9999999999999),$);
……
#186580= IFCBUILDINGELEMENTPROXY('31vPjYM8b9$Aof7XNLJOFw',#52,'Wind Power Generator_modified:60" High:60"
High:201370',$,'60" High',#186579,#186574,'201370',.ELEMENT.);
#186581= IFCPROPERTYSINGLEVALUE('Mark',$,IFCLABEL('OutdoorWindTurbine'),$);
#186583= IFCPROPERTYSINGLEVALUE('Output_power',$,IFCINTEGER(0),$);
……
```

Figure 4.4 Code Segment of Extended BIM IFC File

4.3.2 Design Verification Framework for SGRB

Recall that SGRB is enhanced on efficiency, security and comfort of its human occupants by being aware of the state of the environment and performing autonomous intelligent actions. Such actions performed by the SGRB can be viewed as provisioning a type of service to the building owner or occupants. In literature, these services are also referred to as real-world services (RWS) [64]. Designing a set of adaptive RWS with various smart objects could become an integral part of future SGRB design.

During the design phase of SGRB, uncertainties may arise that could affect the service integrity and performance. For example, there could be doubts whether the sensors are placed in the best locations to execute their tasks, or whether there might be conflicting objectives/requirements between different services. If such uncertainties can be verified during the design phase of the SGRB, it may reduce the amount of rework necessary after the building is built. Furthermore, it can be useful for as-built verification, e.g. when new smart objects and services are to be introduced to an already constructed SGRB. With this motivation, we propose an SGRB design verification framework with BIM, as outlined in Figure 4.5.

In this framework, a three-layer verification is adopted to verify the SGRB design. The three layers are: smart object, single service and inter-service performance verification. The input to the framework is the BIM file produced as discussed in Section 4.3.1.C (in IFC format), which contains the design information on the building and associated smart objects. The performance verification criteria are modelled using XML, which are detailed in the following sections.

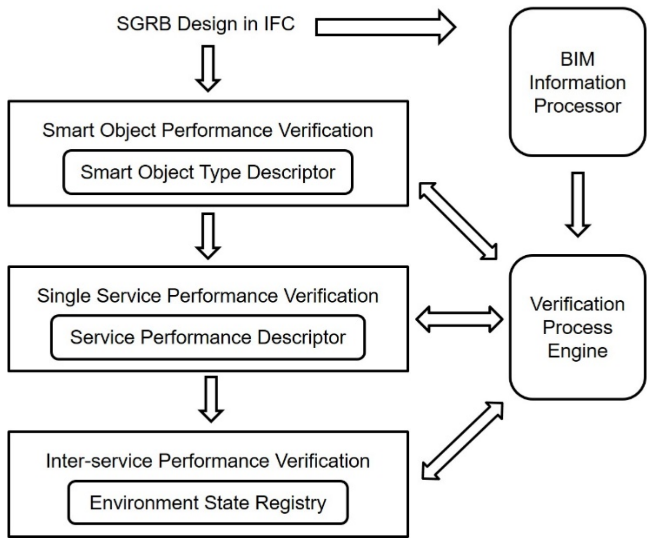


Figure 4.5 Design Verification Framework for Smart-Grid-Ready Buildings with BIM

A. Smart Object Performance

The performance of a smart object can be impacted to different degrees by its surrounding building elements, depending on the type of smart object. For example, a temperature sensor may be mistakenly placed next to a furnace or air conditioner, which can interfere with its proper operation. In [100], it is shown that the performance of an optical sensor can be greatly influenced by the material properties of the target surface it is sensing. The actual verification criteria used are specific to the type of smart objects. A Smart object Type Descriptor (STD) is created as an external XML file to describe the performance constraining factors of each smart object. An example STD is shown in Figure 4.6(a). The verification engine then parses the description and analyses the spatial interactions between the smart object and its surrounding building elements.

B. Single Service Performance

A RWS is defined upon a set of smart objects and building elements involved in delivering the service to the building occupants/owner/manager. For example, as shown in Figure 4.3(b), a room entry monitoring service is defined upon an infrared motion sensor in the room and the door that is within its range space.

Likewise, a Service Performance Descriptor (SPD) is created as a XML file to describe the smart objects and building elements that constitute each service. An example SPD is shown in Figure 4.6(b). Each RWS could be constituted by one or more smart objects. When verifying a service, the verification engine parses the SPD and analyses the smart object's performance constraining factors (from STD) and the building element properties such as operational space and material information (from IFC file) for their impact on the service performance.

C. Inter-Service Performance

In SGRB, each RWS works autonomously in most cases. However, an event may occur that triggers several services, either because the event simultaneously satisfies the trigger conditions of multiple services, or the result of one service leads to another, i.e. chain of services [101]. The confluence between services can be complicated and may not be completely anticipated by the designer. Some consequent impacts can be collaborative and beneficial to the service users, while some can be conflicting and degrading the service quality as a whole.

```
<SmartObjectTypeDescriptor>
  <InfraredMotionSensor>
    <AffectingMaterial>
      <Material name = "Glass">
      <Material name = "Plastic Films">
    </AffectingMaterial>
……
  </InfraredMotionSensor>
  <TemperatureSensor>
    <AffectingFurniture>
      <Furniture type = "Furnace" maxDistance = "2m">
      <Furniture type = "AirConditioner" maxDistance =
"2m">
    </AffectingFurniture>
……
  </TemperatureSensor>
……
</SmartObjectTypeDescriptor>
```

```
<ServicePerformanceDescriptor>
  <Service Name = “HouseEntryMotionSensingService”>
    <SmartObjects>
      <Sensor type = "InfraredMotionSensor" name =
“LivingRoom_1_InfraredMotionSensor_1”>
      <Sensor type = "SoundSensor" name =
“LivingRoom_1_SoundSensor_1”>
    </SmartObjects>
    <BuildingElements>
      <Furniture type = "Door" name = “HouseEntryDoor”>
    </BuildingElements >
……
  </Service>
  <Service Name = “HallwayIlluminationService”>
  <SmartObjects>
      <Actuator type = "WindowBlindsController" name =
“HallwayWindowBlindsControler_1”>
      <Sensor type = "LightSensor" name =
“HallwayLightSensor_1”>
    </SmartObjects>
    < BuildingElements >
      <Furniture type = "Window" name =
“HallwayWindow_1”>
      <Furniture type = "Window" name =
“HallwayWindow_2”>
    </BuildingElements >
……
  </Service>
……
</ServicePerformanceDescriptor>
```

(a) **(b)**

Figure 4.6. (a) Example of Smart Object Type Descriptor. (b) Example of Service Performance Descriptor

For example, during a hot summer, an occupancy sensor senses a user’s presence and instructs the HVAC system to cool the room, while a motion sensor in the room recognizes the same user to be reading a book and instructs the window to roll up its shades to improve illumination. However, the incoming sunshine heats up the room and causes the former cooling service to take more time and consume more energy to achieve its targeted temperature.

Such service conflicts undermine the quality of an SGRB design and impact on the performance of the conflicted services. In literature, this conflict of services is sometimes referred to as Feature Interaction [101], which could be spotted during the design phase by identifying their triggering events and resulting environment state change.

To verify an SGRB design against service conflicts, each service registers its triggering/affecting environment factors, which are also profiled in the SPD, with the Environment State Registry (ESR). The verification engine performs environment state reasoning by analysing the location of smart objects that constitute the different services and the environment factors that they affect. Using the previous example of service conflict, the occupancy sensor and motion sensor may or may not have overlapping range spaces, but they share a common room space. Furthermore, if the room space of two smart objects with common environment factors can be connected through opening a door, a warning should be generated for the design. Once again, BIM provides data on the room space where a smart object resides, and the verification engine queries the ESR and checks against the other services defined upon smart objects in the same or adjacent room connected by a door, as shown in Figure 4.7.

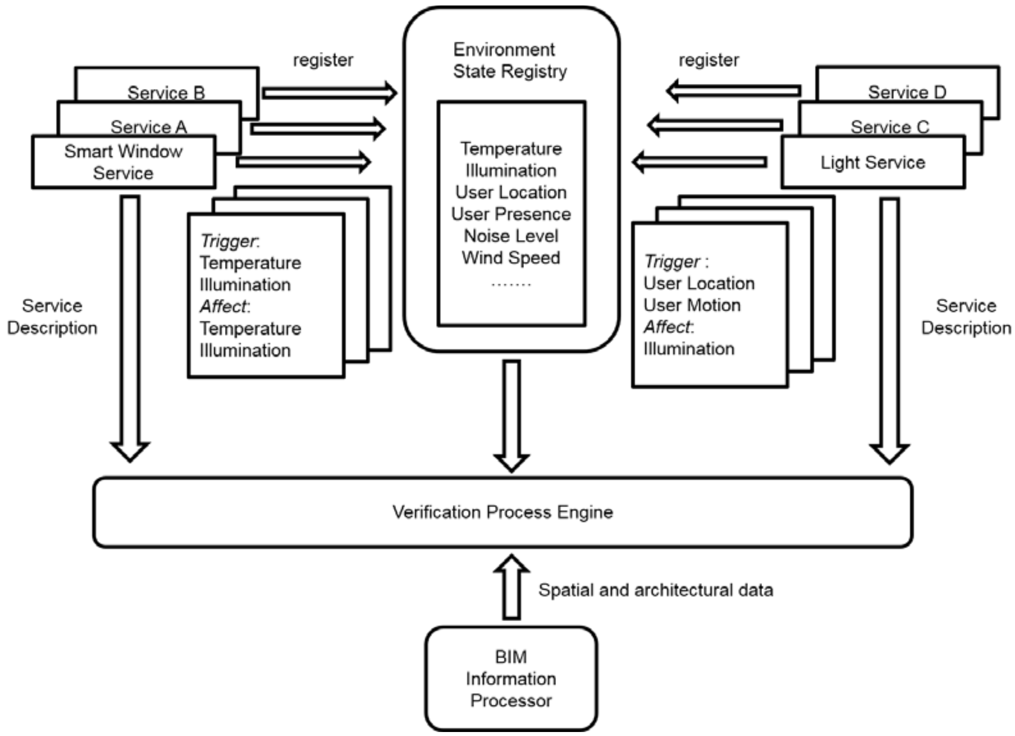


Figure 4.7 Verification with Environment State Registry

4.4 Integrating BIM in Post-Construction Facility Management

The BIM file generated from Revit and validated using the verification framework in the previous section is an output from the SGRB designer or architect during the building design phase. In the post-construction facility management phase, the building manager can apply the information in this BIM file to perform day-to-day building management, and in particular energy management.

To parse the BIM file and read the profiled information, there are two possible options for the design of this research. The first is to extend the Revit using a native Software Development Kit (SDK) to perform the energy management task. The second is to develop a standalone BIM tool as a separate energy management engine. After much contemplation, we decided to go with the second option as we believe that building managers will be more familiar with using a Building Management System (BMS) for their everyday work than with Revit, which is a computer-aided design (CAD) tool for building designers and architects.

Therefore, we opted for the second option and a stand-alone BIM tool for energy management has been developed. We developed the tool using the extensible building information modelling [102] toolkit which provides IFC parsing and 3D presentation utilities.

As different smart objects may have different data input/output interfaces, the properties parameter specified in our BIM design in the previous section provides a convenient way for the BIM tool to handle such low level operations. An adapter layer is designed in this research to process the requests from BIM software which parses the IFC file and demands data exchange for the smart object. The mapping/parsing operation is illustrated in Figure 4.8. The software architecture for our developed BIM tool is shown in Figure 4.9.

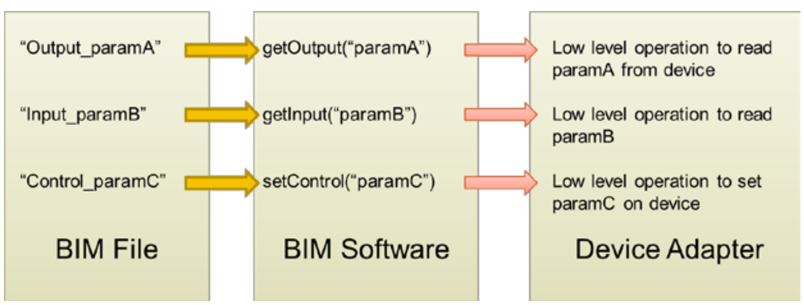


Figure 4.8 Mapping from BIM file to Software Information Interface Programming

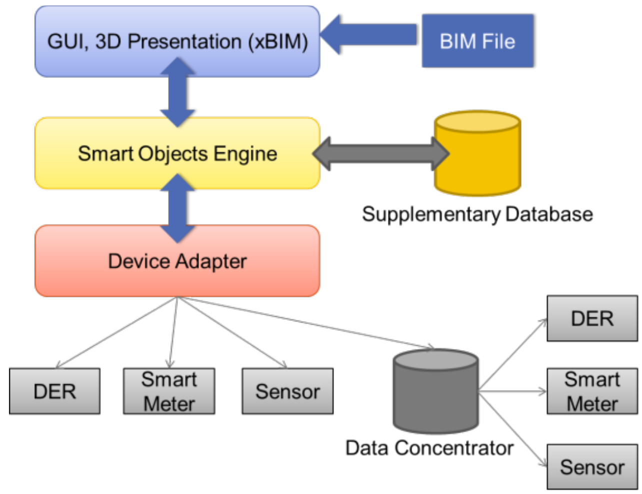


Figure 4.9 BIM-based Energy Management Platform Software Architecture

Real-time data from the DERs, smart meters and sensors are collected and stored in a database. Figure 4.10 shows an instance of the real-time monitoring data from a living room sensor displayed to the user, i.e. home owner or building manager.

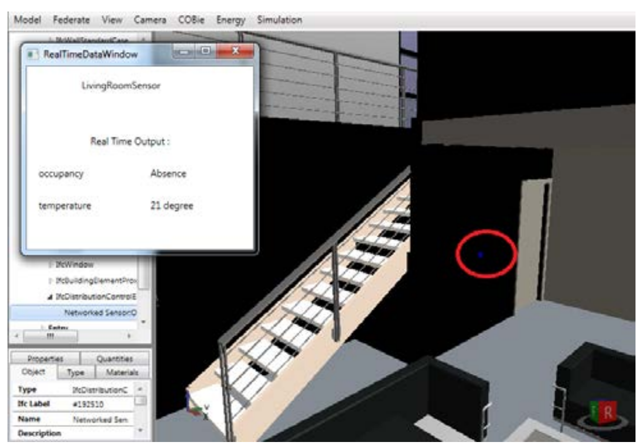


Figure 4.10 Real-time Monitoring Data Display to User

With real-time data from the smart objects, energy management and analysis in BIM software are facilitated and achieved. Real-time generation data of on-site DERs show the current energy production capacity and indicate how many loads can be supplied off the power grid. Weather, temperature, building and occupant data from sensors form a view of the present and future energy generation/consumption as shown in Figure 4.11.

The pricing information from the smart meter allows the building to perform demand response actions in coordination with the power grid.

In our BIM tool, we demonstrated the energy management functionality through a simulation of demand shifting. When the real-time pricing information from the smart meter reaches a user-defined threshold, the software triggers the demand shift process and transmits control commands to the energy consuming appliances.

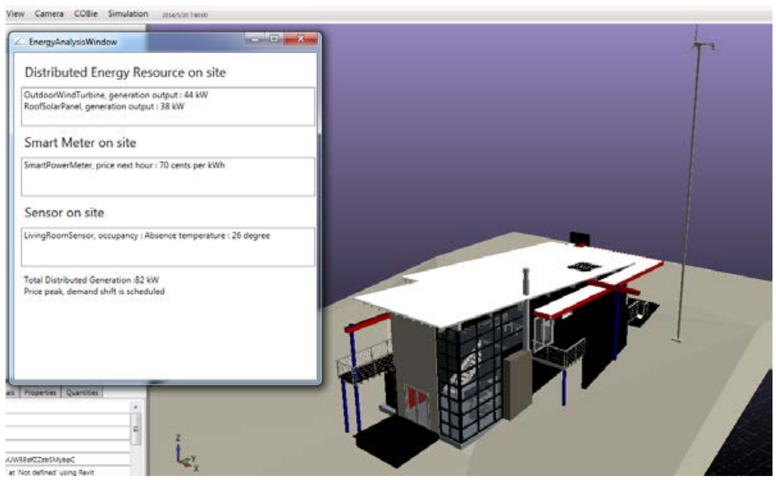


Figure 4.11 Energy Analysis Functionality in Smart-Grid-Ready Building

4.5 Synergies Between SDN and Smart Grid

Just as we examined the role of BIM in SGRB, in this section we further examine the opportunities for SDN in Smart Grid. The vision for SDN in Smart Grid lies in its capacity to perform the following functions:

4.5.1 Ease of Configuration and Management

The separation of packet forwarding intelligence from the data plane to the externally centralized control plane renders the SDN easy to configure and manage. The control plane or network operating system (OS) is aware of the global network state and provides applications or management systems with programmatic interface to configure how packets will be forwarded through the network switches and provide this forwarding knowledge to each switch in the data plane. Packets in the network that do not match any existing forwarding/access control rule in the data plane will be sent to the control plane for setting up new forwarding/access control rules. This is much more convenient than traditional networks in which forwarding/access control rules cannot be reconfigured dynamically after the deployment.

In Smart Grid, the information network connects a diverse and large number of nodes, which can incur considerable costs and workload to configure and manage. Using an underlying SDN infrastructure, such complexity can be simplified. On the other hand, the provision for network owners and operators to programmatically control their infrastructure allows new features to be introduced quickly into the network OS, which in turn fastens the pace of implementing new network services or improving network performances [103]. Considering the rapidly evolving standards and protocols in Smart Grid, where applications are required to be extensible and compatible, it will be extremely advantageous to support service developments with an SDN network infrastructure.

4.5.2 Cross-Domain Content-Based Networking

In Smart Grid, the information exchange takes place across network domains/regions. SDN provides a fine-grained packet classifier and flexible routing, which can facilitate directing a chosen subset of traffic through a set of network devices such as firewalls and NATs [95]. With the programmable capability of classification based on packet content, service requests such as interest messages or subscriptions will firstly be sent to and parsed at the controller, which then instructs the data plane to route the contents of interest to the requesting applications [104]. With its high degree of flexibility for implementing novel networking solutions, SDN has also been the main driving force in the development of new information-centric networking (ICN) functionalities, such as content-centric query/response, content-name based routing, and in-network content caching [105].

Such features can improve the efficiency and scalability when delivering data across network domains/regions in the Smart Grid. We will examine in more detail how SDN enhances the data exchange mechanisms in Smart Grid in the next sub-section.

4.5.3 Virtualisation and Isolation

The SDN paradigm also offers the capability of network virtualization, which groups resources into logically isolated administrative entities, i.e. virtual networks. Virtualization isolates different flows of data, which makes it flexible to perform separate controls on traffic with different interest. Unlike other virtualization technologies such as VLANs or VPNs in which the configuration of individual switches to create virtual networks is tedious and error-prone, SDN enables this process to be automated because an overlay network built on SDN can be reconfigured quickly according to software instructions.

In [106], network slicing is proposed as a means of sharing the home network among multiple service providers. The bandwidth resource of a home network is 'sliced' for different services (which may include Smart Grid services from the power company) by deploying OpenFlow – a notable implementation of SDN architecture, for network virtualization. We take a step further to envision that the virtualization capability of SDN will benefit the process of resource aggregation in Smart Grid, which we will examine in detail in next section.

To illustrate our view of the advantages of using SDN, two potential use cases have been selected to examine how SDN will contribute to: i) distributed energy resources aggregation; and ii) SGRB energy management, in Smart Grid.

4.5.4 Use Case I: Virtual Network for Distributed Energy Resources Aggregation

One of the major developments in Smart Grid in recent years has been the transformation from centralized generation to decentralised distributed generation. In low voltage (LV) and medium voltage (MV) networks, there has been an increasing penetration of DERs, which aims to lower the carbon emission and improve residential power efficiency and reliability.

The control and aggregation of DERs in MicroGrid and VPP have attracted much attention within the research community. One common approach for DER aggregation and coordination solutions is based on Multi Agent Systems (MAS) and fuzzy logic control, which are restricted to the application layer. Again, we envision that SDN technology which enables scalable and efficient virtual networks would provide a novel underlying communication platform for the control and aggregation of DERs, e.g, photovoltaic (PV) systems, micro-combined heat and power systems (μCHP), and electric vehicles (EVs), as shown in Figure 4.12.

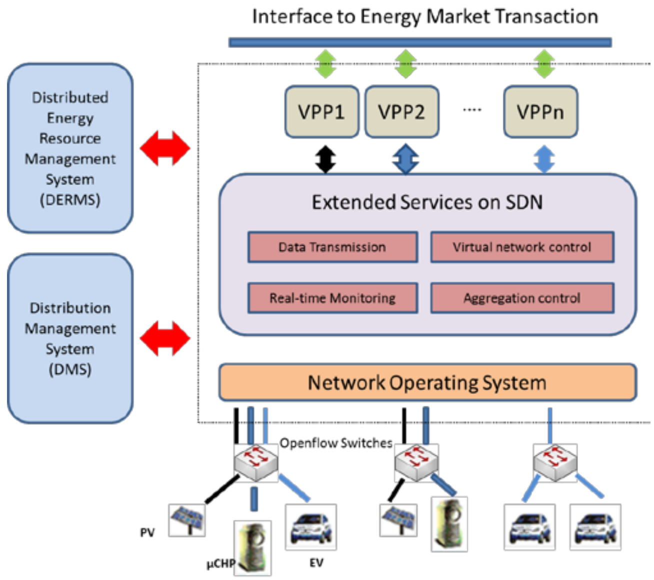


Figure 4.12 DER Aggregation with SDN

Opportunities for SDN: From a logical point of view, a VPP is a software component to control energy transactions through coordination and exchange of data among a group of DERs. By incorporating the SDN paradigm into the design model of VPP, integration and management of DERs will be extended to the underlying network infrastructure.

In a real power distribution use case, different DERs may be connected to the information network of Smart Grid with different communication technologies. Consider energy generation systems such as µCHP and PV systems in homes or offices, as well as energy storage systems such as EVs, which are connected to the Smart Grid information network by a multitude of wired/wireless technologies. The challenge is that DERs have a distinctive requirement on real-time data monitoring and control, e.g. to prevent voltage fluctuations, whereas other connected end devices such as smart appliances exchange data with the grid in a relatively low frequency and less real-time demanding. Thus, network bandwidth and QoS have to be guaranteed for DERs, unlike other devices.

SDN allows aggregating DERs with virtual networks by dynamic software configuration (Figure 4.12). It can provide perfect isolation and separation for different aggregation or management traffic on a single physical connection without interfering with each other. Network resources for DER communication with the Smart Grid can be allocated dynamically on-demand based on software instructions. In such an infrastructure, DERs aggregated to the same VPP are controlled and communicate in an exclusive virtual network, which can be easily deployed and configured by a centralized SDN controller.

As previously mentioned, SDN enhances the data exchange by facilitating pub-sub or other content-based processing at the network layer. The monitoring and control data of DERs are able to be delivered at line-rate speed along with value-added network services such as optimised routing and in-network caching, which enhances not only scalability but also timeliness of data delivery that is critical for real-time market coordination.

Furthermore, when an aggregation criterion, e.g. geographic location restriction, in a VPP is modified, or the energy production rate of a DER has changed due to seasonal weather conditions, which necessitates the relocation of the DER to a different VPP aggregation, this can be performed by applications efficiently via their programmatic interfaces to the SDN controller.

Similarly, adopting a SDN based design for DER aggregation is beneficial when coping with ‘mobile’ DERs such as EVs that join and leave a VPP dynamically. A distributed energy resource management system (DERMS) that is aware of the network status can automatically reconfigure to respond to new aggregation changes. A newly joined EV can be dispatched to the virtual network of the appropriate VPP, and information channels such as charging rate broadcast from the utility will be set up for coordination. The management complexity can be reduced since the whole process from networking to aggregation can be handled by software services based on SDN extension.

4.5.5 Use Case II: Smart Grid Ready Building Management

In this use case, we examine the opportunities for SDN in building management systems for SGRB. Currently there are the Building Automation System (BAS) and Energy Management System (EMS) in the industry for intelligent building energy control and management. These systems gather data from the sensors and appliances, and communicate with the Building Management System (BMS) to control and monitor all facts of the building, such as lighting, fire control, and energy use.

An SGRB is more than the integration of BAS, EMS, and BMS for today's intelligent buildings. The Smart Grid will require a SGRB to possess energy intelligence of finer granularity (e.g. down to appliance level) than today's intelligent buildings, and more importantly, capabilities to support advanced metering, automated demand response, reaction to real-time pricing, and integration of DERs including EVs.

Opportunities for SDN: From the energy perspective, an SGRB can be viewed as a MicroGrid, where local metering and sensing devices, HVACR controllers, energy loads, and DERs are monitored and controlled by advanced ICT systems to optimize the energy cost, efficiency, and performance. Considering the rapid development of SDN in campuses and data centres [107], the technology not only helps to build a novel communication infrastructure for all types of end nodes in SGRBs, but is also convenient to be extended to suit proprietary deployment requirements and implement customized energy control and management functions with different control granularities.

Incorporating SDN, EMS will provide interoperability to control and manage the communication network by programmatic interfaces to the control plane, and fulfill the data transmission demand for metering/sensing applications. More importantly, the building energy management will be facilitated to incorporate MicroGrid functionalities such as DER aggregation as presented in the previous use case in Section 4.5.4.

We envision an advanced platform for SGRB to host Smart Grid services and applications, by incorporating SDN into BIM-based systems, as illustrated in Figure 4.13.

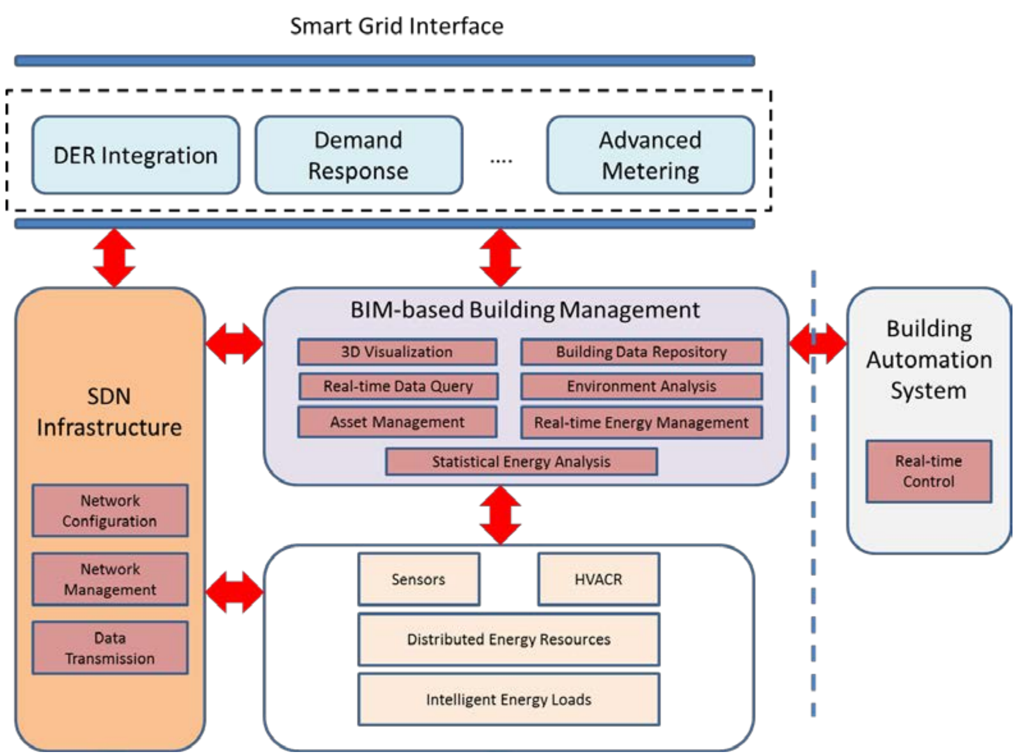


Figure 4.13. Smart-Grid-Ready Building with BIM and SDN

4.6 Chapter Summary

In this chapter, the findings and experiences gained from an investigation into how BIM and SDN can be developed and utilised for Smart-Grid-Ready Buildings are reported. Our work covers the investigation of BIM based methodologies for pre-construction design and verification, and post-construction facility management of SGRB in the Smart Grid era. A basic but functional prototype of a smart house energy management system using Revit and xBIM toolkit was also implemented and successfully demonstrated. Synergies between SDN and Smart Grid are presented, along with two use cases to examine how SDN can contribute to Smart Grid development.

CHAPTER V: Event-based Resource Management Framework for Distributed Decision-Making in Virtual Power Plant

5.1 Introduction

In the literature, Smart Grid is also sometimes referred to as the Internet of Energy, and it enables electricity consumers to become active players in the power system by feeding customer-side generated energy back into the main grid or participating in demand response programs. However, the high penetration of customer-side DERs also leads to new problems such as voltage rising with increasing distance from substation and revenue optimization when offering excess DER energy in the energy market [108].

The virtual power plant (VPP) is a concept for aggregating DERs and controllable loads, and presenting them to the main grid as a single energy trader [109]. The VPP can be centralised or decentralised, depending on whether the energy planning/scheduling is performed by a central controller, or in a distributed manner by "smart" energy resources.

Herein, the energy planning is referred to as consumption adjustment at some future time (e.g. a day ahead) based on forecast data, and energy scheduling as consumption adjustment in real time or very short notice. Compared to centralized VPP, the decentralised VPP has higher scalability and openness because the VPP operator does not directly control the energy consumption/generation or VPP membership but only dispatches information such as price signal and requires minimal knowledge about the aggregated resources [110]. The energy planning/scheduling in decentralised VPP could be posed as a distributed decision-making (DDM) problem [111].

The resource management problem in VPP involves different resources from different domains, e.g. power system domain and ICT domain, requiring complex provisioning and planning by collaborating between different resource management systems that are often owned by different customers. This demands a resource management approach that is more agile and flexible than existing ones, and which explicitly considers the interactions between systems in different domains.

However, a fully decentralised VPP poses intensive computation requirement on VPP participants, who inevitably sends information to each other for resource scheduling problem solving. This thesis studies a hybrid VPP approach, i.e. utilising both centralised and decentralised design to address the resource scheduling problem. The VPP operator does not control the appliances of their participants directly, but performs intensive computation for its participants and sends scheduling messages to aid their base consumption/generation (presented in Chapter 6); while VPP participants proposes to the VPP operator contractual energy offerings, according to which they make decisions in a decentralised manner to adjust their base consumption/generation (presented in this Chapter).

This chapter focuses on addressing VPP resource management issues in decentralized manner and presents resource models, concepts of events and corresponding event processing, based on which an event-based resource management framework is proposed to support distributed decision-making in the VPP. As will be further discussed in Section 5.3, an event in VPP refers to a state transition of, or an action task initiated by a resource. By event-based resource management framework, we refer to a conceptual structure designed to support resource management by providing views on how resources are interrelated and how operations on the resources can be orchestrated based on the transmission and processing of events.

By viewing VPP as a hierarchical structure and abstracting energy consumption/generation as contractual resources, i.e. contractual offerings to curtail load/supply energy, from third party VPP participants, the proposed framework offers flexibility and adaptability to cross-domain system designs, which in turn accelerates the development of energy management applications.

The remaining of this chapter is organised as follows. Section 5.2 presents the proposed resource management framework and corresponding resource model. Section 5.3 describes the events and event processing of the proposed framework for distributed decision-making. The ontology implementation and simulation analysis of the proposed framework are discussed in Sections 5.4 and 5.5, respectively. Finally, Section 5.6 concludes the chapter with some suggestions for future work.

5.2 Resource Management Framework and Corresponding Resource Model

5.2.1 Resource Classification and Resource Management Framework

In the field of Smart Grid, there is not yet a clear definition of the term “resource management”. It is sometimes even confusing to mention the term “resource” because it could refer to the energy offering in the market, equipment in the power system, or the hardware and software in the IT infrastructure.

For example, in IEC 61970 and 61968, two different classes co-exist to represent resources in the power grid: *PowerSystemResource* for equipment in the electric network, such as a generation unit, and Asset for all other devices owned by the power grid company, such as communication media [39, 40].

On the other hand, in cloud computing and IoT, the term "resource" often refers to "a reusable entity that is employed to fulfil a job or request", e.g. processors to perform computation, or objects that can provide data [112] such as sensors.

This thesis proposes a framework for resource management in VPPs, which has been described as event-based because it utilizes the concepts of events and corresponding event processing derived from the resource classification and modelling to be introduced below. In the proposed framework, resources relevant to energy-management are classified into three tiers as shown in Figure 5.1:

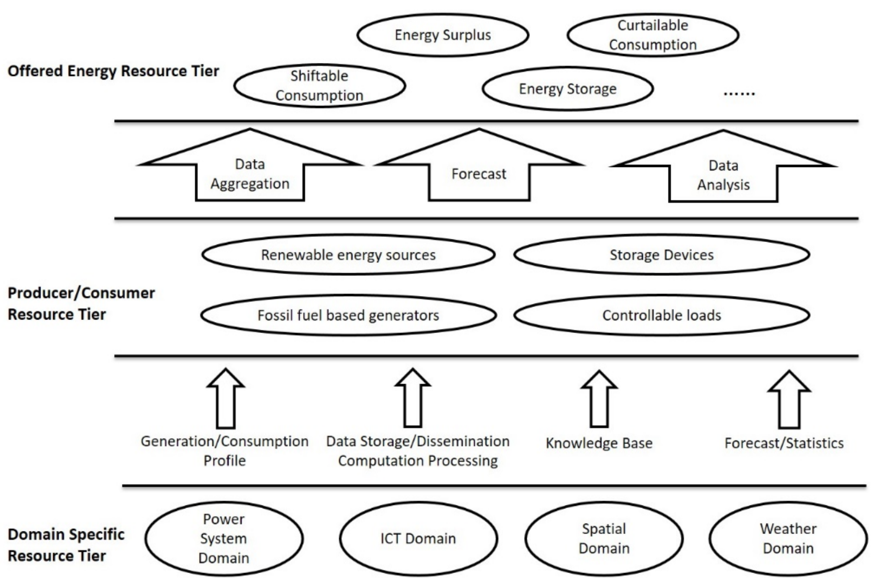


Figure 5.1 Framework for VPP Resource Management

- *Domain Specific Resources* (*DSRs*): These resources refer to those from different domains that contribute to the monitoring and control of energy generation/consumption. For instance, the information resource from the weather domain helps to define the forecast criteria for renewable energy generation, which in turn could alter the demand of energy from the main grid.

- *Producer/Consumer Resources* (*PCRs*): These resources refer to actors of the local power system such as customer-side generation units and controllable loads. For resources that may both consume and produce energy, such as a charging/discharging plugged-in electric vehicle (EV), they can be referred to as "prosumer" resources in this tier.

- *Offered Energy Resources* (*OERs*): These resources refer to customer-side offerings to supply, store, offload, or modify the demand of energy. For example, if a building with on-site generation (prosumer resource) generates more energy than it consumes, it may present to the VPP an offering to sell its surplus energy in the electricity spot market [109]. Such an offering is termed an offered energy resource (OER) in this tier. Furthermore, offerings from multiple PCRs, either co-located or geographically distributed but under the management of the same owner, can be aggregated and presented to the decentralised VPP as a single OER. We refer to an owner of PCR who participates in the VPP's intelligent energy planning/scheduling as an OER provider. The management of OERs is based on data aggregation, data analysis, and forecasting performed on PCRs. In this tier, the resource operations are typically market driven and DDM based.

5.2.2 Primary Domains for Smart Grid

There exist different domains of resources in VPP. Herein we identify the primary ones:

- *Power System Domain*: This is the domain that provides direct information about the PCR's energy consumption/generation profiles. In addition to what has been defined in the IEC suites, this domain should include operator-defined operating parameters (e.g. energy usage priorities) which can be used as criteria for energy scheduling and optimization.

- *ICT Domain*: This domain represents the information and communication technologies (ICT) that enable the smart operations of the electrical power grid, such as data storage, data dissemination, and computation processing services to PCRs. This domain also includes smart objects such as networked sensors and actuators for automated facility monitoring and control. Each PCR may have one or more smart objects streaming data to or receiving control signals from the energy management systems over an information backhaul. Besides sensors and actuators, computing platforms, network infrastructure and data storage devices are some other ICT resources that are crucial to supporting smart energy management.

- *Spatial Domain*: Different spatial configurations of the building and spatial-use patterns of spaces within a building may lead to different consumption patterns of consumer resources inside them. Therefore, in addition to sensory data, spatial-related information of the buildings or facilities is an important resource to achieving accurate energy analysis.

- *Weather Domain*: Similar to spatial information, weather information also contributes to the analysis not only of energy consumption of buildings or facilities, but also of energy generation of on-site DERs. Resources in this domain can be shared among weather-dependent PCRs within the same locality, such as by streaming data from a local weather station to all buildings within the area to facilitate their consumption planning.

5.2.3 OER Modeling and Problem Formulation

The resource management problem in decentralized VPP where time is divided into consecutive time units, and real-time or forecast price signal is broadcast to each PCR is investigated. For example, the electricity wholesale market regulation in New Zealand defines each trading period as half an hour, for which a real-time price signal is broadcast [113].

The OER in VPP can be a contracted load curtailment volume from a consumer resource, or energy supplied from storage discharging on request. All OER providers in a decentralized VPP should be able to determine the optimal operation strategy based on forecast prices. If no dynamics are introduced, the VPP will be in an equilibrium condition where all participants have no intention to modify their consumption/generation patterns. However, a VPP in the Smart Grid is expected to react to energy consumption/generation changes. Those changes could be either a demand response request by the main grid to the VPP to curtail its overall energy demand for peak shaving, or a surge in energy demand experienced by an OER provider due to charging by a large number of visiting EVs unexpectedly. The VPP can select and aggregate one or more OERs in response to various energy change events originating from either within VPP or from the main grid. The definitions to formulate the above problem are as follows:

Definition 1: An energy state matrix (SM) is a matrix representing the energy state of a PCR or OER provider (with one or more PCRs). The matrix contains column-wise tuples of time slot index, volume of energy generated/consumed by PCR or energy exchanged between OER provider and VPP, and the corresponding revenue gain/loss over that time slot period. The revenue in SM is calculated based on electricity price and operational expenditure.

The following shows an example SM of a PCR (e.g. a building rooftop solar panel *SP1*) that contains hourly forecast values for a day (from time slot T to T+23) where the values in first, second, and third row, represents the time in hourly slots, energy generated in kWh, and revenue in cents/kWh, respectively:

$$\mathrm{SM}_{SP1} = \begin{bmatrix} T & T+1 & \dots & T+7 & T+8 & \dots & T+23 \\ 0 & 0 & \dots & 11.2 & 18.5 & \dots & 0 \\ 0 & 0 & \dots & 10.7 & 10.7 & \dots & 0 \end{bmatrix}$$

The energy and revenue values of the above SM at time slot t = {T, T+1,..,T+23} can be represented by matrix elements $\mathrm{SM}_{\mathrm{SP1}}(2,t)$, and $\mathrm{SM}_{\mathrm{SP1}}(3,t)$, respectively. Similarly, for a SM of an OER provider, the energy exchanged between an OER provider *i* and VPP at time slot *t*, and the corresponding revenue, can be represented by $\mathrm{SM}_{\mathrm{i}}(2, t)$, and $\mathrm{SM}_{\mathrm{i}}(3, t)$, respectively.

Definition 2: An OER can be described by a parameter group composed of: (i) available time slot (*TS*); (ii) available energy volume (*Q*); (iii) economic cost (*EcoC*) incurred by revenue gain/loss; (iv) environmental cost (*EnvC*) incurred by environment deterioration during the resource's operation; and (v) social welfare cost (*SwC*) incurred by effects of resource's operation on power system social welfare. Therefore, a given OER *r* can be represented as an array <*TS*, *Q*, *EcoC*, *EnvC*, *SwC*> whose cost is given by a vector $\mathrm{C}_{\mathrm{vector}}$:

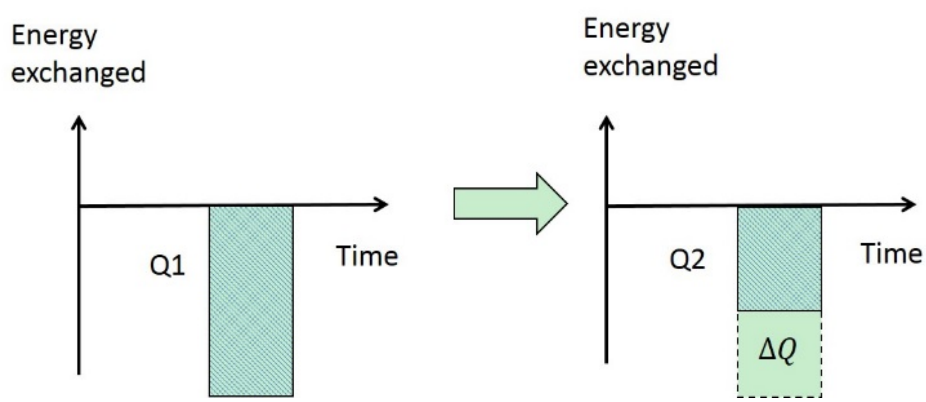
$$C_{\mathrm{vector}}(r) = [EcoC(r), EnvC(r), SwC(r)] \qquad (5.1)$$

Let $Q(r, t)$ denotes the energy volume provided by OER *r*, and $P^{*}(t)$ denotes the forecast prices for purchasing energy in future time slot *t*. The following presents the economic cost models for two different types of OERs:

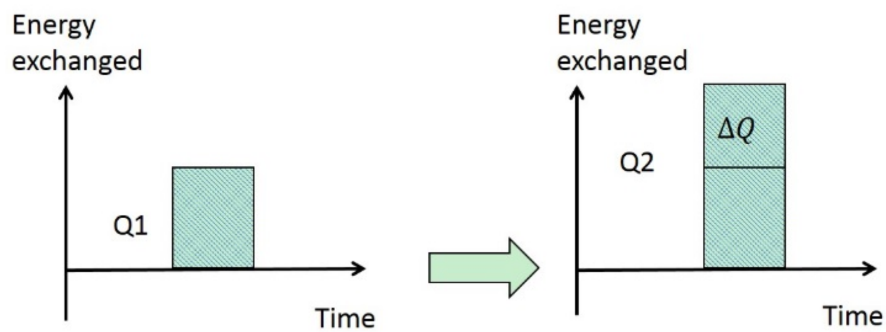
Type 1 OER: Curtailable consumption and dispatchable generation

Curtailable consumption and dispatchable generation are offered from the OER provider to VPP as a modified amount of energy exchange from previous import planning (for consumption) or export planning (for generation) in a specified time slot only, i.e. there are no changes to the planning in other time slots. We group these two types of resources as type 1 OER.

Let the sign of the energy exchanged represents its flow direction: negative for importing energy while positive for exporting. For curtailable consumption, the OER provider reduces its energy consumption by an amount ΔQ ($\Delta Q > 0$) in one or more time slots, potentially sacrificing utility (benefit) generated from energy consumption, e.g. occupant comfort, as a result. For dispatchable generation, the OER provider increases its energy production by an amount ΔQ ($\Delta Q > 0$), potentially with more operational expenditure, e.g. by using more fuels. Figure 5.2 illustrates an example of type 1 OER. In (a), an OER provider has previously planned a consumption of Q1, and it offers a type 1 OER of reducing the consumption by ΔQ to Q2. In (b), an OER provider has previously planned a generation of Q1, and it offers a type 1 OER of increasing the generation by ΔQ to Q2.



(a)



(b)

Figure 5.2 Illustration of type 1 OER: (a) Curtailable Consumption; (b) Dispatchable Generation

As shown in Figure 5.2, these two OERs are similar in that they do not introduce inter-time slot dependencies, i.e. changing the energy planning by an amount ΔQ in time slot *t* is only dependent on $P^*(t)$ and parameters of the aggregated PCR such as generation capacity. Thus, only column t of their respective SM will be modified accordingly.

When scheduling such an OER *r*, the OER provider gains revenue from consumption reduction or generation increase based on $P^*(\mathrm{t})$, while losing revenue from sacrificial of utility or operational expenditure. Therefore, the economic cost for provisioning ΔQ in time slot t for type 1 OER can be given by:

$$EcoC_{type1,r}(\Delta\mathrm{Q},\mathrm{t}) = \left[P^*(\mathrm{t}) - \lambda_{type1,r}(\mathrm{t})\right] \times \Delta\mathrm{Q} \qquad (5.2)$$

where $\lambda_{type1,r}$ is the cost function of a type 1 OER *r* to represent the utility sacrificed, or generation operational expenditure per energy unit.

Type 2 OER: Shiftable consumption and storage charging/discharging:

Shiftable consumption and storage charging/discharging are offered from the OER provider to VPP as a modified amount of energy exchange from previous import planning (for consumption and charging) and export planning (for discharging) in a specified time slot, with corresponding changes to the planning in one or more future time slots. These two types of resources are grouped as type 2 OER.

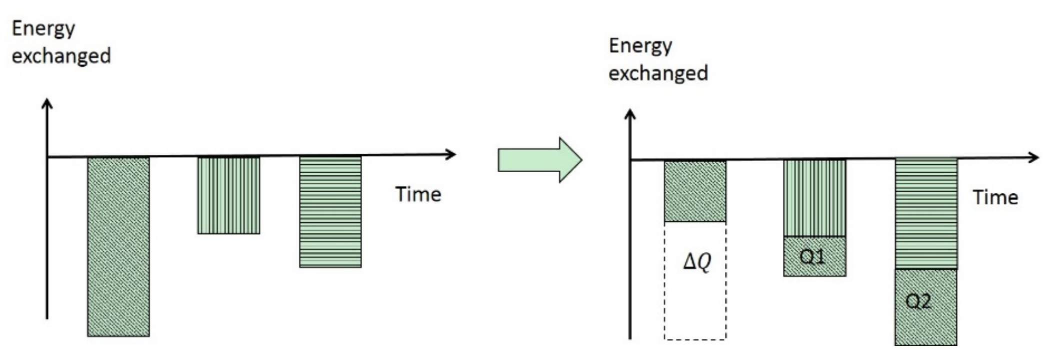
For shiftable consumption, the OER provider reduces (or increases) its energy consumption by an amount ΔQ in time slot *t*, but increases (or reduces) its energy demand by the same amount in one or more future time slots. By shifting consumption to a different time slot, it potentially sacrifices some utility (benefit) that could have been generated from consumption in the original time slot *t*. For example, a cloud data center providing computation services may defer some of its clients' computation tasks (and thus the energy consumption associated with performing those tasks) to some future time slots, which in turn could sacrifice the delivered quality of services to its clients since it would take more time to complete their tasks. For energy storage systems, the OER provider charges to store (or discharges to provide) ΔQ at time slot *t*, while discharges (or charges) by the same amount in one or more future time slots within a cycle time (typically a day). In addition to the electricity cost for charging, there are also costs associated with the operation and maintenance of the energy storage system, i.e. operational expenditure.

Figure 5.3 illustrates an example of type 2 OER. In Figure 5.3(a), an OER provider reduces its consumption in the first time slot by an amount ΔQ, of which an amount Q1 and remaining amount Q2 is added to its consumption in second time slot, and third time slot, respectively. In Figure 5.3(b), an OER provider charges its storage during the first time slot by an amount ΔQ, of which an amount Q1 and remaining amount Q2 is discharged in second time slot, and third time slot, respectively.

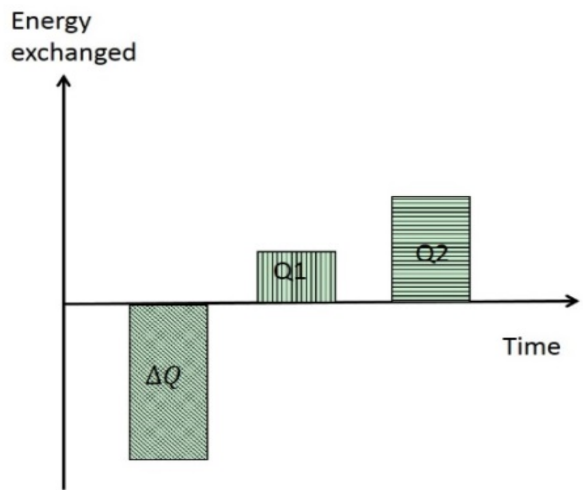
When scheduling a shiftable consumption OER *r*, the OER provider gains revenue from consumption reduction in time slot *t* based on $P^*(\mathrm{t})$, while potentially loses revenue from sacrificed utility and increased consumption in one or more future time slots. In the case of the storage system, the OER provider gains (losses) revenue from discharging (charging) energy in time slot *t* based on $P^*(\mathrm{t})$, but loses (gains) revenue from charging (discharging) energy in one or more future time slot. Denoting M and ΔQ_j as the set of one or more future time slots, and the amount of energy shifted to or charged/discharged in some future time slot $j \in M$, respectively, the economic cost for provisioning ΔQ in time slot *t* for type 2 OER can be given by:

$$EcoC_{type2,r}(\Delta\mathrm{Q}, \mathrm{t}, \mathrm{M}) = P^*(\mathrm{t}) \times \Delta\mathrm{Q} - \sum_{j \in M} \Delta Q_j \times \left[P^*(j) + \lambda_{type2,r}(t, j)\right] \quad (5.3)$$

where $\lambda_{type2,r}$ is the cost function of a type 2 OER *r* to represent the utility sacrificed due to shifting consumption, or storage operational expenditure for charging/discharging per energy unit.



(a)



(b)

Figure 5.3 Illustration of type 2 OER: (a) Shiftable consumption; (b) Storage charging

Since each OER provider has the forecast prices, for type 2 OER, the case where a future time slot set ρ is proposed by the OER provider such that the economic cost incurred for every other possible time slot set is greater than the one in ρ, is investigated as follows:

$$\rho = \underset{M}{\operatorname{argmin}}\, EcoC_{type2,r}(\Delta \mathrm{Q}, \mathrm{t}, \mathrm{M}) \qquad (5.4)$$

To evaluate the social welfare of the power system, the day's peak average ratio (PAR) of the OER provider as the social welfare cost metric is utilized. Let *D* represents the set of time slots for a day of operation. The social welfare cost (*SwC*) and the total cost C_{total} for OER *r* from some OER provider *i* can be given by Eqs. (5.5) and (5.6) respectively:

$$\mathrm{SwC(r)} = \mathrm{PAR(r,i)} = \frac{\max\limits_{t \in D}[\mathrm{SM}_i(2,t) + Q(r,t)]}{\operatorname*{avg}\limits_{t \in D}[\mathrm{SM}_i(2,t) + Q(r,t)]} \qquad (5.5)$$

$$C_{\mathrm{total}}(r) = \mathrm{f}(C_{vector}) = \mathrm{f}[EcoC(r), EnvC(r), SwC(r)] \qquad (5.6)$$

where *f* ( ) is the function agreed by VPP participants to evaluate the total cost of OER *r* using cost metrics in C_{vector}. Furthermore, different resource scheduling algorithms that schedule resources according to VPP participants' cost/revenue, such as in [80] and [114] based on game-theoretic and genetic algorithmic approach, respectively, can be selected for application to the framework by substituting $f\,(\ )$ with the cost/revenue objective function of the applied algorithm. As part of this thesis, a game theory based scheduling algorithm will be presented in Chapter 6, in which the prosumer utility function can be applied as $f\,(\ )$ in Eqs.5.6.

With the above OER model, the problem is formulated as follows: given a set of time slots $t \in D$, available OERs $r \in R$, their cost metrics and an energy amount G to be adjusted from previously planned energy consumption/generation, find a subset of OERs $\varphi \subseteq R$, such that $\sum_{t\in D}\sum_{r\in\varphi} Q(r,t) = G$, while $\sum_{r\in\varphi} C_{total}(r)$ is minimised.

5.3 Events and Event Processing

The resource selection for decentralized VPP is investigated as a DDM problem. The MAS approach is applied to implement one agent for each OER or PCR. The agent structure is shown in Figure 5.4. The event classification and processing of the proposed framework, in which the event sending/receiving between VPP participants is implemented based on the Foundation for Intelligent Physical Agents (FIPA) communication [29], are presented.

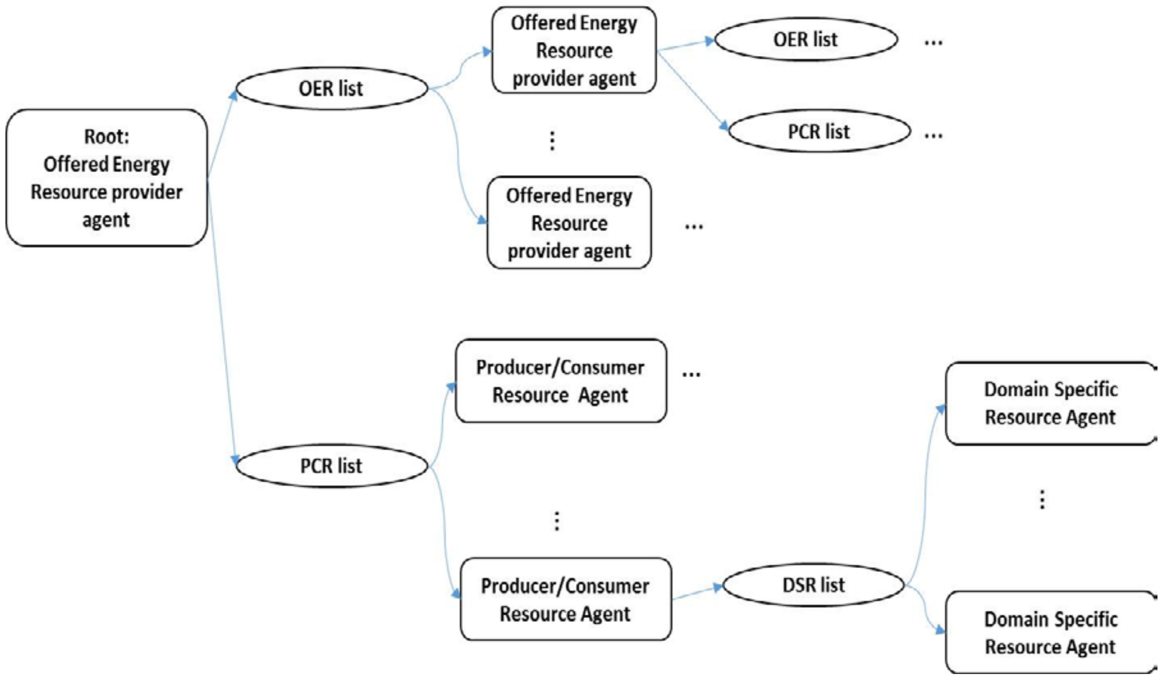


Figure 5.4 Agent Structure

5.3.1 Event Classification

Based on the OER model, the event types are classified as follow:

- *Energy Events*: An energy event e_n is triggered by a request for change in energy quantity over time. Typically, energy events are originated from an OER provider, and are sent/received between VPP participants in the energy resource tier of the proposed framework. An energy event can be described by a parameter group composed of: (i) request time slot (*TS*); (ii) change in energy volume (ΔQ); (iii) originated OER (*OriOER*); and (iv) next processing OER (*NextOER*). Therefore, a given energy event can be represented by an array <*TS*, ΔQ, *OriOER*, *NextOER*>.

- *Domain Events*: A domain event e_d can refer to a state transition event of a DSR or a PCR actuation event initiated by a DSR. Unlike energy events that are abstracted for resource selection, domain events are mostly discrete and occur as DSR state changes, or action tasks initiated by DSRs for PCRs such as the activation of an air-conditioner. They are a form of internal events communicated only within a VPP participant. Natural processes such as changes in the ambient temperature and solar radiation are considered as state transition events in this thesis.

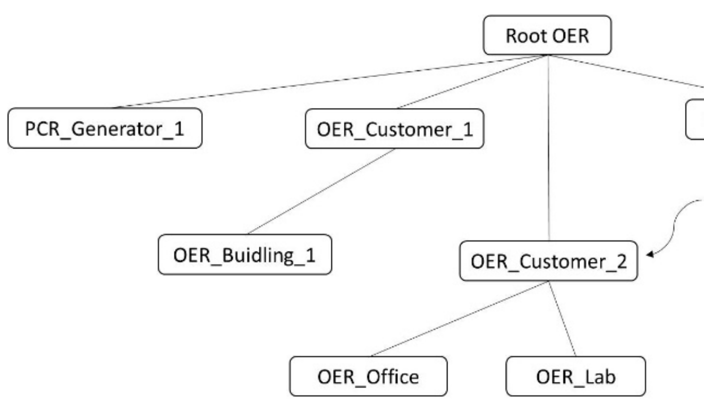
5.3.2 Energy Event Routing

An event routing algorithm for solving the DDM problem formulated in Section 5.2.3 is proposed. One provider agent represents each OER, and the VPP aggregation can be considered as a hierarchical tree with a root OER representing the overall VPP energy offerings to the main grid as shown in Figure 5.4. In addition, the following definition is given:

Definition 3: OERs and PCRs are siblings of each other if and only if they are directly aggregated by the same OER provider such as VPP operator or a customer owning several buildings. An OER is the parent (child) of another OER if it directly aggregates (is directly aggregated by) the other.

Each OER provider agent and PCR agent advertise their SMs to their sibling resources in order to calculate the social welfare cost metric, i.e. PAR, of the OER. Moreover, each OER provider agent maintains an energy event routing table (EERT) that dictates which OER is to be selected for an energy event, i.e. based on the information on this provider's OER, the sibling OERs, and a child OER with lowest cost among all children, the OER with lowest total cost can be identified by Eq. (5.6). An example of EERT is shown in Figure 5.5 for OER_Customer_2.

The initialization algorithm for EERT (Algorithm 5.1) is shown in Figure 5.6. When an energy event is triggered, the OER provider agent that receives the event searches the EERT for the lowest cost OER. If the OER with lowest cost turns out to be its own OER, the provider agent performs the tasks required to provision the OER and propagates domain events to its PCR agents to control generation/consumption. If the lowest cost OER is one of its child OERs, the provider agent generates a new energy event with that child OER's available energy volume, sends the new event to that child and waits for its information update, informs sibling/parent OER on new cost if necessary before repeating the routing algorithm on the event with reduced energy volume. If the lowest cost OER is one of its sibling OERs, the provider agent sets the *NextOER* field of the event to that sibling OER and sends the event to its provider agent. The detailed algorithm (Algorithm 5.2) is shown in Figure 5.7.



OER ID	Relation	Total Cost	Volume
OER_Customer_1	Sibling	100	50
OER_Storage	Sibling	80	30
OER_Office	Child	120	20
OER_Lab	Child	120	10
OER_Customer_2	Own	110	60

Figure 5.5 Example of VPP Tree structure and Energy Event Routing Table

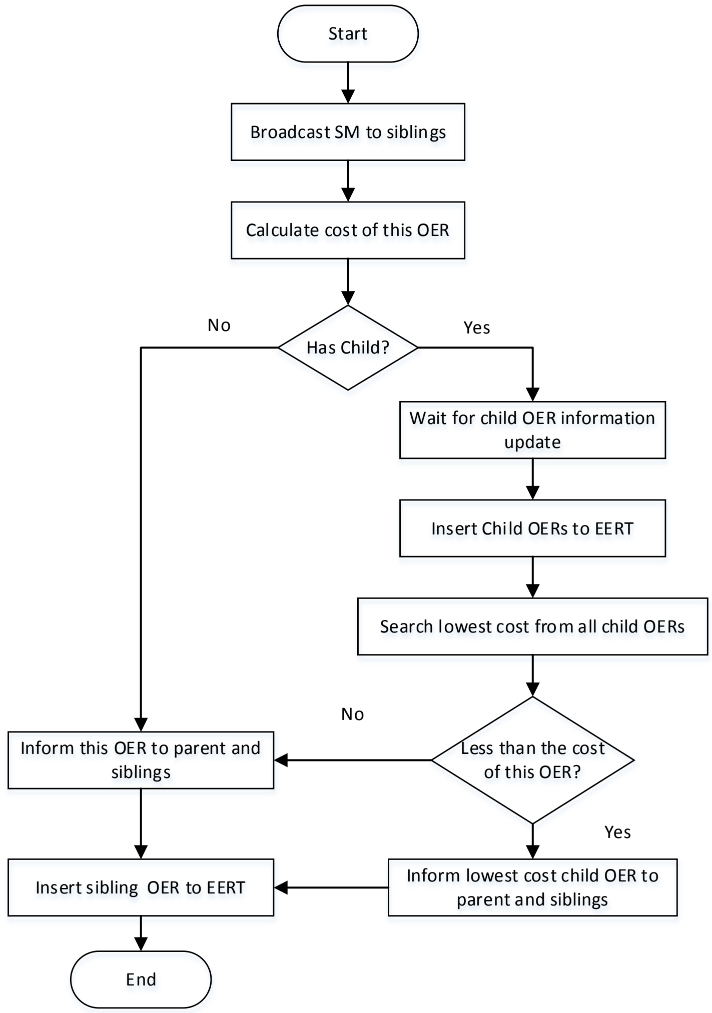


Figure 5.6 Energy Event Routing Table Initialization (Algorithm 1)

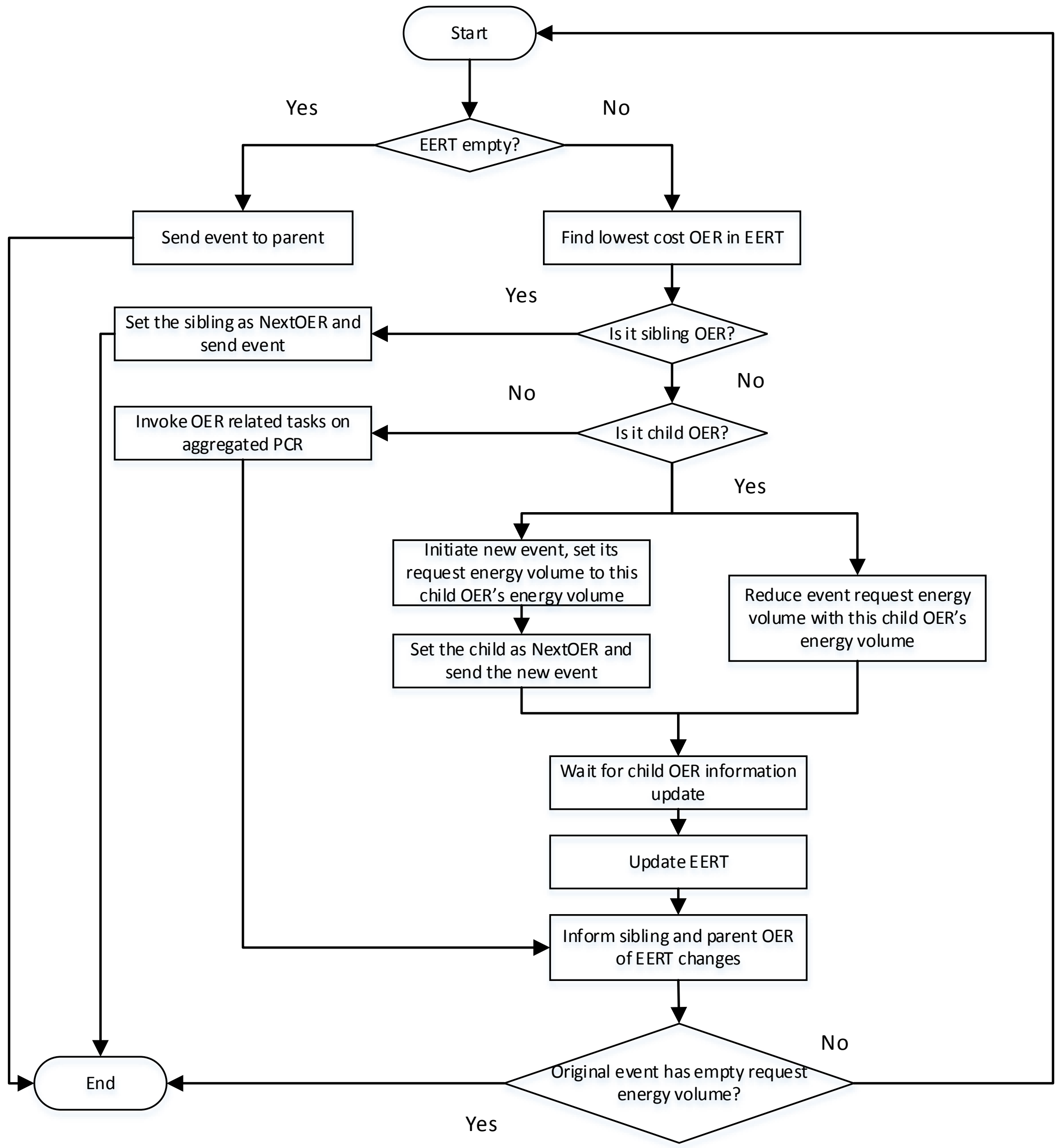


Figure 5.7 Energy Event Routing (Algorithm 2)

5.4 Resource Management Framework Implementation

Implementing the resource information modelling of the proposed framework requires addressing a number of essential issues:

- *Shielding the Heterogeneity*: The Smart Grid has been developed based on a myriad of different technologies, systems and devices. Legacy systems, i.e.

outdated but still in use resource management systems, are also a primary concern for the evolving new standards that are being developed [1]. It is important for the resource model implementation to consider the problem of shielding its users from explicit handling of such heterogeneity and the interoperability between these heterogeneous elements. In the context of a VPP that aggregates multiple buildings, heterogeneity could also be introduced by the disparate energy management systems that may exist within different buildings of the VPP.

- *Merging Different Domain Knowledge Bases*: Different domains have different formats of knowledge base, which usually come in the form of different domain ontologies. In order to achieve semantic interoperability between various domain ontologies, the resource model implementation should consider merging them under a top-level or upper ontology [115] for cross-domain synthesis of the resources in Smart Grid.

- *Predicting User Response*: Having the capability to predict the responses of the energy users in different situations is important for VPP operation. The resource model implementation should facilitate the extraction of user parameters required by machine learning techniques such as Dynamic Bayesian Networks (DBN) for response prediction.

To meet the above requirements, the OWL is used to define the ontology of the framework, and thus the resources are semantically profiled using machine-understandable OWL files based on the model. This approach ensures the compatibility with existing standards and domain knowledge bases, as well as not overlapping with the power system models already defined in IEC 61850 and CIM, but can be incorporated into their future harmonization. Another important aspect is that with the ontology defined in the OWL, resource provisioning and management can utilise domain knowledge in interchangeable format, consequently allowing seamless integration of different software components within the VPP. Figure 5.8 shows the ontology implementation of the proposed resource model:

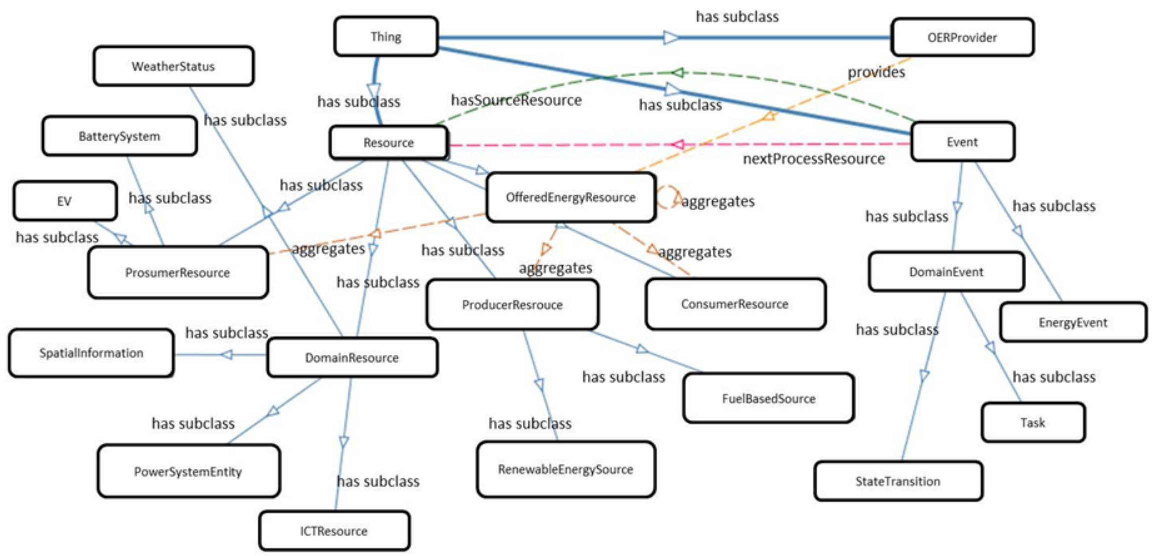


Figure 5.8 Ontology Implementation

A layered ontology structure is adopted, which is divided into upper ontology for OERs and PCRs, and domain ontology for DSRs. In the upper ontology, OERs are abstracted by the *OfferedEnergyResource* class, which has five types: *LoadCurtailmentVolume*, *LoadShiftingVolume*, *EnergyConsumptionVolume*, *EnergyGenerationVolume*, *StorageChargeVolume* and *StorageDischargeVolume*.

PCRs are abstracted by the *ProducerResource*, *ConsumerResource*, and *ProsumerResource* classes, which are designed to be the grouping points of different domain ontologies. Predicates such as *dependsOnWeather* are used to link the PCR with each domain class. New predicates could be introduced as the framework extends to encompass more domains.

In the domain ontology, DSRs are abstracted by the *DomainResource* class, whose subclasses include *PowerSystemEntity*, *ICTResource*, *SpatialInformation*, and *WeatherStatus* for power system domain, ICT domain, spatial domain, and weather domain, respectively. The *PowerSystemEntity* links to IEC/CIM harmonized device profiles and metering results by predicates *hasProfile* and *hasMetering*, whereas the *SpatialInformation* links to the resource's Building Information Modeling (BIM) knowledge base by predicate *hasSpatialInformation*.

Events are classified into *DomainEvent* and *EnergyEvent* classes corresponding to previous event analysis. Event class has a predicate *hasSourceResource* to indicate its originating resource. The predicate *nextProcessResource* denotes the next receiver of event.

To extract knowledge from the resource information model, Simple Protocol and RDF Query Language (SPARQL) [116] is used to query the semantic database that stores the resource profiles. The SPARQL is a World Wide Web Consortium (W3C) standard query language for the semantic web. It can be easily integrated into enterprise software applications by using SPARQL engines such as Apache Jena [117].

5.5 Results and Discussion

This section evaluates the multi-agent system and ontology implementation of the proposed framework for a simulated campus VPP with real building energy data.

5.5.1 Simulation Setup

A full day energy scheduling of a decentralized VPP consisting of campus buildings, renewable generation, fuel cell and energy storage system is considered. Each building has an energy management system, which provides the energy consumption/generation interface to the MAS agents. The energy storage system is controlled by a prosumer resource agent. The topology of the simulated campus VPP is shown in Figure 5.9.

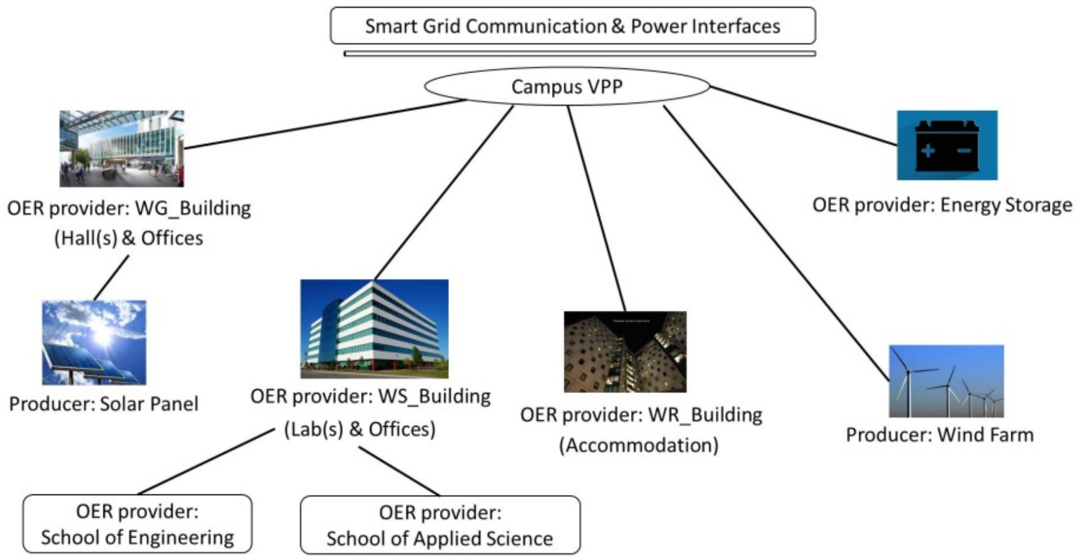


Figure 5.9 Simulated Virtual Power Plant Topology

A normal workday (10th August 2015) during our winter semester is arbitrarily selected for the study case. Figure 5.10 shows the half-hourly electricity price data for that day obtained from the Electricity Authority of New Zealand [118]. The price data is shown for 48 half-hourly trading periods over a full day of 24 hours. As VPP is considered to be capable of participating in the electricity spot market, this price data is utilised for the simulation in this research.

As demand forecasting is a research topic in itself which is beyond the scope of this paper, the historical metered energy data of Auckland University of Technology campus buildings are considered for the building energy consumption planning, i.e. future energy consumption pattern is considered to likely follow historical consumption pattern, which are shown in Figure 5.11. Without loss of generality, it is assumed that the energy storage system initially starts with a random value between 20% and 80% storage capacity, and then subsequently (for next simulated days) starting with the end storage value from the previous day. The parameters of real world 500kWh storage systems [119] given in Table 5.1 are used for the simulated energy storage system. However, the charge/discharge cost has been set to a value lower than main grid's electricity price, as otherwise the customer does not have economic incentive to use the energy storage systems. In the next chapter, we will discuss similar scenarios with prosumer generation through utility theory.

There is no environmental cost on OERs since the system only has renewable generation in VPP. The OERs of the buildings and their cost parameters are listed in Table 5.2.

The weather information used for renewable energy generation forecast is based on the weather profile for the same day obtained from New Zealand's National Institute of Water and Atmospheric Research (NIWA) [120]. The forecast solar and wind energy generation are shown in Figure 5.12.

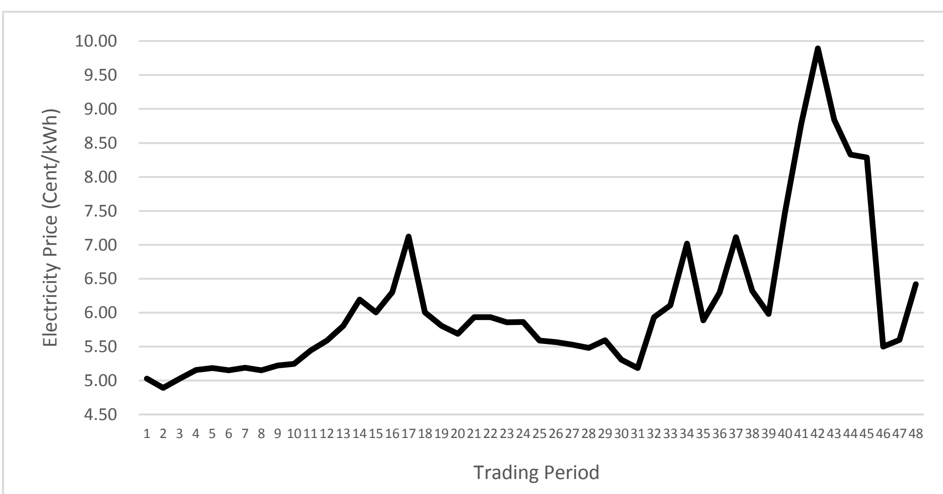


Figure 5.10 Electricity prices for 10th August 2015 from the Electricity Authority

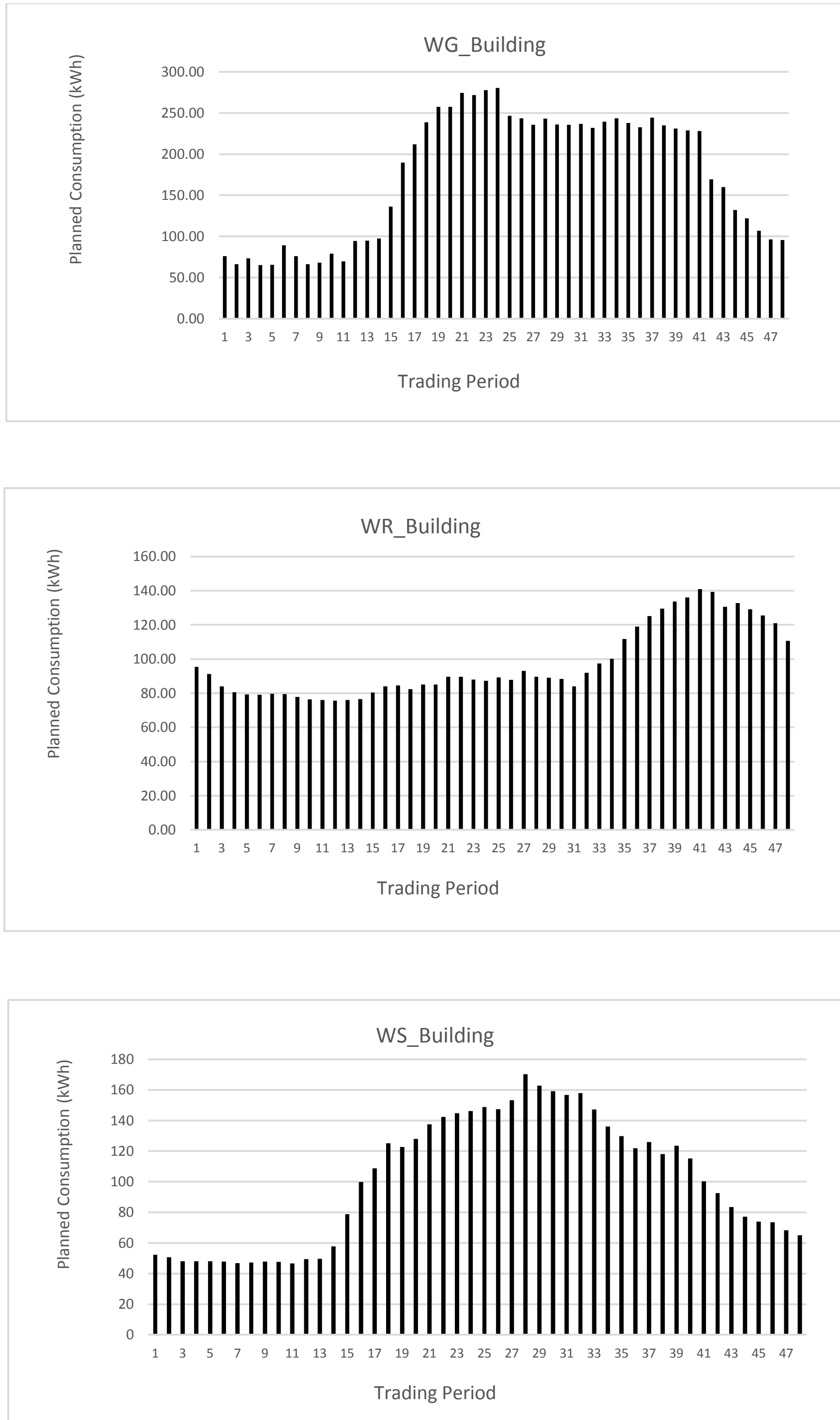


Figure 5.11 Building Energy Consumption Planning from Real-World Historical Data

Storage capacity	500kWh
Charge/discharge efficiency	90%
Charge/discharge cost	2.5 cents/kWh
Maximum charge/discharge power	250kW

Table 5.1 Energy Storage System Parameters

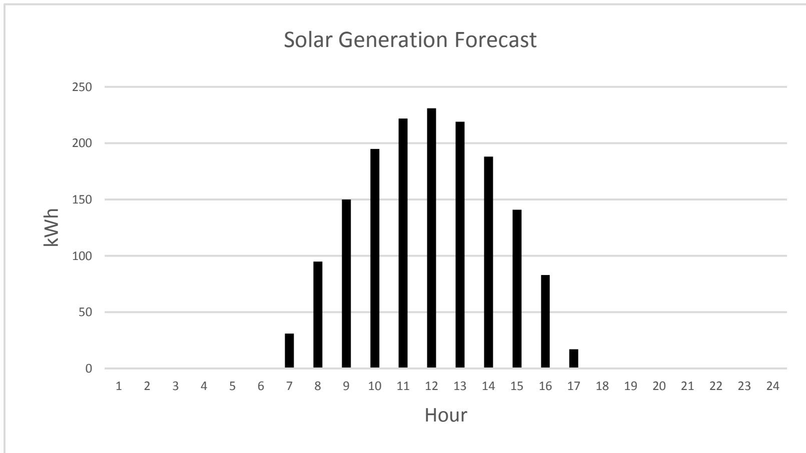
Provider	ID	Volume	OER Type	Available TP	Cost Parameter
WG_Building	G	60kWh	1	16~34	$\lambda_{\text{type1}} = 15$
WR_Building	R	20kWh	2	16~40	$\lambda_{\text{type2}} = 10$
WS_Building	S	10kWh	1	16~34	$\lambda_{\text{type1}} = 10$
School of Engineering	S-E	15kWh	2	16~34	$\lambda_{\text{type2}} = 20$
School of Applied Sciences	S-A	15kWh	2	16~34	$\lambda_{\text{type2}} = 18$

Table 5.2 OERs and Cost Parameters of Campus VPP

Solar System Rated Power	1000kW
Wind Turbine Rated Power	900kW

Table 5.3 Renewable Generation System Parameters

Two types of energy events are introduced in the simulation: wind generation uncertainty and VPP generation plan. Their system size parameters are listed in Table 5.3. Since solar generation is generally more predictable than wind generation, the solar forecast generation is utilized as the actual solar generation. The first illustration in Figure 5.12 shows the average solar generation in August for Auckland. For wind generation, real-world data quality issues which affect its forecast accuracy are considered [121]. Thus, the higher-end value (40%) of the forecast error range for wind generation is adopted. Therefore, at the beginning of each trading period (TP), an energy event will be triggered by the implemented MAS due to the observed difference between the forecast and actual wind generation. At TP 17, 34, 37 and 42 where electricity price peaks, the VPP will initiate an energy event to reduce demands and export as much energy as possible to the main grid.



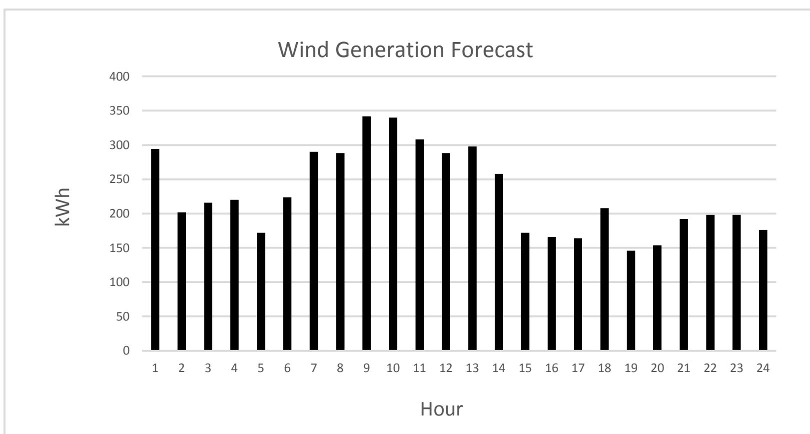


Figure 5.12 Renewable Energy Generation Forecast

5.5.2 Simulation Results

The simulated energy storage capacity for the day is shown in Figure 5.13, and the PAR of each OER provider and the whole VPP against their original planning is shown in Table 5.3. One can see that the energy storage is scheduled according to the price trends in Figure 5.10, and the PAR is reduced (closer to 1) compared to previously planned consumption, i.e. the VPP power system has increased the social welfare.

The investigation is further extended to larger VPPs with up to 100 buildings. The buildings are selected randomly as VPP members, with each building assigned to one of the three building types used in the previous simulation. For example, type G for halls/offices, type S for labs/offices, and type R for accommodation. Furthermore, the buildings have their energy consumption pattern normally distributed with real world consumption data as mean and 0.1 standard deviation. The cost/revenue objective function of the energy consumption game (ECG) [80] is utilized as the function $f(\,)$ in Eq. (5.6) for individual agents, along with a hybrid approach of using ECG for energy planning and our event-based resource selection for real time event processing.

The average results of the proposed event-based resource selection are compared with that of two other approaches: (a) without resource scheduling; and (b) real time ECG that runs the gradient algorithm for demand side management (DSM). In real time ECG, each agent iteratively sends out its energy planning according to price signals to coordinate with each other and adjusts consumption according to events. All agents run on the same computer with 3.2 GHz i5 CPU with 8 GB memory, under 64-bit Windows 7 operating system. The result of VPP revenue, by net energy export of a day, is shown in Figure 5.14. The communication overhead (Figure 5.15) is also measured as the average number of messages sent from agents to one another before the scheduling result is finalized for a time slot. In addition, the computation overhead (see Figure 5.16) is measured as the average total computation time by all agents to finalize the scheduling result for a time slot, using Java Management Extension (JMX) profiling [122]. All results are shown with their 95% confidence intervals where applicable.

The results show that both real time ECG and the approach based on the proposed framework expectedly performed better than without resource scheduling, and the improvement in revenue increases with the VPP size. It is also observed that the proposed approach achieves a revenue performance comparable with real time ECG, and performs better than real time ECG as VPP size increases to over 60 participants. Moreover, by not having to iteratively compute and send messages at every time slot, the proposed approach incurs significantly lower message and computation overheads as compared to real time ECG.

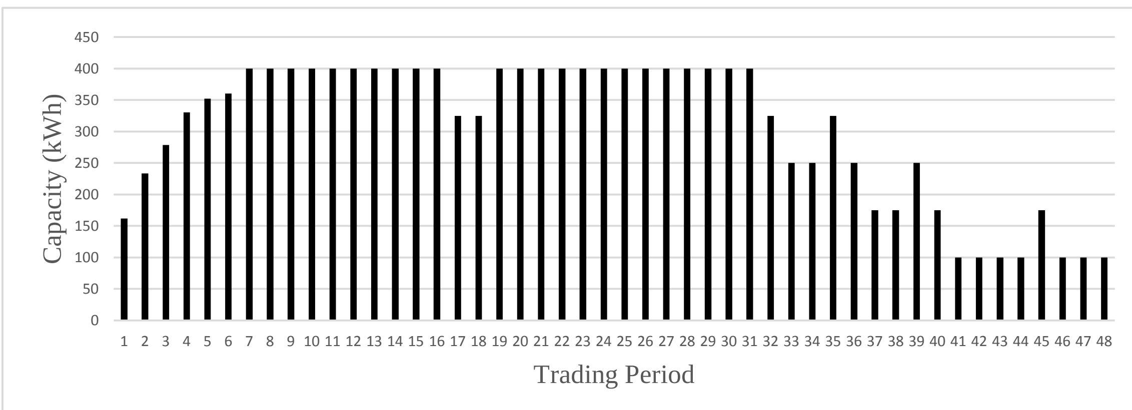


Figure 5.13 Energy storage system capacity

Provider	PAR of planned consumption	Actual PAR
WG_Building	1.605	1.599
WR_Building	1.445	1.440
WS_Building	1.691	1.527
Whole VPP	1.378	1.338

Table 5.4 Peak-average ratio (PAR)

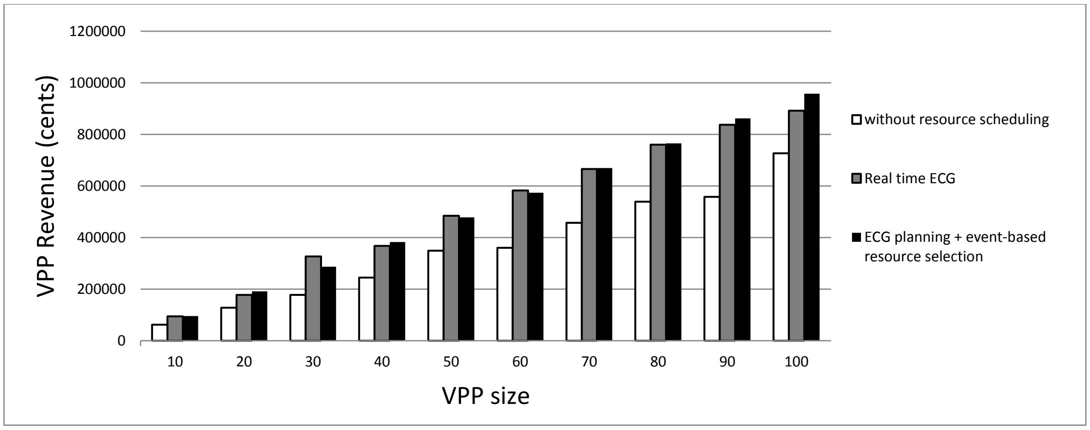


Figure 5.14 VPP Revenue Comparison

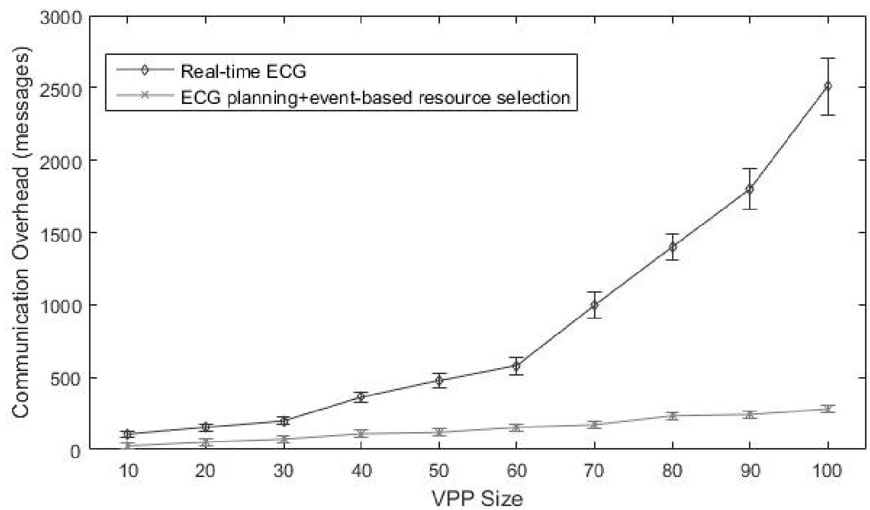


Figure 5.15 Communication Overhead Comparison

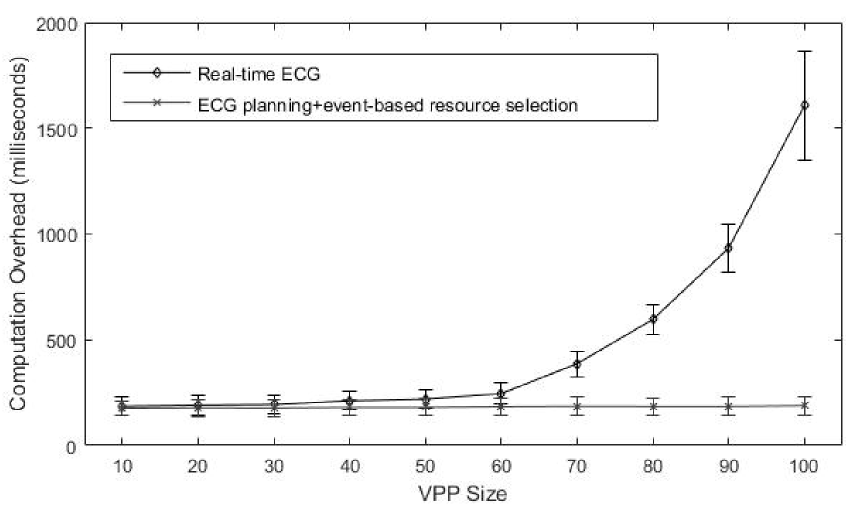


Figure 5.16 Computation Overhead Comparison

5.6 Chapter Summary

In Smart Grid, resource management is complex due to the wide variety of resources and the need for collaboration between systems in different domains. With a view to manage this complexity and to facilitate VPP application development, this chapter proposes a framework, which views VPP as a hierarchical structure and abstracts consumption/generation from third party VPP participants for managing different resource types of relevance to energy-management in decentralized VPP.

Under the proposed framework, resource models and an event-based approach for distributed decision-making on resource selection are presented. The multi-agent system and ontology implementation of the framework are also presented. As evaluation, an analysis is conducted on a simulated campus VPP with real building energy data. The proposed approach has been shown not only to provide flexibility in making energy decisions in a distributed manner, but also to improve the overall revenue of the VPP with low communication and computation overheads. Therefore, the proposed framework could serve as a promising basis for future VPP automation design and accelerate development of cross-domain energy management applications for the Smart Grid.

CHAPTER VI: Game Theoretic Real-Time Energy Scheduling for Virtual Power Plant with Prosumer Resources

6.1 Introduction

The Smart Grid incorporates advanced information and communication technologies (ICT) into the power systems. As one of the most important technologies in Smart Grid, VPP is a virtual entity that aggregates DERs such as renewable energy sources, dispatchable and non-dispatchable generators/loads, and presents them to the rest of power network as one single energy trader in the electricity market [109]. The DERs can be directly connected to the VPP or installed in its participating customer sites. In the latter case, if the customer not only consumes but also produces and feeds energy back to the VPP, it is commonly referred to as a prosumer resource. A typical illustration of VPP is show in Figure 6.1.

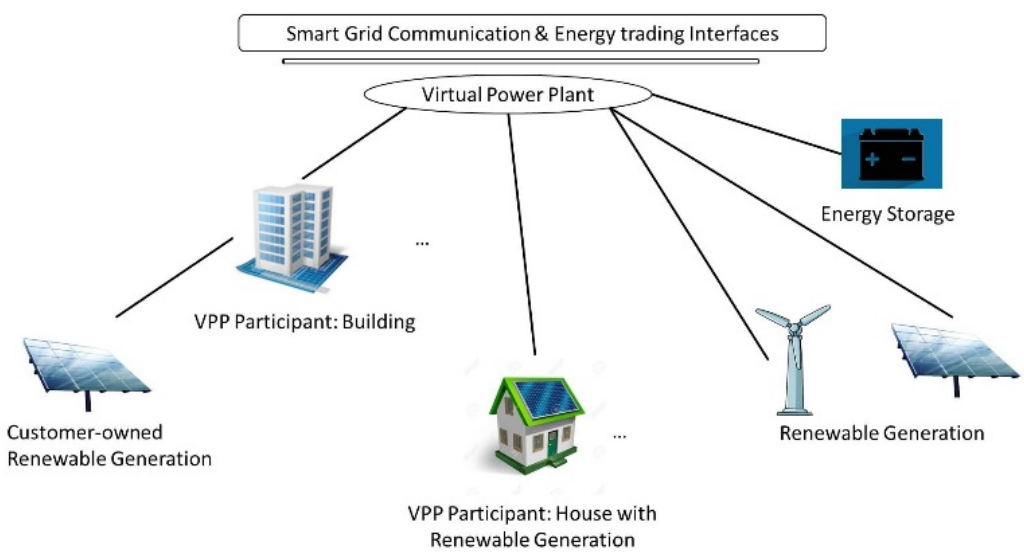


Figure 6.1 Virtual Power Plant

In the presence of renewable generation uncertainties and electricity market variance, the energy scheduling for VPP has to address not only short-term issues such as day-ahead planning, but real time requirements as well, such as scheduling according to very short-term (up to 30 minutes ahead) renewable generation forecast [123] or demand response [54] signals from main grid.

As discussed in Chapter V, the VPPs can be categorised as centralised or decentralised [110], depending on whether the energy scheduling is performed by a central controller, or in a distributed manner by ‘smart’ DERs themselves. A VPP can be also categorised as ‘hybrid’, i.e. neither centralised nor decentralised, if the VPP operator sends scheduling messages to its participants for aiding in their consumption/generation, but does not control the appliances of their participants directly.

This chapter studies the energy scheduling problem for a hybrid VPP which aggregates multiple residential/commercial buildings with on-site generation. Compared to learning algorithms with proven convergence, which are used in day-ahead planning but not real-time scheduling, a novel two-step game theoretic approach to real-time energy scheduling through integrating finite and infinite game models is proposed, in which the game players are prosumer resources in each building of the VPP. Game theory is perceived to constitute a robust framework and a key analytical tool in Smart Grid for addressing the requirements of distributed operation, heterogeneous operating environment and low complexity of distributed scheduling algorithms [79]. Since all VPP participants have their own energy trading objectives, they could be seen as playing an energy trading game with each other.

As commonly perceived by researchers, utility theory forms the foundation of the rationality hypothesis for behavioral decision theory and decision analysis [124]. Based on utility theory, a new prosumer utility function that expresses the willingness to consume/produce by VPP participants is proposed. It differs from other player utility functions in literature, which are either computed typically based on the estimated usefulness of or human comfort provided by some entities to the player, or model player behaviour through consumption preference. The proposed utility function consists of three sub-utilities: consumption, production and consumption-production constraint.

The rest of the chapter is organised as follow. The problem formulation is given in Section 6.2. Section 6.3 proposes a two-step energy scheduling design and describes its implementation as a multi-agent system. The results and discussion are presented in Section 6.4. Finally, Section 6.5 concludes the chapter.

6.2 Problem Formulation

The symbols used in this chapter are listed in the following table:

Symbol	Description	Unit
a_h	First positive constant of (1) at time slot *h*	
b_h	Second positive constant of (1) at time slot *h*	
N	Set of VPP participants	
P_h^*	Forecast energy price for time slot *h*	Cents/kWh
P_h	Actual energy price for time slot *h*	Cents/kWh
$Q_{N,h}$	Amount of energy exchanged between the set *N* of VPP participants and the main grid	kWh
$C_{i,h}$	Consumption demand for prosumer *i* in time slot *h*	kWh
C_i^{max}	Upper bound of consumption for prosumer *i* in a time slot	kWh
$E_{i,h}^*$	Forecast generation for prosumer *i* in time slot *h*	kWh
$E_{i,h}$	Actual generation for prosumer *i* in time slot *h*	kWh
$\tau_{i,h}$	Levelised cost of energy for prosumer *i*	Cents/kWh
δ_i	Standard deviation of generation for prosumer *i*	
$Q_{i,h}$	Amount of energy exchanged between prosumer *i* and VPP in time slot *h*	kWh
$\varphi_{i,h}^c$	Utility gained from consumption by prosumer *i* in time slot *h*	Cents
$\varphi_{i,h}^e$	Utility gained from generation by prosumer *i* in time slot *h*	Cents

$\varphi_{i,h}^{ce}$	Utility gained from adjusting consumption/generation according to constraint by prosumer *i* in time slot *h*	Cents
ρ	Constant for coefficient of risk aversion	
$W_{i,h}^{c}$	Consumption willingness parameter of prosumer *i* in time slot *h*	Cents/kWh
$W_{i,h}^{e}$	Production willingness parameter of prosumer *i* in time slot *h*	Cents/kWh
$u_{i,-i,h}$	Payoff for prosumer *i*, with other prosumers in the VPP denoted as –*i*, in time slot *h*	Cents
$\rho_{i,-i,h}$	Economic cost (revenue) of energy exchanged for prosumer *i*, with other prosumers in the VPP denoted as –*i*, in time slot *h*	Cents
S_i	Combined strategy vector for prosumer *i*	
S_{-i}	Combined strategy vector for all non-*i* prosumers	
$\mathrm{u}(S_i, S_{-i})$	Total payoff of prosumer *i* in time period *H*	Cents
$u^*(S_i, S_{-i})$	Total forecast payoff of prosumer *i* in time period *H*	Cents
H	Target time period	
H'	Time slots during which a consumption or generation change occurred	
$C_{i,h}^{avg}$	Average historic consumption for prosumer *i* in time slot *h*	kWh
$E_{i,h}^{avg}$	Average historic generation for prosumer *i* in time slot *h*	kWh
P_{h}^{avg}	Average historic energy price in time slot *h*	Cents/kWh
$V_{i,H'}$	Volume of consumption/generation change for an event on prosumer *i* in time slots H'	kWh
$\alpha_{i,h}$	Weight of consumption during an event for prosumer *i* in time slot *h*	
$\beta_{i,h}$	Weight of generation during an event for prosumer *i* in time slot *h*	
N'	Set of prosumers who encounters event	
$\Delta_{\boldsymbol{i}}$	Response vector for an event of prosumer *i*	
$C_{i,h}^{Act}$	Actual consumption for prosumer *i* in time slot *h*	kWh
$E_{i,h}^{Act}$	Actual generation for prosumer *i* in time slot *h*	kWh
γ	Scaling factor for consumption-production constraint utility	

Table 6.1 Description of Symbol and Parameters Used

6.2.1 System Model

One popular approach in Smart Grid to enforce demand side management is to have a pricing scheme in which the price to buy/sell electricity from/to main grid depends on the market's real-time demand/supply conditions.

Let P_h denotes the price-energy function for a given time slot h, which can be aligned to the trading period of the electricity market. Typically, P_h is a convex function, meaning that the higher the energy demand, the more expensive it will be for each energy unit [125]. Figure

6.2 shows an example of New Zealand's electricity pricing trend with load demands. In VPP, if the energy consumption of one participant increased while the consumption/generation of other participants remain unchanged, the price for the VPP to import/export energy from/to main grid will change. Therefore, how one participant in the VPP schedules its consumption could impact the cost/revenue for consumption/generation of other participants in the same VPP.

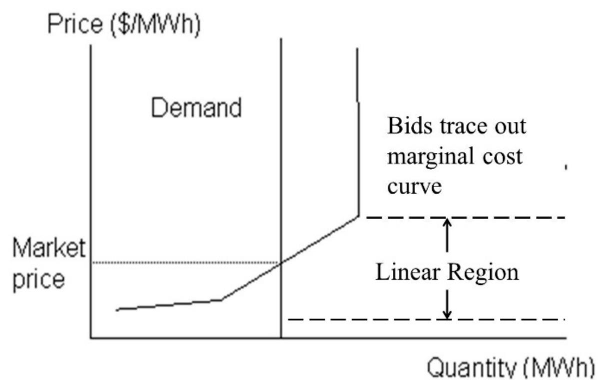


Figure 6.2 Demand Price Curve of NZ Electricity Spot Market

Furthermore, VPPs are able to sell excess energy to the main grid. As market price/demand mostly falls in the lower linear region of Figure 6.2, a convex function can be used to model the price-energy function, which can be linearised as:

$$P_h = f(Q_{N,h}) = a_h|Q_{N,h}| + b_h \tag{6.1}$$

where a_h and b_h are positive constants, and $Q_{N,h}$ is the amount of energy exchanged between the set N of VPP participants and the main grid, which takes a positive value if VPP is importing energy, or a negative value if it is exporting.

As mentioned in Chapter V, this thesis considers a hybrid VPP with prosumer resources, each of which is an aggregation of energy consumers and/or generators. An aggregation with only energy generators can be viewed as a prosumer with zero consumption, while an aggregation with only energy consumers can be viewed as a prosumer with zero energy generation. An energy storage system can be seen also as a prosumer resource since it takes on the role of an energy consumer when it is charging, and the role of an energy generator when it is discharging. Therefore, all VPP participants can be modelled as a prosumer resource under the proposed system model.

Consider all VPP participants share information on their on-site generation/consumption, and obtain forecast energy price P_h^* for any future time slot h from the VPP operator. Further consider a time period H divided into K time slots (h = 1, 2, …, K). For each prosumer i, denote $C_{i,h}$, and vector $(h, E_{i,h}^*, E_{i,h}, \tau_{i,h}, \delta_i)$ as the aggregated energy to be consumed, and aggregated energy to be generated, respectively, at time slot h, where $C_{i,h} \leq C_i^{max}$, $E_{i,h}^*$ and $E_{i,h}$ is the forecast, and actual generation, respectively, which are related by a normal distribution function with variance δ_i representing the generation uncertainty, i.e. $E_{i,h} = N(E_{i,h}^*, \delta_i)$. and $\tau_{i,h}$ is the levelised cost of energy (generation cost). For dispatchable generators such as fuel cells and micro carbon heat producer (μCHP), it is assumed $\delta_i = 0$, since their generation is only dependent on the prosumer's decision.

6.2.2 Prosumer Utility Function

There is cost incurred or revenue gained through importing or exporting energy by prosumers in the VPP. The prices of importing and exporting energy by a prosumer are set by the main grid. Consider each prosumer operates one energy generator (or one aggregated generator if there are multiple generators). Denote the amount of energy exchanged (imported/exported) between prosumer i in the VPP and the main grid in time slot h as:

$$Q_{i,h} = C_{i,h} - E_{i,h} \tag{6.2}$$

which takes a positive value if prosumer is importing energy, or a negative value if it is exporting. Moreover, the prosumer pays some unit price $\tau_{i,h}$ for each unit of energy generated from its energy generator.

The prosumer resources schedule their energy consumption according to their needs, the electricity price, and the available generated energy. Their willingness to consume energy is often driven by a desire to achieve some beneficial objectives. For residential house type prosumer resources, they mostly consume energy to make food, entertainment and comfort. For commercial buildings, energy consumption is an investment to achieve business objectives and create business value. For example, a data centre consumes energy to maintain an ICT infrastructure, which in return yields revenue from providing computation/data storage services to its customers. From the utility theory perspective, energy can be viewed as a good, which is consumed to produce utility, for prosumer resources.

Because prosumers are consumers equipped with generators, in this section, we propose to study the prosumer utility function with three sub-utilities, i.e. consumption utility, production utility, and consumption-production constraint utility.

Consumption Utility Function:

Consider $C_{i,h}$ as an investment (good) of prosumer resource i and denote $\varphi_{i,h}^{c}$ as the yielded utility from the energy consumption $C_{i,h}$. It is reasonable to expect that $\varphi_{i,h}^{c}$ should increase with $C_{i,h}$, i.e.:

$$\varphi_{i,h}^{c}(x) \le \varphi_{i,h}^{c}(y), \qquad x \le y \le C_{i}^{max} \tag{6.3}$$

Therefore, the consumption utility function of prosumer resource is a non-decreasing function of its energy consumed. However, according to the law of diminishing marginal utility introduced in Chapter II, as the energy consumed to yield utility increases, the amount of yielded utility per unit of consumption decreases. Consider the case of a data centre again: revenue yielded from energy consumption increases as long as the provisioned capacity of ICT infrastructure (e.g. number of computation/storage devices switched on) is below customer demand. Further increasing the provision of ICT infrastructure capacity (thus energy consumption) above customer demand will have less impact on yielding revenue. At some point, the energy consumption amount results in no further increase in revenue, and beyond this point, the revenue starts to shrink [126], as expressed by (6.4):

$$\varphi_{i,h}^{c''}(x) \le 0, \qquad x \le C_{i}^{max} \tag{6.4}$$

The function $\varphi_{i,h}^{c}$ is thus concave, and the consumption of prosumer resource is considered risk-averse [127]. Accordingly, it can be modelled using a constant relative risk aversion (CRRA) utility function:

$$CRRA(x) = \frac{x^{1-\rho} - 1}{1 - \rho} \tag{6.5}$$

where x is consumption, and ρ is a constant representing the coefficient of risk aversion. The value of ρ generally ranges from 0 (risk neutral) to 4 (extremely risk-averse) [128] and is believed to around 1 in most cases [129]. Setting ρ=1 and applying L'Hôpital's rule [130], (6.5) can be simplified to:

$$CRRA(x)_{|\rho=1} = \ln(x) \tag{6.6}$$

Since utility is considered to be revealed in people's willingness to pay different amounts for different goods, the utility $\varphi_{i,h}^{c}$ yielded from consumption of a prosumer resource i at time slot h, which is a function of energy consumption $C_{i,h}$, can be rewritten as:

$$\varphi_{i,h}^{c}\left(C_{i,h}\right) = W_{i,h}^{c} \ln C_{i,h}, \qquad W_{i,h}^{c} \geq 0 \tag{6.7}$$

where $W_{i,h}^{c}$ is a scaling parameter representing the willingness of prosumer i to consume energy at time slot h. Clearly, the more willing is the prosumer to consume, the greater is the utility gained by the same prosumer per unit of energy consumption.

Production Utility Function:

For a prosumer, there is economic revenue to be made from exporting (or consuming) its own produced energy volume. Therefore, the production utility function $\varphi_{i,h}^{e}\left(E_{i,h}\right)$ will consider such revenue and the corresponding cost of generating, i.e. levelized cost of energy. However, in countries such as New Zealand, the electricity price from the main grid is often lower than the levelized cost of renewable generation, i.e. $P_h < \tau_{i,h}$, and thus it may cost less economically to import electricity from main grid.

Nevertheless, it is still rational to consider that the prosumer is willing to utilise on-site generation for other causes such as environmental protection and reduction of greenhouse gas emission, i.e. the prosumer has a preference to use on-site generation, even though its cost may be higher than the main grid electricity price. According to the utility theory, such on-site generation preference of prosumer can be modelled by gained utility:

$$\varphi_{i,h}^{e}(E_{i,h}) = W_{i,h}^{e} E_{i,h}, \qquad W_{i,h}^{e} \geq 0 \tag{6.8}$$

In (6.8), $W_{i,h}^{e}$ is the scaling factor representing the willingness of prosumer i to produce energy at time slot h.

Consumption-Production Constraint Utility Function:

This research studies the case where the combination of $E_{i,h}$ and $C_{i,h}$ could be used to define the strategy of prosumer in the game. The relations/constraints between consumption and production can be modelled as follow:

1. The generation of prosumer resources is independent of their energy consumption, i.e. for a prosumer resource i in time slot h, its energy generation $E_{i,h}$ and energy consumption $C_{i,h}$ are related by:

$$\frac{\partial E_{i,h}}{\partial C_{i,h}} = 0 \tag{6.9}$$

2. The prosumer has the preference of adjusting its consumption according to its generated energy, i.e. there exists a utility yielded as:

$$\varphi_{i,h}^{ce}(C_{i,h}, E_{i,h}) = \theta(C_{i,h}, E_{i,h}) \tag{6.10}$$

where θ is a function (agreed between the VPP operator and the participants) to model how prosumers would like to adjust their consumption according to energy produced by on-site generators, which is guaranteed to have a maximum value with the available values of $C_{i,h}$ and $E_{i,h}$. As a result, the prosumer seeks to maximize $\varphi_{i,h}^{ce}$ by adjusting $C_{i,h}$ and $E_{i,h}$. For example, if the prosumer tends to consume as much as it generates by its on-site generation, i.e. the consumption-production constraint utility increases as $C_{i,h}$ and $E_{i,h}$ get closer to each other, θ can be modelled as follow, in which γ is the scaling factor:

$$\theta\left(C_{i,h}, E_{i,h}\right) = -\gamma\left(C_{i,h} - E_{i,h}\right)^2, \quad \gamma > 0 \tag{6.11}$$

6.2.3 Game Model

The VPP prosumer scheduling problem can be formulated as a **non-cooperative game**, in which a group of prosumers (players) schedule their energy consumption, each trying to maximise its own payoff according to its energy generation and electricity prices.

In (6.1), the price P_h is determined by the aggregation of all VPP participants, as:

$$Q_{N,h} = \sum_{i \in N} Q_{i,h} = \sum_{i \in N} (C_{i,h} - E_{i,h}) \tag{6.12}$$

The economic cost (or revenue) of energy exchange for a particular prosumer *i*, in the presence of other prosumers in the VPP (represented by –*i*), at some particular time slot *h* is:

$$\rho_{i,-i,h} = P_h Q_{i,h} + \tau_{i,h} E_{i,h} = (a_h |\sum_{i \in N} Q_{i,h}| + b_h) Q_{i,h} + \tau_{i,h} E_{i,h} \tag{6.13}$$

Let function $\varphi_{i,h}: x, y \rightarrow \boldsymbol{R}$ returns the utility that prosumer *i* gains from consuming energy amount *x* and producing energy amount *y* in time slot *h*. The total payoff (gained utility minus economic cost) for prosumer *i* at time *h* is:

$$u_{i,-i,h} = \varphi_{i,h}\left(C_{i,h}, E_{i,h}\right) - \rho_{i,-i,h} \tag{6.14}$$

The energy generation of prosumer *i* over time period *H* can be represented as a vector $\boldsymbol{E}_i = [E_{i,1}, \dots, E_{i,K}]$, which can be thought of as the prosumer's generation strategy over *H*. In addition, the prosumers adjust their consumption $C_{i,h}$ at the start of each time slot h, which can be also represented as vector $\boldsymbol{C}_i = [C_{i,1}, \ldots, C_{i,K}]$, according to the actual energy available from the aggregated energy generation and price signals from the VPP operator. Similarly, $\boldsymbol{C}_i$ can be thought of as the prosumer's consumption strategy over *H*.

With the generation/consumption strategy vectors and the payoff function in (6.14), the prosumer scheduling problem can be modelled as an *N* player non-cooperative game of prosumer resources. Let $S_i = (\boldsymbol{E}_i, \boldsymbol{C}_i)$ be the combined strategy vector for prosumer i, and each prosumer competes to maximise its total payoff $\mathrm{u}(S_i, S_{-i})$ given by:

$$\mathrm{u}(S_i, S_{-i}) = \sum_{h=1}^{K} [\varphi_{i,h}(C_{i,h}, E_{i,h}) - \rho_{i,-i,h}] \tag{6.15}$$

where S_{-i} denotes the combined strategy vector for all non-*i* prosumers over time period *H*. Equation (6.15) can be expanded as:

$$\mathrm{u}(S_i, S_{-i}) = \sum_{h=1}^{K} \left[\left(\varphi_{i,h}\left(C_{i,h}, E_{i,h}\right) - P_h\left(C_{i,h} - E_{i,h}\right) - \tau_{i,h} E_{i,h}\right)\right] \tag{6.16}$$

Furthermore, in a VPP composed of third-party prosumers, it is reasonable to assume that: 1) communication can only happen between prosumer resources and VPP operator; 2) prosumer resources are honest about the information, e.g. on its energy generation, that it shares with the VPP operator; 3) prosumer resources faithfully perform according to the energy scheduling of the VPP operator.

Expanding $\varphi_{i,h}\left(C_{i,h}, E_{i,h}\right)$ as the sum of utility functions in Section 6.2.2:

$$\varphi_{i,h}\big(C_{i,h}, E_{i,h}\big) = \varphi_{i,h}^{c}\big(C_{i,h}\big) + \varphi_{i,h}^{e}\big(E_{i,h}\big) + \varphi_{i,h}^{ce}\big(C_{i,h}, E_{i,h}\big) \tag{6.17}$$

Therefore,

$$\mathrm{u}(S_i, S_{-i}) = \sum_{h=1}^{K}\Big(\varphi_{i,h}^{c}\big(C_{i,h}\big) + \varphi_{i,h}^{e}\big(E_{i,h}\big) + \varphi_{i,h}^{ce}\big(C_{i,h}, E_{i,h}\big) - P_h\big(C_{i,h} - E_{i,h}\big) - \tau_{i,h}E_{i,h}\Big) \tag{6.18}$$

To determine whether there exists a Nash Equilibrium (as introduced in Chapter II) for our game model with (6.18) as the player's payoff function, we first introduced the following two theorems:

Theorem 1: An equilibrium point exists for every concave *n*-person game [131].

Theorem 2: If a unary function *f* is twice-differentiable, then *f* is concave if and only if f'' is non-positive. If the Hessian matrix of a binary function *f* is negative, then *f* is concave [132].

Consider the game to be played in each time slot as a sub-game. The sub-game payoff for prosumer *i* in time slot *h* is then:

$$u_{i,h} = W_{i,h}^{c} \ln C_{i,h} + W_{i,h}^{e} E_{i,h} + \theta(C_{i,h}, E_{i,h}) - P_h\big(C_{i,h} - E_{i,h}\big) - \tau_{i,h}E_{i,h} \tag{6.19}$$

Substituting (6.1) for P_h in (6.19), and then differentiating it with respect to $C_{i,h}$ and subject the result to constraint given by (6.9), gives:

$$\begin{aligned}\frac{\partial u_{i,h}}{\partial C_{i,h}} &= \frac{\partial W_{i,h}^{c} \ln C_{i,h}}{\partial C_{i,h}} + \frac{\partial \theta(C_{i,h}, E_{i,h})}{\partial C_{i,h}} - \frac{\partial P_h}{\partial C_{i,h}}\big(C_{i,h} - E_{i,h}\big) - P_h \frac{\partial\big(C_{i,h} - E_{i,h}\big)}{\partial C_{i,h}} \\ &= \frac{W_{i,h}^{c}}{C_{i,h}} + \frac{\partial \theta(C_{i,h}, E_{i,h})}{\partial C_{i,h}} - a_h\,\big(C_{i,h} - E_{i,h}\big) - P_h\end{aligned}$$

Differentiating the above equation with respect to $C_{i,h}$ again yields:

$$\frac{\partial^2 u_{i,h}}{\partial {C_{i,h}}^2} = -\frac{W_{i,h}^c}{{C_{i,h}}^2} + \frac{\partial^2 \theta(C_{i,h}, E_{i,h})}{\partial {C_{i,h}}^2} - 2a_h \tag{6.20}$$

If the prosumer consumption-production constraint utility function $\theta(C_{i,h}, E_{i,h})$ can be modelled as (6.11), then (6.20) can be further expanded as:

$$\frac{\partial^2 u_{i,h}}{\partial {C_{i,h}}^2} = -\frac{W_{i,h}^c}{{C_{i,h}}^2} - 2a_h - 2\gamma, \qquad \gamma > 0 \tag{6.21}$$

Since $C_{i,h}$, $W_{i,h}^c$, a_h and γ are all ≥ 0, the result of (6.16) is always non-positive. Following a similar process:

$$\frac{\partial u_{i,h}}{\partial E_{i,h}} = W_{i,h}^e + \frac{\partial \theta(C_{i,h}, E_{i,h})}{\partial E_{i,h}} + a_h\left(C_{i,h} - E_{i,h}\right) + P_h - \tau_{i,h}$$

$$\frac{\partial^2 u_{i,h}}{\partial {E_{i,h}}^2} = \frac{\partial^2 \theta(C_{i,h}, E_{i,h})}{\partial {E_{i,h}}^2} - 2a_h, \qquad \gamma > 0 \tag{6.21}$$

The Hessian matrix of (6.19) is:

$$\begin{bmatrix} \frac{\partial^2 u_{i,h}}{\partial {C_{i,h}}^2} & \frac{\partial^2 u_{i,h}}{\partial C_{i,h} \partial E_{i,h}} \\ \frac{\partial^2 u_{i,h}}{\partial E_{i,h} \partial C_{i,h}} & \frac{\partial^2 u_{i,h}}{\partial {E_{i,h}}^2} \end{bmatrix} = \begin{bmatrix} -\frac{W_{i,h}^c}{{C_{i,h}}^2} + \frac{\partial^2 \theta(C_{i,h}, E_{i,h})}{\partial {C_{i,h}}^2} - 2a_h & \frac{\partial^2 \theta(C_{i,h}, E_{i,h})}{\partial C_{i,h} \partial E_{i,h}} + 2a_h \\ \frac{\partial^2 \theta(C_{i,h}, E_{i,h})}{\partial E_{i,h} \partial C_{i,h}} + 2a_h & \frac{\partial^2 \theta(C_{i,h}, E_{i,h})}{\partial {E_{i,h}}^2} - 2a_h \end{bmatrix} \tag{6.22}$$

If (6.22) is a negative matrix, the utility function is concave. Specifically, when $\theta(C_{i,h}, E_{i,h})$ is modelled as (6.11), it can be proved that (6.22) is a negative matrix. Therefore, by Theorem 2, the sub-game payoff function for every prosumer resource is concave, and by Theorem 1, there is a Nash Equilibrium for each sub-game. Furthermore, as the total payoff for a prosumer (player) is the sum of all his sub-game payoffs, the best payoff he can achieve by unilaterally changing his strategies is the sum of payoffs at each sub-game's Nash Equilibrium, i.e. there exists also a Nash Equilibrium for our proposed energy scheduling game.

6.3 Two-Step Energy Scheduling

As mentioned, this paper studies a hybrid VPP in which the operator has energy consumption/generation information of its participants and the size of their on-site generators/storages, but does not directly control the appliances within them. Instead, it broadcasts the price signals and sends energy scheduling messages for aiding in their consumption/generation. The VPP operator also makes forecasts about the consumption/generation of each prosumer in the VPP ahead of their actual consumption/generation, e.g. from contracts and historical metering data.

Let $\boldsymbol{E}_{i,H}^{*} = [E_{i,1}^{*}, \dots, E_{i,h}^{*}, \dots, E_{i,K}^{*}]$ represents the generation forecast for prosumer *i* over time period *H* (composed of consecutive time slots indexed from 1 to *K*). This generation forecast is a common knowledge shared between the generator owner (prosumer resource) and VPP operator. In the real world, VPP operator will normally acquire information on the type and rated power of their participants' renewable generation, which then can be used for forecasting and other management operations.

The prosumer's energy scheduling is generated using forecast parameters, and the actual payoff can only be measured after consumption/generation has taken place. Replacing the actual with forecast parameters in (6.18), the total forecast payoff $u^{*}(S_i, S_{-i})$ for prosumer *i* over time period *H* can be similarly formulated as:

$$u^*(S_i, S_{-i}) = \sum_{h=1}^{K} \left(\varphi_{i,h}(C_{i,h}) - P_h^*\left(C_{i,h} - E_{i,h}^*\right) - \tau_{i,h} E_{i,h}^*\right) \tag{6.23}$$

The proposed game model considers the VPP operator to act on behalf of its participants and try to maximise the payoff of each of their prosumers. The following details a two-step energy scheduling approach based on the proposed game model for a hybrid VPP with prosumer resources. To simplify the problem without loss of generality, this research uses the consumption-production constraint utility function $\theta(C_{i,h}, E_{i,h})$ as defined in (6.11).

6.3.1 Step 1: Prosumer Profiling and Day-ahead Planning

In the long run, the statistics of historical energy consumption data can reveal a prosumer resource's willingness to consume energy at any given time. By learning and adapting through accumulated games, each prosumer's strategy for a certain time slot can be very close to its optimal response [133], through which its payoff in (6.18) is maximised. Therefore, using such data, VPP operator can compute vector $\boldsymbol{W}_{i,h}^c = [W_{i,1}^c, \dots, W_{i,h}^c, \dots, W_{i,K}^c]$ to profile each prosumer *i*'s willingness to consume across all *K* time slots over time period *H*. This is done by finding the consumption willingness $W_{i,h}^c$ of prosumer *i* for each time slot *h*, using (6.23) obtained from rearranging the equation after differentiating (6.19) with respect to $C_{i,h}$ and equating it to zero. Each value of $W_{i,h}^c$ can be obtained by substituting the variables $C_{i,h}$, $E_{i,h}$, and P_h in (6.23) with their average historical values.

$$W_{i,h}^c = C_{i,h}\left[(2\gamma + a_h)\left(C_{i,h} - E_{i,h}\right) + P_h\right] \tag{6.24}$$

For production willingness $W_{i,h}^{e}$, it should be a parameter agreed between the VPP operator and the prosumers. $W_{i,h}^{e}$ should have a value such that the prosumers will not have negative utility generating energy, i.e. $W_{i,h}^{e} \geq \tau_{i,h} - P_h$.

Using the consumption/production willingness profiles, the VPP operator can generate consumption/generation schedules for day-ahead planning for all prosumers by solving the energy scheduling game to maximise the payoff of each prosumer in the VPP. For this purpose, the Nikaido-Isoda function and associated relaxation algorithm are used, the details of which can be found in [134]. The VPP operator then broadcasts the forecast price and sends the energy scheduling results as day-ahead plans to each prosumer for guiding them in their next day's consumption/generation.

6.3.2 Step 2: Very Short Term Rescheduling

With the day-ahead planning in Step 1, all prosumer resources have a consumption/generation benchmark for maximizing their payoffs. However, in the real world, inevitable changes in actual consumption/generation can take place, which requires making very short term (up to 30 minutes ahead) rescheduling to the planned consumption/generation:

- *Renewable generation variation*: As actual weather may differ from what was forecast, renewable sources such as PVs and wind turbines may have generation outputs that are different from what were used in the day-ahead planning. To tackle such problems, very short term renewable generation forecast [123] methods can be applied to make accurate forecasts 5 to 10 minutes before the actual generation.

- *Demand response request from main grid*: The main grid initiates demand response by sending request signals for peak shaving to its energy consumers, typically in a pre-determined manner, e.g. by contracts. However, in case of emergencies such as power plant outage, the main grid might initiate demand response in short notice. Upon receiving such requests, the VPP operator contacts prosumer resources that are contracted to perform load curtailing/shifting, and makes changes to their planned consumption.

- *Casual EVs charging and discharging*: Since the VPP participants can include buildings, which are frequented by people for commercial/residential activities, casual (non-scheduled or unanticipated) charging (consuming energy) or discharging (supplying surplus energy from battery) operations by visiting EVs parked on-site can induce real-time consumption demand/generation output changes.

These consumption/generation changes in very short notice are the rescheduling events, which will be simply referred to as 'events' in the rest of this chapter. Specifically, an event occurred to prosumer *i* can be represented as a vector $\boldsymbol{V}_i = [H', V_{i,H'}]$, where $H' \subset H$ is the set of consecutive time slots spanned by the event duration, and $V_{i,H'}$ is the volume of consumption/generation change in time slots H'. For practicality, events of the same prosumer cannot overlap in time, i.e. the timeslot set for one event has no intersection with that for another event of the same prosumer. When a prosumer resource encounters an event, it responds by introducing a change $\Delta C_{i,h}$, and $\Delta E_{i,h}$, to its previously planned consumption and generation schedules, respectively, for each time slot in H', satisfying:

$$\sum_{h \in H'} (\Delta C_{i,h} + \Delta E_{i,h}) = V_{i,H'} \tag{6.25}$$

With the aforementioned, this chapter models the very short term scheduling as a sub-game of *n*-person finite non-cooperative game formed upon the result of Step 1: Let $h = k_1, k_2, \dots, k_m$ be the time slot index of H', and $i \in N' \subset N$ where N' denotes a set of prosumer resources who encounters events. Each prosumer i in N' has a response vector $\Delta_{\boldsymbol{i}} = [\Delta C_{i,k_1}, \dots, \Delta C_{i,k_m}, \Delta E_{i,k_1}, \dots, \Delta E_{i,k_m}]$, which is subject to the constraint of (6.25) and price function of (6.1). The prosumer resources in N' compete with one another, each trying to maximise its own payoff:

$$\mathrm{u}(\Delta_i, \Delta_{-i}) = \sum_{h=k_1}^{k_m} \left(W_{i,h}^{c} \ln C_{i,h}^{Act} + W_{i,h}^{e} E_{i,h}^{Act} + \theta (C_{i,h}^{Act} - E_{i,h}^{Act}) - P_h \left(C_{i,h}^{Act} - E_{i,h}^{Act} \right) - \tau_{i,h} E_{i,h}^{Act} \right) \qquad (6.26)$$

where the actual consumption $C_{i,h}^{Act}$ for prosumer i in time slot h is defined as the planned consumption $C_{i,h}$ plus its very short term scheduled change $\Delta C_{i,h}$ according to events. Similarly, the actual generation $E_{i,h}^{Act}$ is defined as the planned generation $E_{i,h}$ plus its very short term scheduled change $\Delta E_{i,h}$. To solve a finite game with (6.26), the *n*-person game non-linear optimization function (NPG) library [135] can be utilized. If a Nash Equilibrium does not exist, NPG is still able to give the best possible response.

At the start of H', a prosumer resource encountering an event sends the event vector $\boldsymbol{V}_i$ to the VPP operator, which gathers information on all concurrent changes, computes the solution for the very short term scheduling problem as *n*-person finite game, and sends the best response $\Delta_{\boldsymbol{i}}$ to each event-encountering prosumer in the form of an energy scheduling message. Upon receiving such message, the prosumer resources modify their day-ahead planned consumption/generation according to $\Delta_{\boldsymbol{i}}$.

The complete two-step process is illustrated in Figure 6.3.

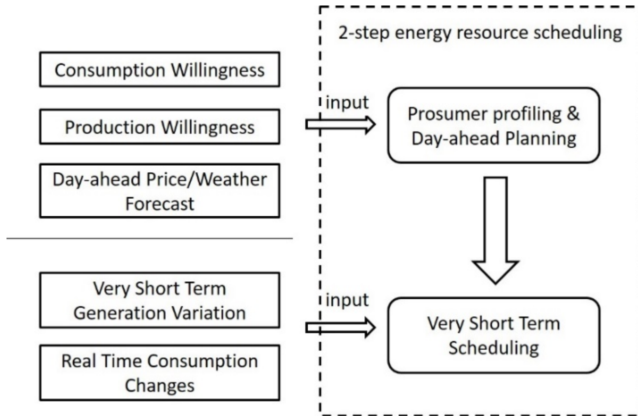


Figure 6.3 Two-step Energy Scheduling

6.3.3 Implementation in Multi-agent System

The proposed two-step energy scheduling is implemented using multi-agent system (MAS) design in JADE platform [136], as shown in Figure 6.4.

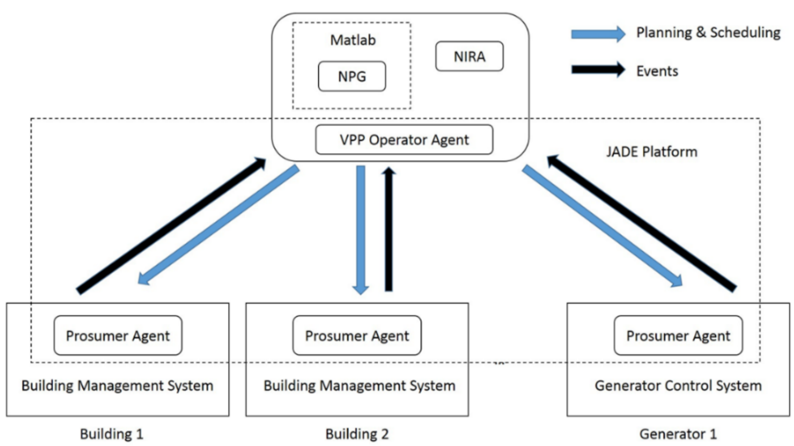


Figure 6.4 MAS Implementation in JADE

One agent represents the VPP operator, while each of the other agents represents one prosumer resource and manages its own device control. The prosumer resource agents only need to send events to or receive scheduling messages from the VPP operator agent, i.e. there is no communication needed between prosumer resource agents themselves.

The VPP operator agent communicates with a solution component that executes the Nikaido-Isoda function and relaxation algorithm [137] for day-ahead planning, and embeds a *n*-person game non-linear optimization function [135] to solve the very-short term scheduling problem. Using the MAS implementation, the performance of the proposed game theoretic real-time scheduling is simulated and analysed in the next section.

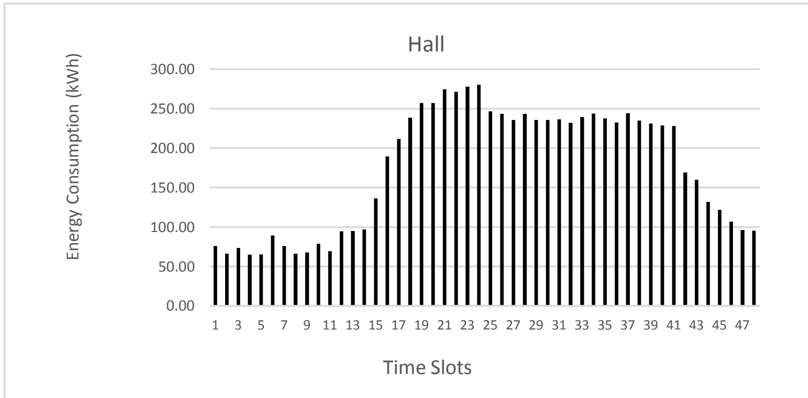
6.4 Results and Discussion

6.4.1 Simulation Setup

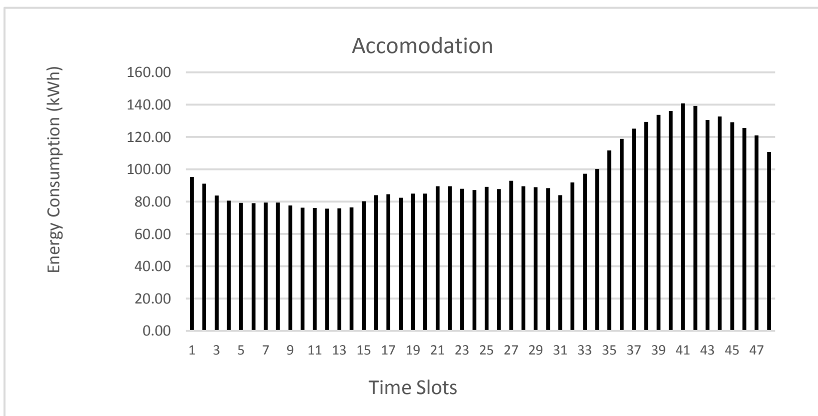
Real New Zealand electricity market data are used to produce the demand-price curve for the simulation using the vSPD tool [138] provided by the electricity authority. The simulation time slot length is set to New Zealand's market trading period (TP), which is half an hour, and thus there are 48 time slots per day.

A VPP with 100 buildings as prosumer resources is simulated. Three types of prosumer resources are introduced, namely: hall, accommodation, and office buildings. Figure 6.5 shows a typical day's consumption for each prosumer resource type obtained from metering data of real-world buildings on the authors' university campus. Each prosumer resource in the VPP is randomly assigned as one of the three types, and has on-site solar and wind generators. Their forecast generation according to weather data [120] is shown in Figure 6.6 (averaged for the same month as that for electricity consumption, demand and price data in Chapter 5), with the levelized cost of energy parameters ($\tau_{i,h}$) listed in Table 6.2. The production willingness parameter $W_{i,h}^{e}$ is set to $(\tau_{i,h} - P_h)$ so that prosumers are not losing revenues by using on-site renewables while not being eager to use fossil-fuel generators other than for emergencies. The consumption-production constraint is modelled as (6.11) with

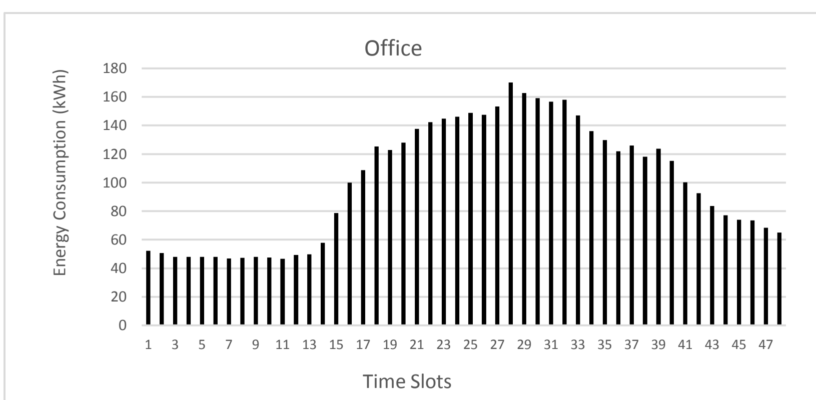
$\gamma = 1$ so that the proportion of utility gained from consumption/generation constraint does not overwhelm those of consumption and production.



(a)

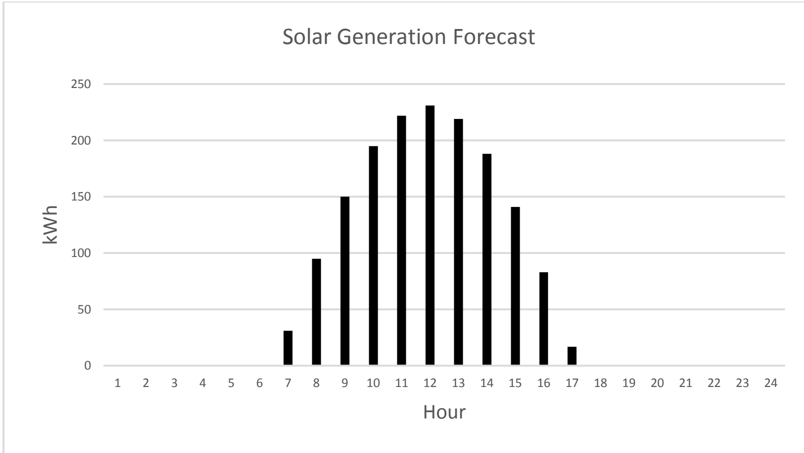


(b)



(c)

Figure 6.5 Typical Day's Consumption Data from Real-World Buildings for Each Prosumer Type: (a) Hall; (b) Accommodation; and (c) Office



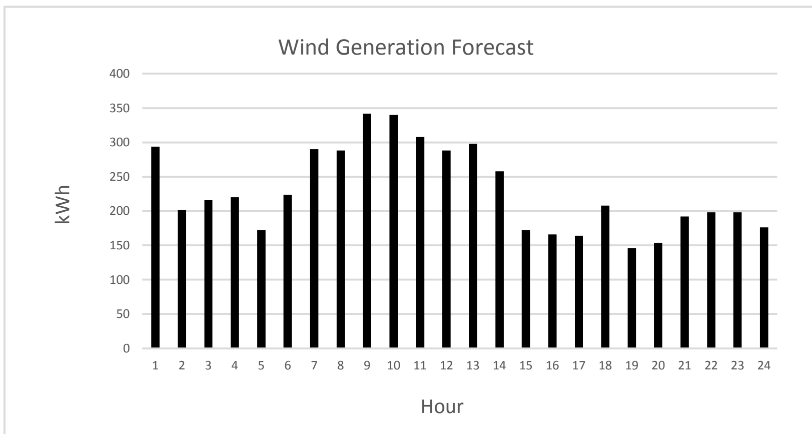


Figure 6.6 Renewable Energy Generation Forecast

Solar System	20 cents/kWh
Wind Turbine	9 cents/kWh

Table 6.2 Levelized Cost of Energy Parameters for Renewable Generation

Two types of rescheduling events are considered in the simulation: wind generation uncertainty and demand upsurge. Since solar generation is generally more predictable than wind generation, the solar forecast generation is utilised as actual solar generation. For wind generation, real-world data quality issues which affect its forecast accuracy are considered [121]. Thus, the higher-end (40%) of the forecast error range for wind generation is adopted.

Therefore, at the start of each time slot, an energy event will be triggered by the implemented MAS due to the observed difference between the forecast and actual wind generation.

Every two hours, prosumer resources will be randomly selected for 20–40% demand upsurge on planned consumption from the day-ahead planning. Upon encountering an event, each prosumer resource will initiate possible strategies and send them to the operator agent of the VPP. The simulation runs on a PC with 3.2 GHz i5 CPU with 8 GB memory, under Windows 7 64-bit operating system.

6.4.2 Simulation Results

Figure 6.7 shows the average total payoff as the number of prosumer resources increases. It compares the proposed two-step scheduling (day-ahead planning and game theoretic very short-term rescheduling) with three other approaches, namely no scheduling, only day-ahead planning (Step 1), and a current game theoretic energy scheduling (GTES) scheme [85]. The proposed scheduling is observed to achieve the best payoff, with gain margin over other approaches increasing with larger number of prosumer resources.

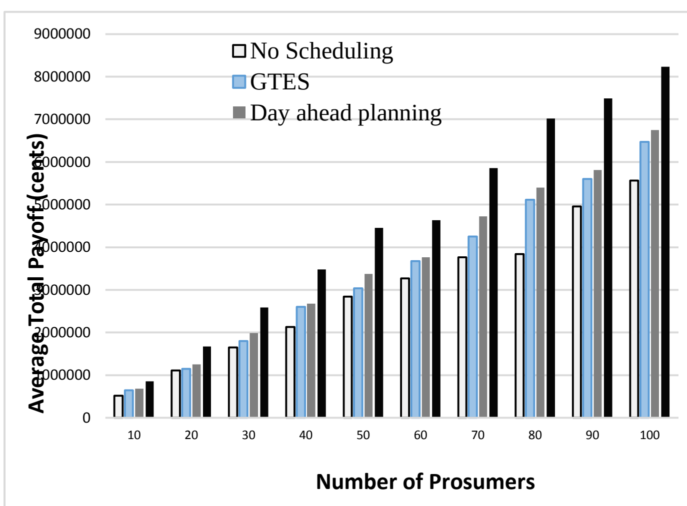


Figure 6.7 Average Total Payoff

Figure 6.8 compares the peak-to-average ratio (PAR) reduction performance between the proposed scheduling and GTES. It is seen that the proposed scheduling achieves better PAR reduction of approximately 20% in the presence of consumption/generation variations in the VPP.

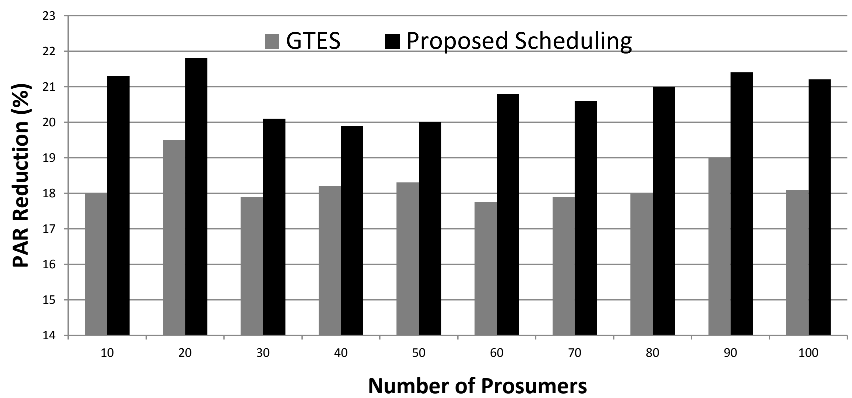


Figure 6.8 PAR Reduction

Figure 6.9 compares the average total computation time for one trading day between the proposed scheduling and GTES. The computation time for the proposed scheduling includes the time for all prosumers to execute their day-ahead planning (Step 1) and very short-term rescheduling (Step 2). The former is performed only once a day while the latter may be performed at the start of each time slot if one or more events have occurred. For GTES, it incurs computation time only when finding the Nash Equilibrium for its game-based day-ahead planning. Table 6.3 further shows the decomposition of the result for proposed scheduling into average computation time for Step 1 and Step 2.

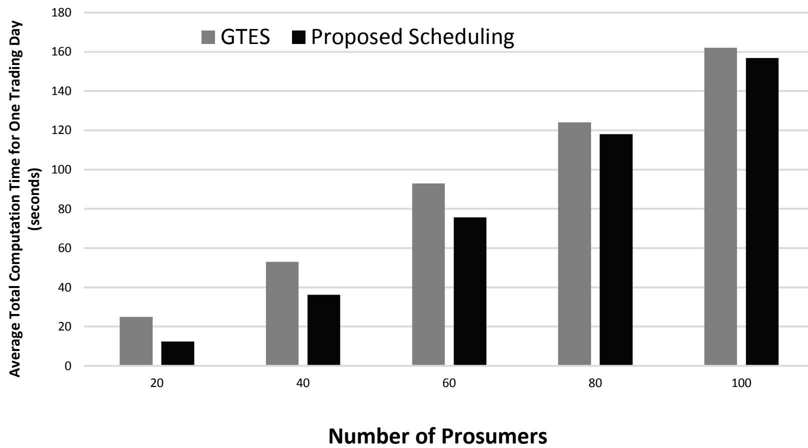


Figure 6.9 Average Total Computation Time

Number of Prosumers	20	40	60	80	100
Step 1 (seconds)	0.191	0.212	0.246	0.596	1.607
Step 2 (seconds)	12.21	35.99	75.45	117.4	155.29

Table 6.3 Average Computation Time for Step 1 and Step 2 of Proposed Scheduling

It is seen that the proposed scheduling generally incurs less computation time than GTES. This is mainly because the GTES performs a very time-consuming optimization process based on interior point method on each prosumer. On the other hand, the proposed scheduling, which uses Nikaido-Isoda function and relaxation algorithm with proposed willingness profiles, converges much quicker to solve the energy scheduling game. Although their performance gap appears to be closing with increasing number of prosumers in the VPP, this is due to more rescheduling being performed by the proposed scheduling in response to more event occurrences, which however has led to an improved average total payoff as previously shown.

6.5 Chapter Summary

This chapter proposes a two-step game-theoretic energy scheduling approach for hybrid VPPs with prosumer resources composed of both residential and commercial buildings. The energy scheduling is modelled as a game with prosumer resources as players. The two steps include day-ahead planning and very short-term rescheduling to address changing market and real-time conditions. A prosumer utility function is introduced, which expresses the willingness to consume/produce by the prosumers to achieve certain desired objectives. It consists of three sub-utilities: consumption, production and consumption-production constraint. The proposed scheduling is implemented as a multi-agent system, from which the performance of proposed game-theoretic real-time scheduling is simulated using real market and consumption data. Compared with existing approaches, the proposed scheduling can achieve better total payoff particularly when the number of prosumer resources in the VPP increases.

CHAPTER VII: Conclusion

This thesis undertakes an in-depth investigation on the problem of energy resource management in Smart Grid via the application of middleware technologies, with a particular focus on virtual power plants (VPPs). The first three chapters of the thesis presented the introduction, background and literature review of the research topic. The next three chapters detailed the original research contributions of this thesis, which are summarised in the following section.

7.1 Summary of Contributions

- In Chapter 4, a novel methodology of utilising building information modelling (BIM) and software-defined networking (SDN) to render the buildings Smart Grid ready is proposed. The proposed methodology covers the building phases from architectural design to facility management.

  Firstly, BIM is extended for the design phase to provide Material/Device profiling and information exchange interface for various smart objects. Next, a three-layer verification framework is introduced to assist BIM users in identifying possible defects in their Smart Grid ready building (SGRB) design. For the post-construction phase, a facility management software tool is designed and implemented to provide advanced energy management of SGRBs where smart objects as well as distributed energy resources (DERs) are deployed.

  Furthermore, the opportunities for SDN in Smart Grid are examined through several use cases to explore how SDN can contribute to flexible implementation of novel networking solutions to improve the performance of distributed systems in large and complex network environments such as VPPs in Smart Grid. To the best of our knowledge, this is one of the first studies on the utilisation of SDN in Smart Grid.

- In Chapter 5, an event-based resource management framework is proposed to support distributed decision making in VPPs. The proposed framework views VPP as a hierarchical structure, and abstracts consumption/generation from third-party VPP participants for managing different resource types of relevance to energy-management. Under this framework, resource models and an event-based approach for distributed decision-making on resource selection are presented. The multi-agent system (MAS) and ontology implementation of the framework are also presented.

  Through simulation, the proposed approach has been shown not only to provide flexibility in making energy decisions in a distributed manner, but also to improve the overall revenue of the VPP with low computation overheads. Therefore, the proposed framework could serve as a promising basis for future VPP automation design, and to accelerate the development of cross-domain energy management applications for the Smart Grid.

- In Chapter 6, a two-step game theoretic approach to prosumer energy resources scheduling is proposed, in which the game players are the prosumer resources in each building of the VPP. The two sequential steps include day-ahead planning and very short term scheduling (up to 30 minutes ahead) to address real-time market/prosumption conditions through integrating finite and infinite game models. In addition, a new prosumer utility function expressing the prosumer's willingness to consume/produce energy is proposed, which differs from other player utility functions in literature, which are either computed typically based on the estimated usefulness of or human comfort provided by some entities to the player, or model player behaviour through consumption preference. The proposed utility function models prosumer through three sub-utilities: consumption willingness, production willingness and consumption-production constraint.

  The multi-agent system (MAS) implementation of the proposed approach and the simulations based on real-world energy data are presented.

7.2 Future Work

This section outlines some possible directions for future research:

- To utilise the proposed approaches for real-world control of building energy consumption/generation in VPPs, BIM should be further extended to incorporate information related to various building management system protocols, such as BACNet and ModBus.

  Furthermore, with continuing development and application of the Internet of Things (IoT) technologies to 'smartify' buildings, there could be further work on adapting BIM processes and tools to IoT for enabling more autonomous and intelligent building energy management.

- There still exist a number of key challenges to be overcome before SDN can be effectively used in Smart Grid. For example, the centralised (physical or logical) nature of the SDN controller can make it vulnerable to intrusions and cyber-attacks, e.g. distributed denial-of-service (DDoS) attacks launched from compromised smart meters and appliances.

  Equally important is guaranteeing the confidentiality, integrity, and availability of the information flow in Smart Grid, the most critical of which include: control commands, metering data, and pricing information.

  Being a critical utility infrastructure, Smart Grid is also expected to require its information network to meet carrier-grade requirements, particularly in terms of: i) scalability; ii) reliability; iii) quality-of-service (QoS); and iv) service management. The current OpenFlow standard for SDN provides only limited QoS support and has difficulty achieving fast failure recovery that is necessary for high reliability due to its dependency on a centralised controller. Thus, further research on SDN is needed in order to fulfil our envisioned goals for this technology in Smart Grid.

- Recent developments on building energy management systems have harnessed cloud computing technology. Similarly, future VPP resource scheduling may be performed with each participant and VPP operator operating on cloud platform. Therefore, as with SDN, security concerns, as well as the issues of critical data management and protection, have to be adequately addressed.

- Other advances in technology may also result in VPP developments that change some of the presumptions in this thesis such as on the methods of energy trading and the types of real-time pricing schemes, which may in turn warrant a relook at the approaches devised in this thesis.

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