Curtin Business School
School of Information Systems

Development of a Community-based Framework to Manage Prosumers in Smart Grid

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This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University

July 2014

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

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Abstract

The smart grid has opened up a new role of an economically motivated "prosumer", who not only consumes energy but also generates the green energy and shares the surplus with energy buyers. Managing the prosumers connected to the smart grid has become pivotal within the energy sharing network, and the concept of prosumer community groups is an innovative approach to fulfil that requisite.

For the prosumer community groups to emerge and meaningfully interact with the smart-grid infrastructure, several socio-technical challenges have to be addressed. However, in literature, there are hardly any effective proposals to address those challenges.

This dissertation provides a survey of the state of the art of prosumer community groups, as well as the literature exists in the context of smart grid and online virtual communities to highlight their adaptability to the development of prosumer community groups and ultimately highlights the unresolved issues. Moreover, this dissertation proposes solutions to address four key problems of managing prosumers in the form of prosumer community groups: (i) a framework to define and characterize prosumer community groups that clusters the prosumers based on their homogeneity while detecting outliers and ultimately defining prequalification criteria for prosumer community groups, (ii) a framework to recruit new prosumers to the prosumer community groups, which proactively monitors and evaluates the new prosumers' real-time energy behaviours before final recruitment, (iii) a framework to manage multiple goals within the community-based energy sharing network and to define mutual goals using linear goal programming techniques and (iv) a framework to assess and rank the members within the prosumer community groups using multiple criteria decision-making techniques. The theoretical concepts and the proposed solutions are tested in a simulation environment and a multi-agent community-based energy sharing network prototype system is created in order to demonstrate the effectiveness of the overall community-based energy sharing network.

Acknowledgements

It is a great pleasure to thank everyone who helped me write my dissertation successfully.

I would like to express my special appreciation and thanks to my supervisors Dr. Vidyasagar Potdar for his excellent supervision and support in this research. His constructive advice and teaching, good company, enthusiasm, and inspiration have been invaluable. This thesis is as much his effort as it is mine.

I would like to express my gratitude to my current co-supervisor Dr. Omar Hussain, former co-supervisor Prof. Elizabeth Chang and chairperson Prof. Graham Pervan for guiding, motivating and supporting me throughout the work done in this thesis.

I would like to thank Prof. Tharam Dillon and Dr. Jaipal Singh for their valuable critique, insights and suggestions for improving my research.

I am grateful to many of my colleagues for their helpful suggestions and peer reviews of my research. My thanks also extend to staffs and students at the School of Information Systems for making it such a friendly and enjoyable work environment.

I dedicate my thesis to my mother, Malinie Jayatissa, my father, Jayatissa Rathnayaka, and my parents-in-law, Chandrasiri Kuruppu and Chintha Herath, for their love and support.

Moreover, I dedicate this thesis to my husband, Samitha Kuruppu, and my beautiful daughter, Dishara Kuruppu, for their understanding. Without my husband’s love and support, and my daughter’s inspiration, I would not have been able to tackle challenges head on. I am very fortunate to have my family by my side and enrich my life with love and happiness.

Lastly, I am thankful to all my friends for all their emotional support, companionship, entertainment, love and care.

List of Publications

Refereed Journal Publications [2012-2014]

1. **Rathnayaka, A. J. D.**, Potdar, V. M., Dillon, T., Hussain, O., & Chang, E. (2014). Methodology to Find Influential Members in Prosumer-Community-Groups. IEEE Transactions on Industrial Informatics, 10(1), 706-713. **ERA A.**
2. **Rathnayaka, A. J. D.**, Potdar, V. M., & Dillon, T. (2014). Framework to Manage Multiple Goals in Community based Energy Sharing Network in Smart Grid. International Journal of Electrical Power & Energy Systems, accepted, in press.
3. **Rathnayaka, A. J. D.**, Potdar, V. M., Dillon, T., & Hussain, O. (2014). Goal Oriented Prosumer Community Groups for Smart Grid. IEEE Technology and Society Magazine, 33(1): 41-48
4. **Rathnayaka, A.J. D.**, Potdar, V. M., & Dillon, T. (2014). Formation of Virtual Community Groups to Manage Prosumers in Smart Grids. International Journal of Grid and Utility Computing, accepted, in press.
5. **Rathnayaka, A. J. D.**, Potdar, V. M., & Dillon, T. (2014). Prosumer Recruitment Framework for Prosumer Community Groups in Smart-grid. International Journal of Computer Systems Science & Engineering, accepted in press.
6. **Rathnayaka, A. J. D.**, & Potdar, V. M. (2012). Design of Smart Grid Prosumer Communities via Online Social Networking Communities. International Journal of Infornomics, 5, 544 - 556.
7. **Rathnayaka, A. J. D.**, & Potdar, V. M. (2013). Wireless Sensor Network transport protocol: A critical review. Journal of Network and Computer Applications, 36(1), 134-146. **ERA A.**

Refereed Conference Publications [2010-2014]

8. **Rathnayaka, A. J. D.**, & Potdar, V. M. (2012). Evaluation of wireless home automation technologies for smart mining camps in remote Western Australia. In Sustainability in Energy and Buildings (pp. 109-118): Springer Berlin Heidelberg. **ERA A**
9. **Rathnayaka, A. J. D.**, & Potdar, V. M. (2012). Energy resource management in smart home: State of the art and challenges ahead. In Sustainability in Energy and Buildings (pp. 403-411): Springer Berlin Heidelberg. **ERA A**

10. **Rathnayaka, A. J. D.**, Potdar, V. M., Dillon, T., & Hussain, O. (2012). Analysis of energy behaviour profiles of prosumers. In Industrial Informatics (INDIN), 2012 10th IEEE International Conference on (pp. 236-241): IEEE.
11. **Rathnayaka, A. J. D.**, Potdar, V. M., Hussain, O., & Dillon, T. (2011). Identifying prosumer's energy sharing behaviours for forming optimal prosumer-communities. In Cloud and Service Computing (CSC), 2011 International Conference on (pp. 199-206): IEEE.
12. **Rathnayaka, A. J. D.**, Potdar, V., & Ou, M. H. (2012). Prosumer management in socio-technical smart grid. In Proceedings of the CUBE International Information Technology Conference (pp. 483-489): ACM.
13. **Rathnayaka, A. J. D.**, Potdar, V. M., & Kuruppu, S. J. (2011). Evaluation of wireless home automation technologies. In Digital Ecosystems and Technologies Conference (DEST), 2011 Proceedings of the 5th IEEE International Conference on (pp. 76-81): IEEE.
14. **Rathnayaka, A. J. D.**, Potdar, V. M., & Kuruppu, S. J. (2011). An innovative approach to manage prosumers in smart grid. In Sustainable Technologies (WCST), 2011 World Congress on (pp. 141-146): IEEE.
15. **Rathnayaka, A. J. D.**, Potdar, V. M., Sharif, A., Sarencheh, S., & Kuruppu, S. (2010). Wireless Sensor Network Transport Protocol-A State of the Art. In Broadband, Wireless Computing, Communication and Applications (BWCCA), 2010 International Conference on (pp. 812-817): IEEE.
16. **Rathnayaka, A. J. D.**, Potdar, V. M., Sharif, A., Sarencheh, S., & Kuruppu, S. (2010). Wireless sensor networks: Challenges ahead. In Broadband, Wireless Computing, Communication and Applications (BWCCA), 2010 International Conference on (pp. 824-829): IEEE.
17. Deshpande, V., Helonde, J., Wadhai, V., Potdar, V., & **Rathnayaka, A. J. D.** (2012). Handling the Quality of Service for the data dissemination in Wireless Sensor Networks. In Proceedings of the CUBE International Information Technology Conference (pp. 853-856): ACM.

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Chapter 1

Introduction

This chapter provides:

- The background information on smart grid, managing prosumers and energy sharing
- An overview of prosumer community groups
- The significance and importance of managing prosumers in the form of prosumer community groups
- The motivation and objective of this research
- The structure of this dissertation

1.1 Introduction

The demand for energy in the world is continually rising year after year. According to US Energy Outlook (2010), the worldwide energy consumption in 2035 is expected to increase by 49% over the level of 2007. Most of the current energy demand is met by non-renewable sources of energy, such as coal, petroleum and liquid petroleum gas. However, the society is now faced with the twin problems of dwindling already-scarce non-renewable energy resources and increased green-house gas emissions, resulting in acute shortage of power on the one hand and unpredictable climatic changes on the other (Xinghuo, Cecati et al. 2011).

In order to address the aforementioned issues faced by the society, today's power industry is being restructured dramatically by various large forces, such as rising penetration of renewable energy, enormous utilization of smart devices, federal support and industry investment in green energy and the diversity of consumer anticipations. For instance, traditionally, the power industry participants have been strictly differentiated as either producers or consumers of electricity (Grijalva and Tariq 2011). The energy producers generate and supply energy to the consumers, who are charged based on the amount of energy consumed (Erlinghagen and Markard 2012). Today, this unidirectional power generation–transmission–distribution–consumption model has been transformed into a bidirectional energy and information model that allows conventional energy users not only to consume energy but also to generate energy and feed it back to the utility grid (Verbong, Beemsterboer et al. 2013).

In order to achieve such an interactive bidirectional energy-information infrastructure, the concept of Smart Grid (SG) has been mooted in the literature (Cecati, Mokryani et al. 2010; Gungor, Sahin et al. 2011).

1.1.1 What is smart grid?

The SG is defined as "an electricity network that can intelligently integrate the behavior and actions of all users connected to it – generators, consumers and those that are both – in order to deliver sustainable, economic and secure electricity supplies" (Cecati, Mokryani et al. 2010).

The concept of SG has been initiated with automatic meter reading, which was then evolved into the idea of Advanced Metering Infrastructure (AMI) to enhance the demand-side management, the energy efficiency and the self-healing of electrical grids, while achieving grid protection to natural disasters or malicious sabotage (Fang, Misra et al. 2012). Over the past years, the new driving forces such as the importance of environmental protection, the need for more reliable grid, requirement for improvement in operational efficiency, the need for managing stakeholders connected to SG, etc. have persuaded the research community as well as the organizations to reshape and expand the initial technical scope of SG with socio-economic attributes (Fang, Misra et al. 2012).

In order to satisfy these new driving forces, several models for SG have emerged in the literature (Fang, Misra et al. 2012). For instance, a layered structure for socio-technical SG has been presented as shown in

Fig. 1.1 (Fang, Misra et al. 2012; Rathnayaka, Potdar et al. 2012). Accordingly, SG comprises five layers, which we briefly discuss in the subsequent subsection.

1.1.1.1 Layered structure for socio-technical SG

Smart infrastructure layer

Smart infrastructure domain is the base structure for SG, which emphasizes on the advancing of power equipment technology. The key components of this domain are: smart sensors that sense the power flow information, actuators that make intelligent decisions in end devices based on the sensed data, smart storages that intelligently store or release energy as required and smart meters that provide two-way energy and information flow between the electric meter at home and the utility grid.

With the emergence of SG, a smarter utility provision has become available to the customers, where the customers integrate their distributed energy resources (DERs) to the main power grid. DERs are small-scale energy generation and storage systems, which are installed on dispersed sites. In the recent era, new paradigms to connect DERs to smart gird have been evolved such as a virtual power plant (VPP) (Dimeas and Hatziargyriou 2007; Chalkiadakis, Robu et al. 2011), micro-grids (Hatziargyriou, Asano et al. 2007; Asmus 2010) and vehicle-to-grid/ grid-to-vehicle (V2G/G2V)) technology (Fangxing, Wei et al. 2010; Ka, bisch et al. 2010).

A VPP is a group of DERs connected via a dedicated technical infrastructure with an aggregated capacity analogous to a usual power plant. On the other hand, the concept of micro-grid has emerged in recent years as a localized grouping of DERs, which is somewhat similar to that of a VPP, but has some key differences as follows. The micro-grids are smaller in size and concerned with a locality in operation, while the VPPs can vary from small to large sizes and follow the energy trading on a large scale. By contrast, vehicle-to-grid or grid-to-vehicle corresponds to a connection of electric vehicles such as plug-in hybrid vehicles that consume energy through SG. The electricity transfer between the grid and the vehicle makes use of batteries, which could be used to let electricity flow from the vehicle to the power lines and back as required (Fangxing, Wei et al. 2010; Ka, bisch et al. 2010).

Bidirectional communication layer

The SG communication backbone fulfils the following key functions: captures data from various sources within the utility grid such as voltage or current detection on the customer premises. It uses sensors for high-power-consuming appliances and smart storages. It also integrates external data sources such as weather forecasts and price variations in electricity market. The communication medium is also responsible to offer real-time, two-way communications between the energy provision components, the consumers and prosumers, the utility company, grid operators, etc. Two types of communication can be identified: wired such as fibre optics and wireless such as Zigbee and Z Wave.

Data processing and control layer

The data processing and control layer encompasses the IT backbone that presents advanced computer technologies to analyse and process the power flow data, and energy market data, in order to make decisions regarding the demand-side responses, efficient grid operation, minimize emissions, etc.

For instance, the smart meters within the energy environments generate a massive amount of data, including energy consumption and energy generation per time interval, voltage, alarms, tampering events, etc. There are passive concentrator nodes to collect smart meter readings from different households, which will then send the data to the processing nodes. These nodes are actively involved in calculating electricity generation and consumption statistics together with relevant billing.

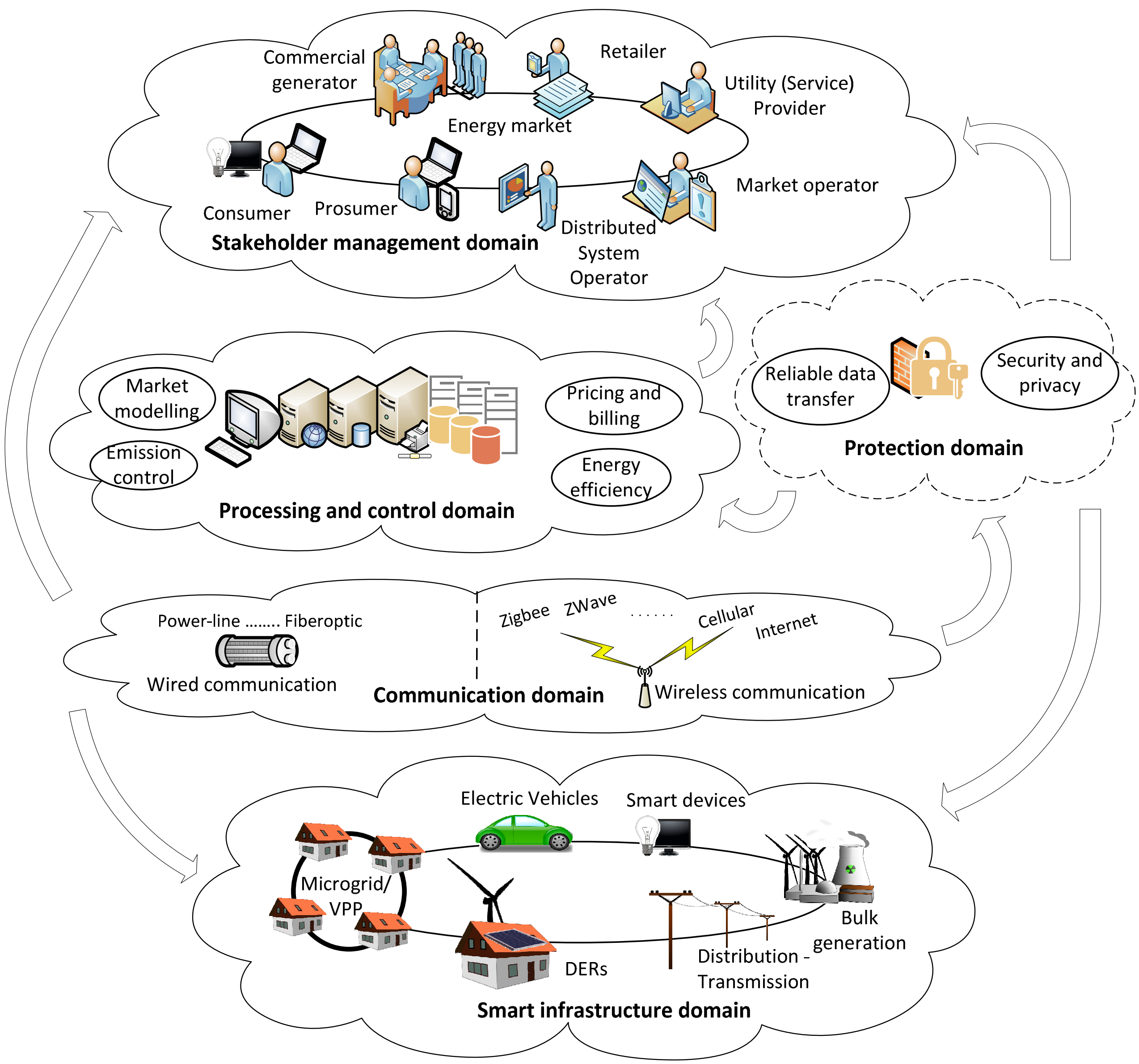

Figure 1.1: Layered architecture for smart grid

Protection layer

The protection layer provides an advanced grid reliability analysis and failure protection, and security and privacy protection services (Fang, Misra et al. 2012). The reliability of an SG is its capability to function error-free under a stated environment. Failure protection, on the other hand, comprises prediction of failures, when the system forecasts the failures in SG components before the actual occurrence; failure identification and diagnosis, when the system identifies the failure and recognizes the possible solutions; and failure recovery, when the system fixes the failures and returns to the normal functional status (Fang, Misra et al. 2012). Avoidance of failure occurrence or recovering from missing data might be extremely vital in certain scenarios; for instance, if the energy generation data are lost and unrecovered.

Stakeholder management layer

The stakeholder management layer is involved in addressing and fulfilling both technical and social requirements of actors connected to the SG through the energy sharing marketplace (Grijalva and Tariq 2011). The key actors involved are consumers, prosumers, large-scale energy generators, distribution system operators, transmission system operators, energy retailers, utility providers and market operators. During the last few decades, substantial restructuring has been taking place in energy sharing markets all over the world. The cost minimization paradigm has been transformed into profit maximization paradigms, where the stakeholders interact through an energy marketplace seeking to attain their individual goals and maximize their respective profits (Fang, Misra et al. 2012).

The key research focus of this thesis is on the role of prosumers; in the subsequent subsection, we briefly discuss about the role of prosumer.

1.1.2 Who is the prosumer?

The emergence of SG has introduced a new role of “prosumer,” where the “prosumer” is defined as “an energy user, who generates renewable energy in its domestic environment and either stores the surplus energy for future use or vends to the interested energy buyers” (Rathnayaka, Potdar et al. 2011).

Figure 1.2 demonstrates the structure of a prosumer in the energy sharing process.

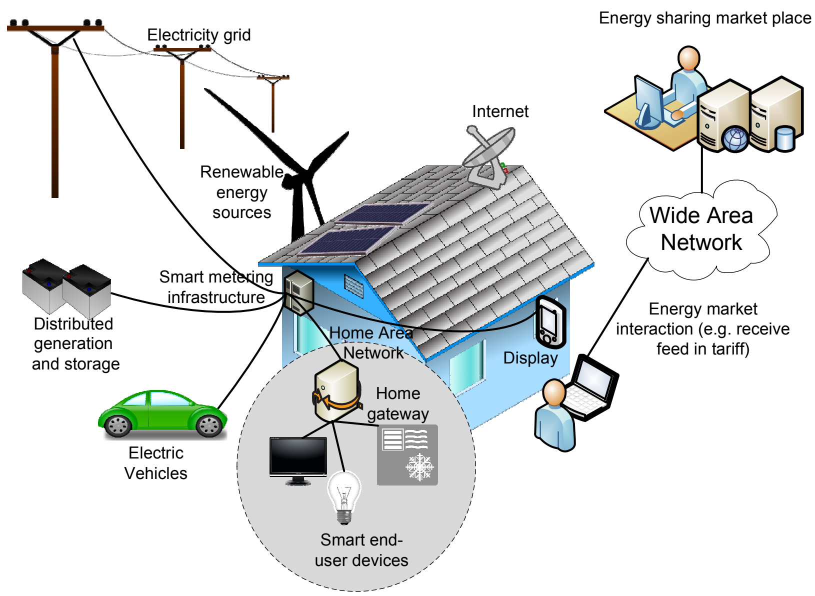

Figure 1.2: Structure of a prosumer energy sharing process

The prosumer infrastructure consists of a combination of components: DERs, power loads, energy storages, electrical vehicles and smart meters (Fig. 1.2). The DERs represent the renewable sources, which would be the roof-top solar systems and small scale wind turbines that generate green energy. The power loads can be heating and cooling devices, audiovisual devices, lighting, etc., that are operated on the basis of the regular and irregular energy requirements of different energy end users in prosumer households. Energy storages are used to store the unused energy for future use, e.g. in electric vehicles and generators (Fangxing, Wei et al. 2010; Ka, bisch et al. 2010). Smart meter is a bidirectional capable meter that allows the prosumers to both receive energy from the utility grid and feed it back to the grid.

As shown in Fig. 1.2, power loads, DERs, storages and electrical vehicles are connected to each other via a home gateway in the home area network. The home area network is further linked to the local power distribution network (i.e. utility grid/provider communication network) through smart metering infrastructures (SMIs), forming a local area network whereby the prosumers and the utility providers communicate.

From an information communication technology (ICT) perspective, the SG relies on the “Internet of Things” (Dillon, Talevski et al. 2009; Dillon, Zhuge et al. 2011) to provide the prosumers with information and choice of supply. More specifically, the “Internet of Things” infrastructure comprises numerous electronic devices, such as sensors, actuators and smart meters, that form a collaborative digital ecosystem, where the web protocols such as URI (uniform resource identifier), HTTP (Hypertext Transfer Protocol) and REST (Representational State Transfer) are utilized to access the functionality of the smart objects (Xinghuo, Cecati et al. 2011). The prosumer interacts with the energy marketplace through the Internet to share the produced green energy (we call this “energy sharing”) to the energy buyers such as the main utility grid and other energy consumers (Cecati, Mokryani et al. 2010).

Up to now, a large number of consumers have transformed themselves into prosumers due to many reasons, such as the strong societal attitude in favour of alleviating negative climatic impacts, the desire to reduce power bills and various government regulations promoting this trend, e.g. generous feed-in tariff schemes (Rathnayaka, Potdar et al. 2011). With considerable increase in the number of prosumers, it is expected that they will most likely demand a market with total freedom of energy sharing (Nair and Zhang 2009). Such economically motivated prosumers can form smart energy ecosystems, if they are offered the required technical know-how and information allowing them to attain their own goals (Lampropoulos, Vanalme et al. 2010). The prosumer has a set of functions related to interaction with the external world, such as consuming or producing energy and participating in the market (Momoh 2009; Nair and Zhang 2009). Under these circumstances, managing prosumers to achieve a sustainable and reliable energy sharing process has become pivotal to an SG(Rathnayaka, Potdar et al. 2011). In the subsequent subsection, we discuss the managing prosumers in SG energy sharing (Lampropoulos, Vanalme et al. 2010).

1.1.3 Managing prosumers in SG energy sharing

The prosumer is the fundamental stakeholder for a prosumer-focused energy-sharing marketplace, who is encouraged to generate green energy and share in the marketplace. The prosumers' motivations behind green energy generation are generally incentive related, which is mostly monetary and also non-financial (such as social responsibility to alleviate the emissions). Therefore, smart energy management services are required to enable the prosumers to make decisions on whether or not he wants to deliver, to whom and when and at what price, while negotiating with other actors in the energy market.

The prosumers are managed in the SG energy sharing process either as individual entities, who individually generate and share energy in the energy market, or as prosumer groups, who individually generate the energy and collectively share the energy in the energy market (Belhomme, Asua et al. 2008).

Generally, individual prosumer energy sharing involves direct connection between the prosumer's SMI and the utility grid or other energy buyers as shown in Fig. 1.3, and the energy sharing decisions are made based on corresponding individual perceptions. The prosumer receives tariff for the green energy generated and shared, directly from the utility provider or the retailer.

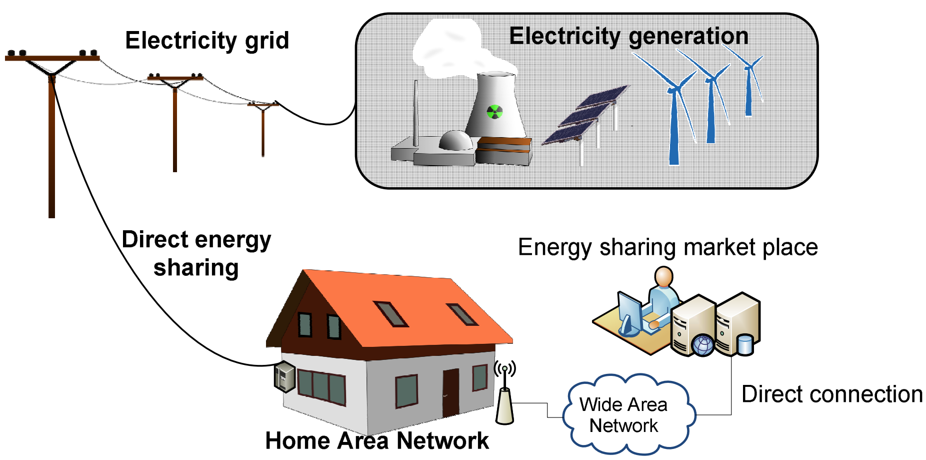

Figure 1.3: Individual prosumer energy sharing

The key motivations for individual prosumer involvement is that it offers the prosumers independent decision-making power, enabling them to freely decide the amount of energy they produce and the amount they share with the energy buyers. They can initiate the contract with the preferred utility provider/retailer, and shift from one provider to another, as the electricity rate and contract terms and conditions may be different for different utility provider companies (Rathnayaka, Potdar et al. 2011).

The primary deficiency of the direct energy sharing from the single prosumer is that such individual prosumers are often excluded from the wholesale energy market due to their perceived inefficiency and unreliability (Karnouskos 2011). For example, in most cases, the individual renewable generators, such as solar systems and wind turbines, are too small to compete effectively in the market with large-scale power generators. Therefore, in most cases, as a single entity, a prosumer is not going to produce enough energy to have any real bargaining power, and will therefore have to settle for a low price per kilowatt.

Moreover, the individual distributed energy sources are not only too small but more importantly their supply is unpredictable in as much as it depends on uncertain climatic conditions (Rathnayaka, Potdar et al. 2011). In certain scenarios, the individual prosumers may fail to achieve the energy request of energy buyers, and might therefore be left out of the entire energy-sharing marketplace.

On the other hand, in some scenarios, the prosumer groups are connected to the SG though dedicated technical infrastructures like VPPs or micro-grids (Dimeas and Hatziargyriou 2007; Hatziargyriou, Asano et al. 2007; Pudjianto, Ramsay et al. 2007; Asmus 2010; Bernhard, Thomas et al. 2010; Chalkiadakis, Robu et al. 2011). Figure 1.4 illustrates the basic view of the prosumer groups.

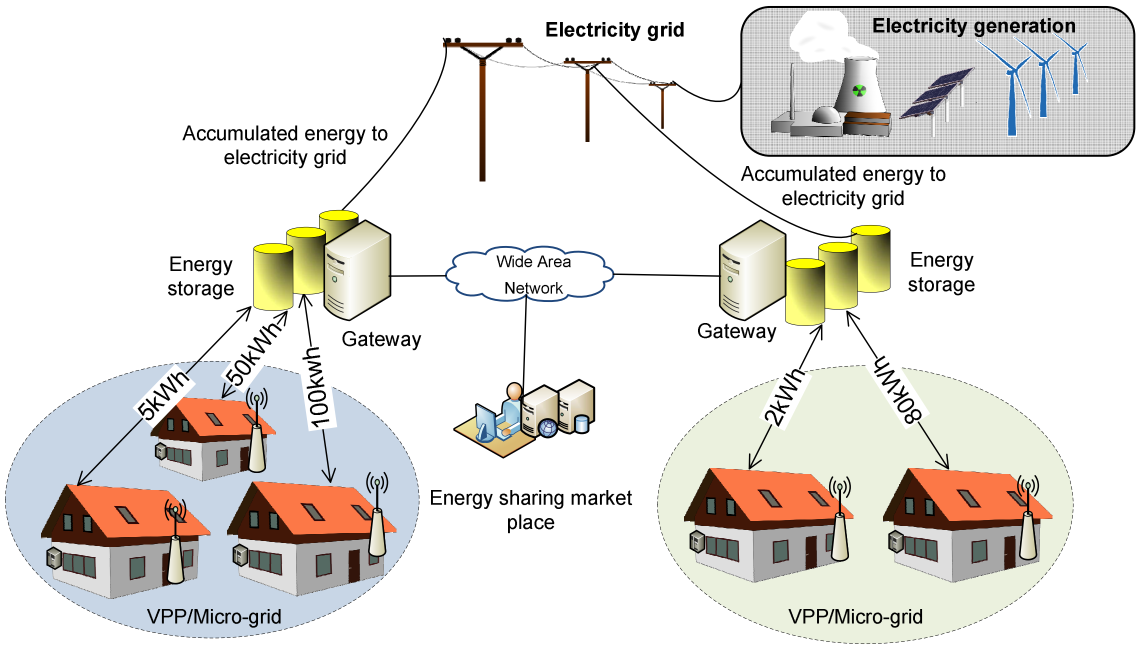

Figure 1.4: Prosumer group involvement in the form of VPP/micro-grid

As shown in Fig. 1.4, the prosumers' home area networks are electrically connected to the group gateway that communicates with the utility provider and the electricity grid. For example, prosumers living geographically closer, who supply weekly energy of 5 kWh and those who supply weekly energy of 100 kWh energy, are electrically connected.

The key motivation for prosumer groups is their ability to generate higher quantities of energy in the competitive energy market. The prosumers can individually generate green energy and collectively sell higher amounts of energy compared to individual prosumers, thus achieving a higher price per kilowatt in the energy market. Furthermore, a group of prosumers can satisfy the energy buyers' demands, and therefore, compared to individual prosumers, prosumer groups are more effective in meeting the energy requirements of the energy buyers (such as utility grids).

However, several deficiencies are apparent with prosumer groups that are formed through dedicated technical infrastructure (VPPs and micro-grid). The key deficiency is that this type of fixed architecture may result in inflexibility, which makes it complex to add or remove new members to/from the VPP/micro-grid. For instance, some prosumers may offer whatever amount of energy they can contribute, or prefer to contribute, resulting in an unreliable energy supply to the energy buyers in the long term, ultimately resulting in negative morale towards the entire VPP or micro-grid-enabled prosumer group. Moreover, in a social perspective, such prosumer groups are not goal oriented, as well as the prosumers have been merely interconnected via a technical infrastructure without considering their diverse energy sharing preferences and behaviours into account. This may cause possible disagreements among members in existing prosumer groups because of their differing energy sharing interests and preferences. Moreover, the lack of goal-oriented behaviour reduces the reliability in energy supply to the energy buyers in the long term.

In order to address the aforementioned deficiencies of existing prosumer groups, as well as to promote sustainable societal aspects with regard to the prosumer management in the long term, the concept of goal-oriented Prosumer Community Groups (PCGs) has emerged in the literature.

In this thesis, we concentrate on the managing prosumers in the form of PCGs, which we further discuss in the next section.

1.2 Goal-oriented Prosumer Community Groups

A “goal-oriented prosumer community group” is defined as “a network of prosumers having relatively similar energy sharing behaviors and interests, which make an effort to pursue a mutual goal and jointly compete in the energy market” (Rathnayaka, Potdar et al. 2013).

Unlike VPP and micro-grid, in PCGs the prosumers are virtually interconnected and may not be necessarily connected technically/electrically (Karnouskos 2011). In the social perspective, similar to generic communities, the goal-oriented PCGs are also formed by aggregating the members having similar energy profiles and inspired to achieve a mutual goal. In fact, this concept of goal-oriented PCG is a socio-technical improvement upon the existing prosumer group paradigms built on VPPs and micro-grids.

Figure 1.5 illustrates the concise overview of the PCG architecture.

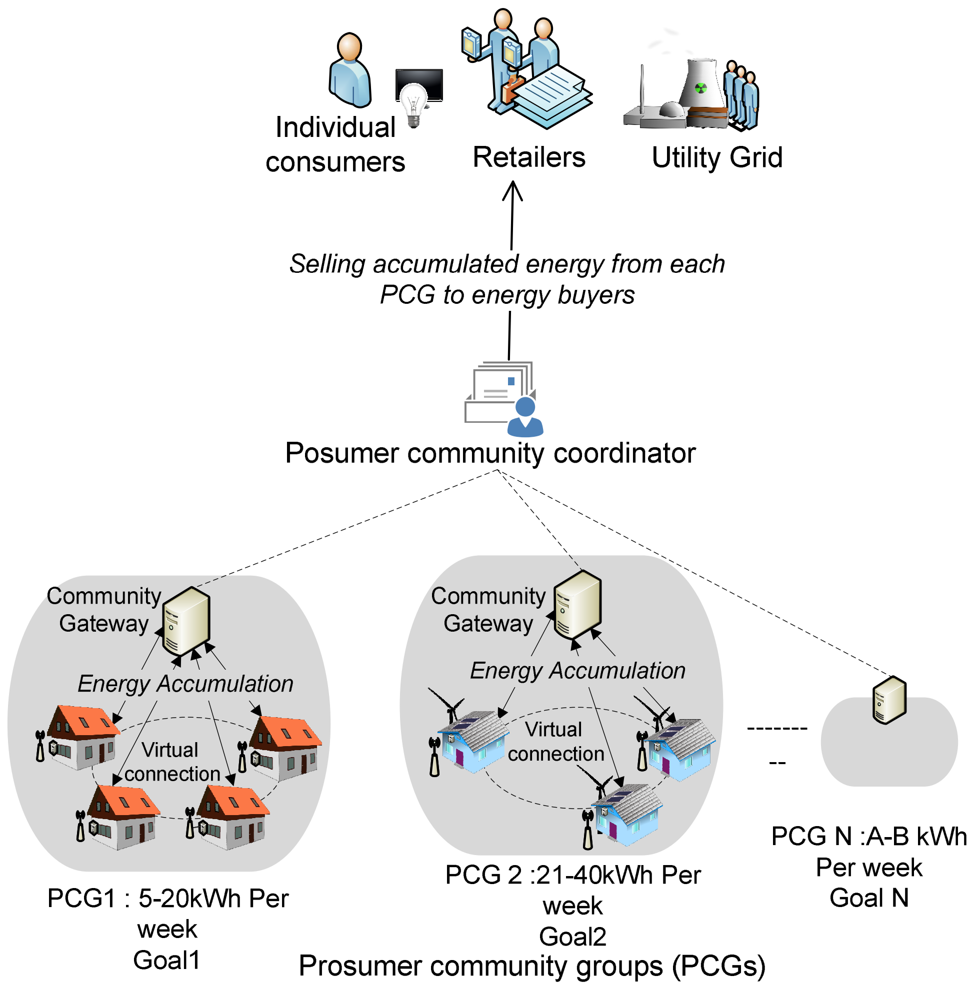

Figure 1.5: Prosumer community group involvement

There, PCGs interact with each other and with the local distributor/retailer/utility grid/other consumers through the community gateways. The community gateway refers to a smart intermediate that bridges the external power system participants with smart gateways of each DER that belongs to a PCG, in order to achieve mutual goals based on the PCG's interests and policies. The prosumer community coordinator is an entity, or a group of entities, involved in managing all the PCGs. Furthermore, the members of a PCG are inspired to achieve the mutually decided goal, which can be different from other PCGs. For instance, one PCG may want to gain high profits by selling the energy to the energy buyers, whereas another group may attempt to reduce greenhouse emission or energy costs, etc. (Rathnayaka, Potdar et al. 2013).

The main purpose of this research is to develop a approach to manage prosumers in the form of PCGs. However, it should be noted that the current literature highlights some key problems associated with managing prosumers as PCGs; these research gaps serve as the motivation for this study. In the next section, we discuss such research motivations.

1.3 Research Motivations

For the PCGs to emerge and be able to meaningfully interact with the envisioned SG infrastructure, several services have to be in place; some of these are already deployed as a core part of the SG (Galus and Andersson 2008; 2010; Järventausta, Repo et al. 2010; Ka, bisch et al. 2010; Lampropoulos, Vanalme et al. 2010; Miller, Batterberry et al. 2010; Gungor, Sahin et al. 2011; Chun-Hao and Ansari 2012; Dinusha Rathnayaka, Potdar et al. 2012; Zhong, Kulkarni et al. 2013), and some exist in other contexts (e.g. social network communities) (Milchtaich and Winter 2002; Demiris 2005; Porra and Parks 2006; Parsell and Duke-Yonge 2007; Nguyen, Loke et al. 2008; Radovanović, Lukkien et al. 2008; Subercaze, Maret et al. 2008), while others need to be developed. Additionally, integration of all these services has to be accomplished with energy as the target focus area.

The aforementioned existing research studies are associated with several open research issues when applied to the area of managing prosumers in the form of PCGs.

These key gaps include:

- **Deficiencies in single-prosumer energy sharing and prosumer groups in the form of VPPs and micro-grid when applied to the context of managing prosumers.**

As discussed earlier, the single prosumer involvement as well as the prosumer group involvement that exist in literature have shown several deficiencies in managing prosumers, leading to the necessity of developing a novel method. For instance, a single-entity prosumer as well as some prosumer groups particularly if the groups are formed without a clear analysis of the individual prosumers' fluctuating energy behaviours are often excluded from the wholesale energy market since their incapability in reaching the energy needs of the energy buyers in long-term.

- **Some aspects of managing prosumer in the form of PCGs are not comprehensively investigated in the existing literature.**

This concept of PCGs is still in its infancy, and therefore, the existing literature has very little to offer, by way of either reviewing the related concepts or resolving the associated challenges. In fact, this scant amount of research studies on PCGs is deficient in addressing some aspects of PCGs particularly the aspects of managing prosumers. Some of those drawbacks are as follows: definition and formation of PCGs with comprehensive pre-qualification criteria is not present; lack of goal-oriented nature of existing PCGs can cause inconsistent energy supply to the energy buyers; approaches to motivate the prosumers to join the PCGs are absent; limited approaches to evaluate the prosumers' energy contribution within the PCG; limited approaches to identify risks associated with the behaviours of prosumers within the PCG; and lack of incentive distribution schemes for PCGs.

- **Complexity in adopting generic community-based approaches in other context (such as online virtual communities) to create PCGs.**

The complex characteristics of PCGs make it difficult to adopt generic community-based approaches in other contexts (Milchtaich and Winter 2002; Demiris 2005; Porra and Parks 2006; Parsell and Duke-Yonge 2007; Nguyen, Loke et al. 2008; Radovanović, Lukkien et al. 2008; Subercaze, Maret et al. 2008) to manage the prosumers in the form of PCGs. For instance, in contrast to any Internet user subscription method of joining most of the online virtual communities, the membership of a PCG is limited only to the prosumers having DERs and the subscription process is a long and complex process. Moreover, the users in most online virtual communities do not receive monetary benefits for their contributions; thus, the motivational schemes to attract new members are not related to financial enticement. However, the prosumers' motivations behind green energy generation are mostly financial incentive (feed-in tariff) related.

Based on the foregoing issues, it is clear that this area of PCG research is quite young but needs immediate attention. The deficiencies in existing schemes on managing prosumers (i.e. individual prosumer and prosumer groups interconnected via a dedicated technical infrastructure) necessitate improving the aspects of developing a community-based energy sharing.

1.4 Research Objectives

The main research objective of this study is to develop an approach to manage prosumers in SG in the form of prosumer community groups. This will require a critical review of the related literature, the development of solutions to specific research issues, the construction of models for these solutions, and the verification and validation of the model. The following research objectives have been derived from the main goal of this dissertation.

Objective 1: To develop a framework to define and characterize PCGs

Here, we intend to develop a framework to define and characterize PCGs. The existing research studies on PCGs present state-of-the art descriptions of fundamental requirements necessary to form PCGs

(Karnouskos 2011); however, none of those proposed frameworks address how these prosumer communities are defined and how their memberships are characterized. Therefore, in this thesis, we address the open research issue of PCG definition and characterization, in which the proposed framework classifies the prosumers' energy sharing behaviours, while detecting the outliers, and characterizes PCGs' pre-qualification criteria.

Objective 2: To develop a framework to recruit new prosumers to the predefined PCGs

The current literature lacks any systematic method to recruit the new prosumers to the PCGs. Therefore, for the second objective of this research, we address the aforementioned research issue by presenting a framework for prosumer recruitment in PCGs. The proposed prosumer recruitment framework suggests the use of an iterative evaluation process to proactively monitor the performance of the prosumers before assigning them to the PCGs.

Objective 3: To develop a framework to manage multiple goals of community-based energy sharing network and define optimal mutual goals for PCGs

In this objective, this research aims to develop an effective framework to negotiate among the multiple goals in community-based energy sharing network and also to define optimal mutual goals for each PCG. Here, the conflicting multiple goals, in which one goal may be achievable only at the expense of other goals, are negotiated in order to assure the satisfactory level of attainment of all the goals. Moreover, a linear goal-programming model is developed to address the problem of conflicting goals that is solved to find the optimal set of goals.

Objective 4: To develop member assessment and ranking framework that can be adapted to determine relatively influential members within a PCG

Here, we intend to develop a member assessment and ranking framework that assesses the contribution made by individual prosumers of a PCG and ranks them, thus finding a subset of the most influential prosumers. We have assessed the long-term and short-term energy behaviours of prosumers based on a multiple evaluation criteria, and accordingly decide the ranks of the prosumers, whereby the higher-ranked prosumers are deemed to be more influential in enhancing the long-term sustenance of the PCG.

Objective 5: Verify the concepts of the proposed methods and develop a realistic model for community-based energy sharing network

In this objective, we verify the theoretical concepts used by the aforementioned frameworks in a simulation environment. The framework to define and characterize PCGs is verified using MATLAB, where we demonstrate the practical functionality of the framework using a data set of 550 prosumers. Similarly, MATLAB is also used to verify the prosumer recruitment framework, which we use a data set of 100 prosumers. Moreover, LINDO is used to solve the linear goal-programming problem in the multiple goal management and mutual goal definition framework. Similar to the verification of the first two frameworks, the fourth framework, prosumer assessment and ranking framework, is also verified using MATLAB. In order to demonstrate the effectiveness of the overall community-based energy-sharing network, we created a multi-agent community-based energy sharing network prototype system using Java Agent DEvelopment Framework (JADE).

1.5 Scope of the Thesis

As mentioned earlier, there are significant numbers of challenges in developing PCGs in the SG energy sharing process. However, it should be noted that we only address four key research problems in this thesis that relates purely to the domain of managing prosumers in the form of PCGs in SG energy sharing. The four research problems are as follows: problems of defining and characterizing PCGs, problem of recruiting new prosumers to the PCG, problem of managing multiple goals within the community-based energy-sharing network and allocating mutual goals to PCGs and problem of assessing and ranking members within a PCG.

In next section, we analyse the significance of this research.

1.6 Significance of Research

The significance of the problems addressed in this thesis is twofold and the benefits resulting from this research include socio-economic and technical advantages.

1.6.1 Socio-economic

1.6.1.1 Reliable energy supply increases bargaining power in energy market

The PCGs achieve higher market visibility in the long-term by offering a sufficient quantity of energy to energy buyers in the long-term. Therefore, the prosumer community group has a stronger bargaining power in the energy market than an individual prosumer. The social impact of this leads to a more symmetrical interaction between a community group of prosumers and the large-scale energy buyers (i.e. utility companies).

1.6.1.2 Promotes energy sharing between PCGs and customers (energy buyers)

The consumers can directly buy energy from geographically closer PCGs, rather than interrupting the main utility grid. In fact, the goal-oriented PCGs, which will often deliver the power they commit to, can fulfil the customer's energy demands in the long term in a more consistent manner than individual prosumers or existing prosumer groups

1.6.1.3 Creates dynamic ecosystem of cooperating prosumers

Compared to an individual prosumer and existing prosumer groups, being part of a bigger community group can be seen as a big motivator for behavioural changes with regard to energy use, because the impact of a systematically formed community group's behaviour can be more relevant and stronger than the impact of individual behaviour. As a result, the PCGs can create a dynamic ecosystem of cooperating prosumers. This is particularly advantageous in remote areas that do not have abundant energy resources and incur huge costs as well as face difficulties in transporting energy to meet the energy needs of the users. In such situations, a strong interaction among the prosumers, consumers and the utility grid will induce individuals to work together to more efficiently manage their electricity use. Such strategies are essential to act as incentives for the users to conserve energy and later utilize it for their own benefit.

1.6.1.4 Effective prosumer management

The PCGs are formed based on the relative homogeneity of energy sharing behaviours of prosumers. This minimizes the overhead to assess each single member in distributing incentives as well as the chances of possible disagreements among members that may occur because of their differing energy sharing capacities. This leads more sustainable groups in the long term. Further, the grid and distribution companies can make contracts with the PCGs, rather than each individual prosumer. This makes the process of managing prosumers much more efficient, because the grid or the distribution company does not have to worry about interacting with many small producers or small groups.

1.6.2 Technical

1.6.2.1 Coining the concept managing prosumers in the form of PCGs

There is no comprehensive study in the current literature on managing prosumers in SG in the form of PCGs. The scant amount of research on PCGs mainly investigates the importance of developing PCGs, but none of them addresses associated challenges in managing prosumers in the form of PCGs. Hence, there is the need to address the challenges of developing PCGs. The main technical significance of this research is to address four key challenges of managing prosumers in the form of PCGs.

1.6.2.2 Proposes an innovative framework to define and characterize PCGs

The foremost task to form and evolve PCGs would be the definition and characterization of favourable PCGs with appropriate pre-qualification criteria, where the new prosumers can consider these pre-qualification criteria as a benchmark in joining the PCGs. In this study, we use time-series cluster classification tree (CCT) techniques to analyse historic daily energy profiles of prosumers, while detecting outliers, and ultimately determining a set of characteristics for a viable number of PCGs for community-based energy sharing network. As per our knowledge, this work is first of its type proposing such a framework for PCG definition and characterization.

1.6.2.3 Proposes an innovative framework to recruit new prosumers to PCGs

In this study, we develop an innovative framework to recruit the new prosumers to the PCGs, which evaluate the real-time energy sharing behaviours of early adopters to determine the complying and non-complying prosumers before prosumer recruitment. As per our knowledge, this work is first of its type proposing such a framework for new prosumer recruitment in PCGs.

1.6.2.4 Proposes an innovative framework for managing conflicting goals and mutual goal definition to achieve goal-oriented nature in PCGs

The goal-oriented nature of the PCGs or following an optimized mutual goal inspires the members to achieve the set goal, and hence ensures a reliable energy supply to energy buyers in the long term. In this study, we develop an innovative framework to negotiate among the conflicting multiple goals in community-based energy sharing network and the definition of most favourable mutual goal for each PCG by using multiple criteria goal programming (MCGP) techniques. As per our knowledge, this work is the first of its type proposing such a framework.

1.6.2.5 Implements an innovative framework to assess and rank the members within the PCGs

Assessing and ranking members is significant to find the more influential members within a PCG, which can be used as a stepping stone to achieve several management functions in PCGs such as fair distribution of incentives, member motivation, risk assessment, etc. In this study, we develop an innovative framework to assess and rank members within the PCG using multiple criteria decision-making (MCDM) techniques. As per our knowledge, this work is the first of its type proposing such a framework.

1.6.2.6 Presents a realistic platform that exhibits the operation of PCGs

In this study, we create a multi-agent system that assists the user (prosumer community coordinator) to manage goal-oriented PCGs using JADE platform.

1.7 Structure of Dissertation

The remainder of this dissertation is organized as follows.

Chapter 2 presents a comprehensive review of related research on PCGs. In this chapter, we provide a survey and evaluation of PCGs – survey and evaluation of approaches exist in the field of energy as well as other contexts that possibly adaptable to PCGs – and current research gaps in developing PCGs.

Chapter 3 defines four research problems in managing prosumers in the form of PCGs– problems of defining and characterizing PCGs, problem of recruiting new prosumers to the PCG, problem of managing multiple goals within the community-based energy sharing network and defining mutual goals to PCGs and problem of assessing and ranking members within a PCG. These problems are defined based on insights gained from the literature review in Chapter 2. In addition, this chapter also defines several preliminary concepts that are used in defining solution requirements. Given the clearly defined problems, issues and requirements, it then discusses the science and engineering approach that will be used to solve these four problems and address these research issues.

Chapter 4 proposes the conceptual framework that addresses the selected research issues. The platform infrastructure is defined based on requirements stated in Chapter 3. Conceptual models are constructed and seven different steps are provided in order to illustrate the conceptual framework.

Chapter 5 presents the PCG definition and characterization framework that classifies the prosumers' energy sharing behaviours into PCGs, while detecting the outliers, and defines the pre-qualification criteria of PCGs. Further, we also demonstrate the practical functionality of the proposed framework using a prosumer data set.

Chapter 6 presents a framework to recruit new prosumers to the PCGs. This framework suggests the use of an iterative evaluation process to proactively monitor the performance of the prosumers before assigning them to the PCGs. Further, we also simulate the functionality of the proposed framework using a prosumer data set.

Chapter 7 proposes a framework to manage the multiple goals in community-based energy sharing network and define optimal mutual goals to the PCGs. Here, the conflicting multiple goals are negotiated in order to assure the satisfactory level of attainment of all the goals. Further, a linear goal programming model is developed and solved to find the optimal set of goals and to ascertain what changes are required in goal constraints to reach the satisfactory-level attainment of all the goals.

Chapter 8 proposes a framework to assess and rank the members within the PCGs. Here, the members are assessed in terms of their long-term and short-term energy behaviours based on a multiple evaluation criteria, and accordingly decide the relative ranks of the prosumers, whereby the higher ranked prosumers are deemed to be more influential in enhancing the long-term sustenance of the PCG. Further, we also simulate the functionality of the proposed framework using a prosumer data set.

Chapter 9 presents the implementation of the single realistic platform that shows the operation of PCGs.

Chapter 10 concludes the whole thesis work by summarizing what has been achieved and its major benefits, identifying the remaining work that needs to be done and envisioning future work under this research direction.

1.8 Conclusion

Managing prosumers is a crucial issue for today's SG energy sharing, and the goal-oriented PCGs are an effective way to achieve that end. However, the current literature has not covered the community-based approach to manage prosumers (or PCGs) in depth and the outcome of efforts to date is inadequate. The aim of this research is to address the four vital research challenges of managing prosumers in the form of

PCGs, namely PCG definition and characterization, new prosumer recruitment, multiple goal management within the community-based energy sharing network and mutual goal definition to PCGs, and prosumer assessment and ranking within a PCG.

Chapter 2

Literature Review

This chapter provides:

- A survey of existing literature on PCGs to manage prosumers in SG
- A survey and evaluation of approaches that exist in the field of SG and their adaptability to manage prosumers in the form of PCGs
- A survey and evaluation of approaches that exist in other contexts (online virtual communities) and their applicability to manage prosumers in the form of PCGs
- Discussion of current research gaps in developing PCGs

2.1 Introduction

In the previous chapter, we discussed the background information associated with managing prosumers in the form of PCGs, while providing introduction to the fundamental concepts like SG, energy sharing and managing prosumer. We also highlighted and explained the importance of developing PCGs to manage prosumers in SG energy sharing process.

As mentioned in Chapter 1, the PCG refers to a network of prosumers having relatively similar energy sharing behaviours, who make an effort to pursue a mutual goal and jointly compete in the energy market (Rathnayaka, Potdar et al. 2014). For the PCGs to emerge and be able to meaningfully interact with the envisioned SG infrastructure, several services have to be in place; some of these services are discussed in scant amount of existing research contributions on PCGs; some of the services are already deployed as a core part of the SG, some exist in other contexts (e.g. social network communities) and some require to be developed.

This chapter provides an overview of the literature pertaining to PCGs, while giving an evaluation of existing methods in the area of SGs as well as other contexts such as social network communities to address their adaptability to establish PCGs. Accordingly, this dissertation covers the studies in the literature in three main sections as shown in Fig. 2.1.

It is to be noted that, in this chapter, we comprehensively explain the existing research works on PCGs. However, we do not discuss all the aspects of the SG projects and research studies and also the research studies in other contexts (online virtual communities) in detail, as the aim and scope of this thesis is managing prosumers in the form of PCGs; thus, we focus on how those relevant approaches of existing research can be adapted to manage prosumers in the form of PCGs.

The rest of the chapter is organized as follows: in Section 2.2, we provide a review on the literature on PCGs and illustrate the open research issues that require further attention. In Section 2.3, we evaluate the commercial projects and research contributions on SG and outline existing open issues. In Section 2.4, we review the studies on community-based approaches in other contexts such as social network communities and assess their applicability to establish PCGs. Section 2.5 discusses the PCG design challenges and requirements based on the critical review of the existing relevant literature. Finally, the concluding remarks are given in Section 2.6.

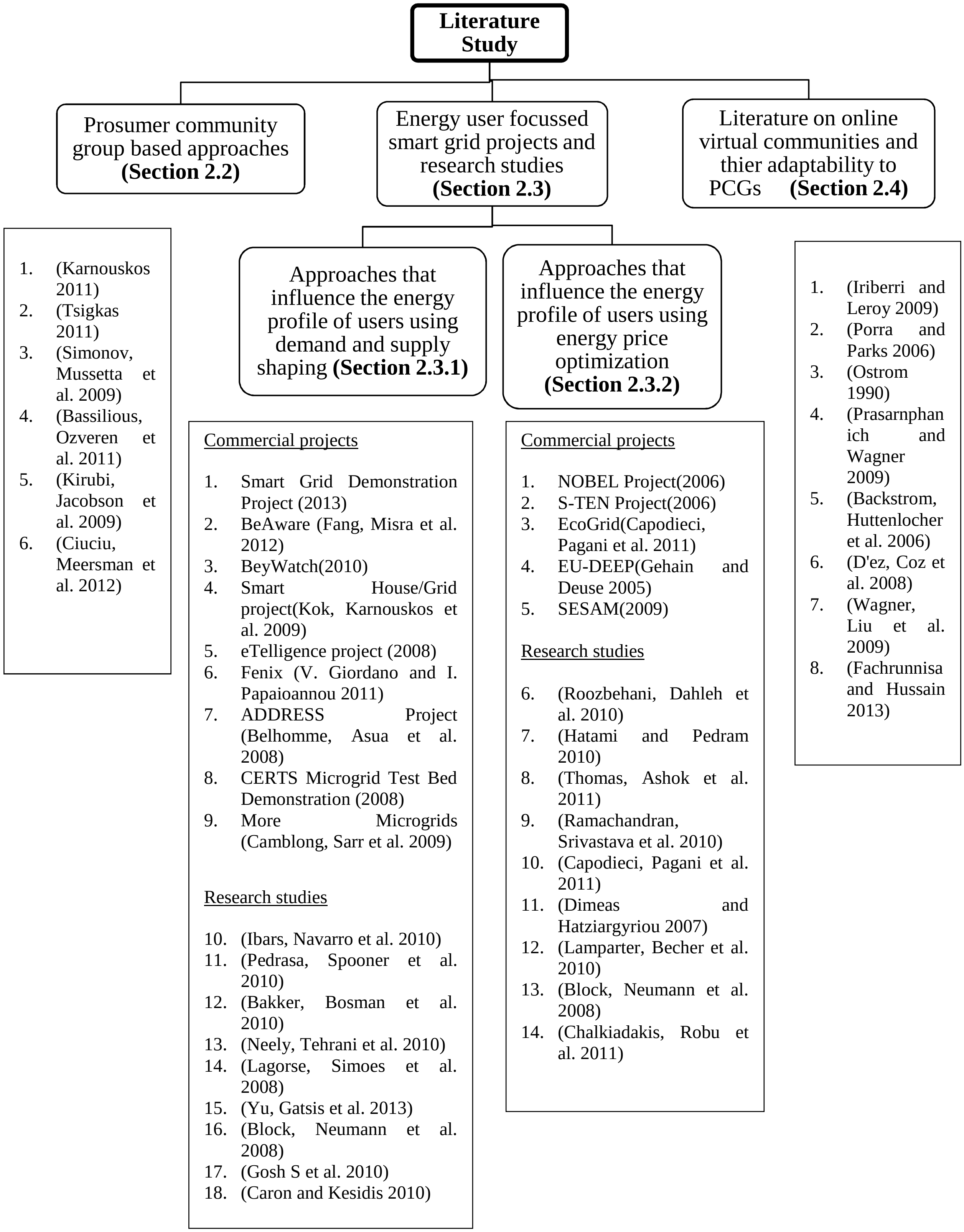

Figure 2.1: Literature Survey Structure

2.2 Prosumer Community Group based Approaches

In the literature, there is a scant amount of work by different researchers that proposes community-based approaches or PCGs for energy sharing in SG. In this section, we give an overview and summarize the working of those approaches.

The concept of PCG is still in its introductory phase, and therefore, the existing literature has little amount of research contributions (Bassilious, Ozveren et al. 2011; Karnouskos 2011; Tsigkas 2011). Here, we demonstrate these research contributions in detail.

For instance, Karnouskos (Karnouskos 2011), as a part of NOBEL project (Marqués, Serrano et al. 2011), introduces the concept of “communityware smart grids.” First, we discuss the key highlights of this research.

Key highlights

- The importance of the goal-driven prosumer communities to reach the critical energy mass, and to attain the interactions which may have significant impact, is discussed.
- It is argued that the prosumer communities require open service-driven paradigm and communityware auxiliary services to facilitate real-time information access and interactions, security, trust and privacy and policy and regulatory framework.
- The different types of services required for the prosumer communities to emerge, such as energy brokering, community behavioural simulation, energy-information services, real time energy monitoring, etc., are discussed.

This research work has several limitations when focusing on managing prosumers in the form of PCGs, which we describe as follows:

Limitations of the work

- This work is more like state-of-the-art descriptions on “communityware smart grid,” and presents neither methodologies to achieve the communityware SGs nor any simulation or practical verifications.

- This work illustrates what services are required to create the PCGs, but does not discuss how these PCGs are defined and characterized with suitable entry requirements, and about suitable methods of recruiting new prosumers.
- Although the authors discuss the importance of goal-driven communities, this work lacks how multiple goals are managed in the community-based energy sharing network and how mutual goals are defined and allocated to the PCGs.
- In addition to the aforesaid weaknesses, this study does not address several other concepts of managing prosumers in the form of PCGs; some of them include assessing prosumers, motivating individual prosumers as well as the PCGs, incentive distribution, etc.

On the other hand, the research work of Tsigkas (Tsigkas 2011) presents the concept of open lean electricity supply communities (OLESC), which are value-added communities with a self-organized and self-regulated network of distributed electricity supply sources to manage and fulfil customers' energy demand requests. The key highlights of this research are illustrated as follows;

Key highlights

- This work suggests that the service providers set up virtual private networks similar to virtual community groups and offer the prospect to their customers to design customized demand load profiles that is fit to the individual customer needs.
- Such communities facilitate the integration of locally available renewable energy sources (prosumers) upon the customer demand.
- This study presents the fundamental components of the required information systems architecture in order to enable OLESC.
- The management of OLESC is undertaken based on two parts of activities: first, "electricity planning and logistics" that addresses power plant production scheduling, operational

management, etc., which are designed to generate electricity as a service. Second, “electricity operations and control,” which concerns activities regarding operations such as dispatching electricity, distributed production, scheduling, reliability assurance, etc., designed to deliver electricity on demand and responding to customer request for a service.

However, this research work has following limitations and differences;

Limitations

- Similar to the research done by Karnouskos (Karnouskos 2011), this work also does not comprehensively present frameworks to build OLESC and relevant simulation and verifications; rather it provides the descriptions of fundamental concepts of the required information systems architecture in order to enable OLESC.
- In addition, the issues related to managing prosumers are not comprehensively addressed such as member assessment and ranking, member motivation schemes, incentive distribution, etc.

Going a step further, the segmentation of micro-grids to form social network communities has been proposed by Simonov et al. (Simonov, Mussetta et al. 2009); the key highlights of the research are as follows:

Key highlights

- This work endeavours to build a local micro-grid community in order to optimize the electric energy consumption locally.
- The key technical concerns related to the micro-grid communities addressed by this research are as follows: smart real-time metering giving the real life energy profile, energy production forecast and the optimized local minimum.
- Simulation results have been provided to explore the performance of the proposed method. According to the simulation set-up, the authors categorize the power consumption curves into

two types: "residential users" and "small industrial users (having photovoltaic (PV))." These profiles are synthetically generated following the realistic patterns. According to their results, authors claim that the most favourable performance of the micro-grid community is achieved by grouping the "residential prosumers" with "small industrial user" into one segment.

- This work develops different prosumer clusters having a mix of small-scale prosumers and consumers, where they are technically connected to each other through micro-grid.

However, this research work also has several limitations and differences, particularly if applied to the aspects of managing prosumers in the SG.

Limitations

- This work is more like creating smaller micro-grid communities inside a large micro-grid. The prosumers within the micro-grid are technically connected to each other, rather than virtually connecting the prosumers. Therefore, the same deficiencies of micro-grid such as infeasibility when adding new prosumers to the technically connected set of prosumers are applied to the prosumer communities focused here.
- Although this research addresses the issue of defining a mutual goal of achieving the local demand of PCGs, the proper method to define or allocate mutual goals to PCGs is not present.
- Moreover, certain issues related to managing prosumers in the form of PCGs such as member assessment and ranking, member motivation schemes, incentive distribution, etc. are not discussed.

On the other hand, Bassilious et al. (Bassilious, Ozveren et al. 2011) segment the DERs based on geographic area to create community area networks. The key highlights of this research are as follows:

Key highlights

- The prosumers are grouped based on geographic area and are connected to each other through dedicated infrastructure like in micro-grids/VPPs.

- In this research, the energy is provided to the end users through an optimized combination of energy purchase contracts, conventional on-site generation (such as combined heat and power, diesel generation, etc.) and renewable generation (such as wind turbines or PV sources).
- The suggestions have been presented to improve the quality of the forecast for the aggregated demand and the resulting analysis has been used to create a forward demand curve, while meeting the local aggregated demand.

However, this research has shown the following limitations in the context of managing prosumers in the form of PCGs.

Limitations

- Similar to most of the aforesaid research works, this work also extensively describes the fundamental aspects that are involved in developing the proposed DER segments; however, it does not present a verification of the research or any simulation results.
- Moreover, the issues of managing prosumers in the DER segments in community area networks such as how these segments are defined and how new prosumers are recruited, what would be their mutual goals, incentive distribution, etc. are not considered.

Furthermore, Kirubi et al. (Kirubi, Jacobson et al. 2009) present a case study analysis of a community-based electric micro-grid in rural Kenya. The key highlights of this study are illustrated as follows;

Key highlights

- The electric micro-grid was treated as a local community of geographically closer energy producers that enables easy access to electricity.
- The ultimate aim of this study is to improve the delivery of social and business services from a wide range of village-level infrastructure (e.g. schools, markets and water pumps) while

improving the productivity of agricultural activities.

This work exhibits the following limitations when applied to the PCGs.

Limitations

- Similar to the work done by Bassilious et al. (Bassilious, Ozveren et al. 2011), this work also creates local communities of geographically closer energy producers that are connected through a dedicated infrastructure similar to micro-grids, rather than virtually connecting them, thus exhibiting the same deficiencies of micro-grids.
- Moreover, the issues of managing prosumers in the local prosumer communities such as how these communities are defined and how new prosumers are recruited, inspiring the communities to achieve a common goal, incentive distribution, etc., are not considered.

Moreover, Ciuciu et al. (Ciuciu, Meersman et al. 2012) investigate the social network of smart-metered homes for grid-based renewable energy exchange. The key highlights of this research are illustrated as follows:

Key highlights

- Discuss the heterogeneous data collection from meters, sensors and actuators of different prosumers and the detection of smart meters with similar goals to create prosumer communities.
- Investigate the process of exchange and aggregate data from multiple autonomous physical or virtual meters, and achievement of demand response for the community involved.
- Each prosumer is represented as a node on the Internet of Smart Meters (IoSM) through their electricity meters, sensors and actuators, facilitating energy exchange among the participants by expressing their goals in a standardized language through hybrid ontologies.
- The key architectural components are as follows: a layered demand-response architecture, multidisciplinary knowledge base and community evolution for sustainable growth (based on

cyber physical system).

However, this research has shown the following limitations in the context of managing prosumers in the form of PCGs:

Limitations of the work

- This work discusses about the ICT backbone for community evolution for sustainable growth, and its objectives such as determining the financial incentives, assisting the community members' positive behaviours, creating awareness among the prosumers about the related benefits, etc., however do not present methodologies of how to achieve those objectives, as well as does not provide any simulation or practical verifications.
- In addition to the aforesaid weaknesses, this study does not address several other concepts of managing prosumers in the form of PCGs; some of them include evaluation techniques for recruiting new prosumers, assessing and ranking of the prosumers, motivating individual prosumers as well as the PCGs, etc.

Overall, it is clearly noticeable that the aforementioned research studies on PCGs are deficient in addressing the key aspects of managing prosumers. This gap in the literature motivated us to address the key challenges of developing prosumer community groups to manage prosumers in the SG. In next subsection, we illustrate the shortcomings of PCGs in the context of managing prosumers in detail.

2.2.1 Shortcomings of existing PCG-based approaches

- **Definition and characterization of PCGs is not broadly analysed.** None of the aforesaid research studies provide a comprehensive analysis of PCG definition and characterization and any challenge associated with it, such as identifying the prosumers' varying energy sharing behaviours, determining suitable pre-qualification criteria for PCGs, etc. Some works such as Bassilious et al. (Bassilious, Ozveren et al. 2011), Kirubi et al. (Kirubi, Jacobson et al. 2009) and Simonov et al. (Simonov, Mussetta et al. 2009) have offered segmenting prosumers based on their geographic location within a micro-grid; however, the concept of PCGs is a broader view that virtually aggregates the prosumers into long-term sustainable PCGs and involves them in the energy sharing process. The aforesaid works are more like the segmentations of micro-grids than implementing the PCGs.

- **Lack of goal-oriented nature in PCGs.** The existing community-based approaches have shown very little attention in inspiring its prosumers to achieve common mutual goals. For instance, the approach proposed by Simonov et al. (Simonov, Mussetta et al. 2009) highlights the key inspiration of this framework is to fulfil the local energy consumption by using their local generation. However, the authors do not comprehensively address the challenges of negotiating among the multiple conflicting goals within the community-based framework, or developing custom-tailored goals for different communities based on their characteristics, etc.

- **Approaches to inspire the prosumers to join the PCGs or inspire the existing members to supply more energy are absent.** The existing literature on PCGs does not propose frameworks for prosumer motivation. The possible motivation strategies such as reward schemes to offer more rewards to the prosumers who supply higher amount of energy and more opportunities for prolonged members of the PCGs are lacking in the current research.

- **Limited approaches to assess and rank the prosumers' energy contribution within the PCGs.** The contribution assessment of individual prosumers within a PCG is important in finding more influential prosumers whose future behaviour will facilitate the long-term sustainability of the community group, resulting in more fair incentive distribution among the prosumers within the PCG. However, the existing literature on PCGs does not address this challenge.

- **Limited approaches to identify risks associated with negative behaviours of prosumers within the PCG.** Like general community groups, even in a PCG, it is necessary to identify prosumers' negative behaviours, analyse the associated vulnerabilities and resolve the problems caused by these negative events, in order to avoid long-term negative effects. However, the existing methods lack these techniques.

- **Lack of comprehensive prosumer reward distribution schemes that consider both financial and non-financial incentives.** Prosumer reward schemes play a critical role in creating a motivated prosumer base. These rewards can be either financial incentives like feed-in tariff given for the energy generated and supplied to the grid or non-financial rewards, such as social respect, reputation and popularity, because of generating and sharing green energy. In order to establish an effective rewards scheme, both financial and non-financial incentives should be optimally amalgamated and offered fairly to the prosumers. However, the aforementioned research on PCGs has not focused on developing effective reward distribution schemes within the PCGs.

Nevertheless, there is a considerable number of SG projects that address different areas of SG, such as electrical infrastructures, communication medium, energy pricing strategies, market mechanisms, stakeholder management, etc. It can be debated that the concepts used in existing SG projects and research studies may be adoptable to manage prosumers in PCGs. Therefore, in the next section, we evaluate the existing SG projects and research studies and their adaptation to manage prosumers in the form of PCGs. It should be noted that we focus mainly on the efforts involving prosumers (or energy users) in the SG as the key research thought of this thesis is managing prosumers using community-based approach.

2.3 Energy User-focused Smart Grid Projects and Research Studies

In this section, we briefly describe the energy user-focused approaches implemented by existing SG projects and research studies and their adaptation towards the managing prosumers in the form of PCGs.

After analysing the objectives of energy user-focused existing works, we categorize their research focus as follows:

1) ***Approaches that influence the energy profile of users using energy demand and supply shaping:*** Here, we discuss the existing literature that endeavours to alter the energy behaviours of the user by scheduling the energy demands or distributed energy generation, for instance, moving the energy loads to different zones during the day to achieve optimal demand–supply balance, personalized energy management, etc. Moreover, we analyse how we can use the different aspects of those existing literature towards developing PCGs.
2) ***Approaches that influence the energy sharing profile of users using energy price optimization:*** Here, we illustrate the literature that influences the behaviours of energy users by providing favourable energy prices and trading possibilities to the energy users when they buy or sell energy. Furthermore, we review how we can use the different aspects of the existing literature towards developing PCGs.

In subsequent subsections, we discuss the existing literature based on the aforesaid two categories. Tables: Table. 2.1 (has three parts) and Table 2.2, respectively, describe the existing commercial projects and research studies that mainly focus on influencing the energy profile of users using energy demand and supply shaping, whereas Tables: Table. 2.3 and Table. 2.4, respectively, describe the existing commercial projects and research studies that mainly focus on influencing the energy sharing profile of users through energy price optimization. It is to be noted that some commercial projects and research studies on SG have addressed more than one aforesaid category. In such scenarios, we describe that project/research study under one selected category.

2.3.1 Approaches that influence the energy profile of users using energy demand and supply shaping

Here, we first provide an overview of influencing the energy sharing profile of users by energy demand and supply shaping. The two key characteristics that influence the energy sharing behaviours of users are energy consumption behaviours and energy generation behaviours; thus, shaping the energy consumption and generation characteristics of users has a direct impact on energy sharing behaviours of users.

Energy demand and supply shaping of users refers to restructuring the energy demand or consumption profile of consumers or the energy supply or generation profile of energy generating companies and domestic prosumers. In literature, there are several works to describe demand–supply balance (Demirbaş 2001; Strbac 2008), though all have the same basic underlying idea which is expected to set to zero algebraically the sum between energy demand and supply as illustrated in Equation 2.1.

Let $D_{\Delta t}$ be the sum of all the demands of all consumers in a given time interval Δt, then $C_{\Delta t}$ is the number of consumers at time interval Δt, D_k is the energy demand by the k^{th}-energy Buyer, S^z is the energy supply provided by the z^{th} source of energy, N_g is the total number of number of generating companies, G_{ci} is the i^{th} generating company, M_p is the total number of prosumers who shares energy and P_{rj} is the j^{th} prosumer:

$$D_{\Delta t} = \sum_{k=1}^{C_{\Delta t}} \mathrm{D}_k = \sum_{i=1}^{N_g} \mathrm{S}_{\Delta t}^{G_{ci}} + \sum_{j=1}^{M_p} \mathrm{S}_{\Delta t}^{P_{rj}} \qquad \text{Equation 2.1}$$

Tables 2.1 and 2.2, respectively, provide a brief overview of the commercial SG projects and research works that focus mainly on energy demand and supply shaping of energy consumers and prosumers, and their adaptation to develop PCGs.

First, we look at the literature on SG commercial projects (Table 2.1).

Table 2-1: Smart grid commercial projects that focus on influencing the energy profile of users using energy demand and supply shaping

SG project	Concepts	Adaptation to prosumer community group development
Smart Grid Demonstration Project (2013)	**Objective:** develop techniques to improve utility-grid side and customer side **Approach:** The distribution system voltage management to preserve energy (utility-grid side), home area networks and interval metering (customer side)	The technical and ICT infrastructures may be adapted to develop the technical and ICT infrastructures of prosumer community groups with major revision However, the aspects of managing prosumers are not addressed
BeAware (Fang, Misra et al. 2012)	**Objectives** : Real-time awareness of energy consumption; power conservation; value-added service platforms and models **Approach**: Energy Life: mobile phone application service platform; Watt-Lite Twist: ambient interface to communicate alerts; Service Layer: solution providing data to the interfaces; and Sensor Layer: sensor network infrastructure	"Energy Life" can be used to enable prosumer community group members to monitor their individual and group energy consumption; "Watt-Lite Twist" to communicate among the prosumer community group members and prosumer community coordinator; "Service Layer" to build the data interfaces among the prosumer community group members; and "Sensor Layer" to build the electrical infrastructures in community-based energy sharing network However, the aspects of managing prosumers are not addressed
BeyWatch(2010)	**Objectives:** Energy savings, efficient distribution of the excess renewable energy at neighbouring levels, electricity load balance, flexible energy consumption contracts **Approach**: Energy-aware white goods, combined PV & solar home system, energy consumption monitoring & control, low-cost home networking, intelligent energy-aware home-management system, business models	The technical and ICT infrastructures such as intelligent energy-aware home-management system to control the power limits, tariffs and user preferences can be beneficial for PCGs, however should be revised to address the PCG characteristics. However, the aspects of managing prosumers are not addressed
Smart House/Grid project (Kok, Karnouskos et al. 2009)	**Objectives**: Promote DER integration, improve energy efficiency **Approach**: ICT and communication infrastructures to enable communication and negotiation among nodes, decentralized and bottom-up device control, higher security of supply levels	The similar ICT infrastructure can be adapted and further modified to communicate and negotiate among the nodes, which can be assumed to be prosumer agents and the prosumer community coordinator agent However, the aspects of managing prosumers are not addressed

Table 2.1: Continued: Smart grid commercial projects that focus on influencing the energy profile of users using energy demand and supply shaping

SG project	Concepts	Adaptation to prosumer community Group development
eTelligence project (2008)	**Objectives**: Integration of VPPs, reduce the load on the power grid, fully automated plug and play appliances **Approach**: Feedback systems for household customers (paper, web portal, iPod Touch), and market platform for automatic market participation	The similar electrical infrastructure of VPP can be used for the electrical infrastructure of PCGs (although it is not mandatory to provide a dedicated electrical grid among the prosumer community group members) The similar market platform can be altered to provide intraday bids, and day-ahead bids when placed on the wholesale market by PCGs with major revision However, the aspects of managing prosumers are not addressed
Fenix (V. Giordano and I. Papaioannou 2011)	**Objectives**: promote DER through aggregation into large-scale virtual power plants (LSVPP), decentralized management **Approach**: Technical-VPP (TVPP), Commercial-VPP (CVPP)	The similar electrical infrastructure of VPP can be used for the electrical infrastructure of prosumer community groups if required. The similar TVPP concept can be used with major revision to provide system balancing and ancillary services, when prosumer community group network is connected to the DSO and TSO. Similar CVPP concept can be used to facilitate energy trading services to the prosumer community coordinator However, the aspects of managing prosumers are not addressed.
ADDRESS Project (Belhomme, Asua et al. 2008)	**Objectives**: Active Demand: real time interaction among power system participants based on price and volume signals **Approach**: Commercial and technical framework both in consumer (prosumer) side and market side, the role of the aggregator, who acts as an interface between the power system participants and the market	The role of aggregator might be adapted and modified as prosumer community coordinator with revision. The aggregator requests each prosumer to trade energy individually; on the other hand, the prosumer community group coordinator virtually accumulates energy units from all the members of prosumer community group and trades them as a single unit However, the aspects of managing prosumers are not addressed

Table 2.1: Continued: Smart grid commercial projects that focus on influencing the energy profile of users using energy demand and supply shaping

SG project	Concepts	Adaptation to prosumer community Group development
CERTS Microgrid Test Bed Demonstration (2008)	**Objectives**: Integration of DERs in the form of micro-grids, islanded conditions, system reliability and flexibility, automated network **Approach**: An intelligent network to enable automation, an electrical protection system, reliability management through market mechanisms, control strategies	The similar electrical infrastructure and security mechanisms of the project can be revised to build the technical infrastructure and the security mechanisms for the prosumer community groups.
More Micro-grids (Camblong, Sarr et al. 2009)	**Objectives**: Micro-generation through Micro-grids concept, multi-micro-grids management **Approach**: "Micro-Grid Controller" to decide the quantity of energy that the micro-grid should draw from the distribution system, load controllers for efficient integration, protocols for technical and commercial integration of multi-micro-grids	The similar electrical infrastructure of micro-grid can be used for the electrical infrastructure of PCGs if required. The ICT infrastructure of "Micro-Grid Controller" can be adapted and further modified to decide the quantity of power required for each PCG from the distribution system to satisfy the local PCG members' energy needs However, the aspects of managing prosumers are not addressed

For example, the Smart Grid Demonstration Project (2013) develops techniques to improve both the utility-grid side and the individual customer side. The utility side is improved to manage the distribution system voltage in order to preserve energy without making any negative impact on the customer equipment, while the customer side is improved by using home area networks and interval metering which monitors and measures the changes in the individual customer's energy use behaviour. This project provides the customers with the tools and knowledge to become smarter energy consumers. This project was applied in both small urban and rural settings, and evaluated techniques to monitor consumer activities real time, maintain data exchange on supply and demand and adjust power use to changing load requirements. When applied to the development of PCGs, similar ICT infrastructure and tools can be used to improve the individual prosumer side in PCGs; however, this requires major revision.

The BeAware (Fang, Misra et al. 2012) project, on the other hand, aims at power conservation by individual households, while reducing energy wastes without impacting on comfort working conditions. It considers the different socio-cognitive models for characterizing the energy consumption behaviour in individual households, believing that consumers can be turned into active players if and only if they receive feedback in a comprehensible way. The key approaches presented by this project are “Energy Life,” which is a mobile phone application service platform; “Watt-Lite Twist,” which is an ambient interface to communicate alerts; “Service Layer,” which is a solution providing data to the interfaces; and “Sensor Layer,” which is a sensor network infrastructure. The aforementioned key approaches can be altered and applied to PCGs in different ways; for instance, “Energy Life” can used to enable PCG members to monitor their individual and group energy consumption; “Watt-Lite Twist” to communicate among the PCG members and prosumer community coordinator; “Service Layer” to build the data interfaces among the PCG members; and “Sensor Layer” to build the electrical infrastructures in community-based energy sharing network.

Continuing in the same direction, the Beywatch European project (2010) aims at developing an ICT structure to enable the consumers to visualize and control the volume of their energy consumption. Moreover, it also addresses efficiently distributing the excess renewable energy at neighbouring levels, thus allowing for electricity load balance as well as flexible energy consumption contracts. The key concepts forwarded by the project are energy-aware white goods, combined PV and solar home system, energy consumption monitoring and control, low-cost home networking, intelligent energy-aware home-management system and business models. However, when applied to develop PCGs, similar approaches can be used to improve the energy behaviours of individual members within the PCG, for instance, energy-aware white goods to control the consumption/and distributed generation profile, combined PV and solar home system for active energy production and intelligent energy-aware home-management system to control the power limits, tariffs and user preferences at domestic level of individual prosumers within PCGs.

The key focus of smart house/SG project (Kok, Karnouskos et al. 2009) is increasing the penetration of renewable energies, diversifying and decentralizing Europe’s energy mix and is improving energy efficiency. The concepts of the project are built on available open industry standards from both ICT and energy worlds, which aim to intelligently manage the smart houses enabling them to communicate, interact and negotiate with both customers and energy devices in the local energy grid to achieve maximum overall energy efficiency as a whole. When applied to manage prosumers in the PCGs, the similar ICT infrastructure of the smart house/SG project can be modified to communicate and negotiate among the nodes, which can be assumed to be prosumer agents and the prosumer community coordinator agent.

By contrast, the eTelligence (2008) project implements a market-oriented framework integrated to the centralized control, which allows the VPPs to place any quantities of energy on the market, using an automated infrastructure. The producers and consumers can offer system services and idle power, and help reduce the load on the power grid. In addition to the VPPs, even private households can put minute amounts of electricity on the market by using almost fully automated plug-and-play appliances that operate automatically in the market, in line with the pre-programmed instructions of the appliance owners. However, the similar electrical infrastructure of VPP can be used for the electrical infrastructure of PCGs, although it is not mandatory to provide a dedicated electrical grid among the PCG members. The similar market platform can be altered to provide intraday bids and day-ahead bids when placed on the wholesale market by PCGs.

On the other hand, the Fenix project (V. Giordano and I. Papaioannou 2011) identifies two roles for the VPP in its centrally controlled VPP framework, namely Commercial-VPP (CVPP) that handles market participation and Technical-VPP (TVPP) that handles system management activities. Technical-VPP (TVPP), which consists of DER from the same geographic location and services and functions, includes local system management for a distribution system operator (DSO), as well as providing transmission system operator (TSO) system balancing and ancillary services. CVPP facilitates services like wholesale energy trading, trading portfolios management and services provision through submission of bids and offers to the system operator. When applied to develop PCGs, a similar electrical infrastructure of VPP can be used for the electrical infrastructure of PCGs (although it is not mandatory to provide a dedicated electrical grid among the PCG members). The similar TVPP concept can be used to provide system balancing and ancillary services, when the PCG network is connected to the DSO and TSO. A similar CVPP concept can be used to facilitate energy trading services to the prosumer community coordinator.

Similarly, the ADDRESS (Active Distribution networks with full integration of Demand and distributed energy RESourceS) project (Belhomme, Asua et al. 2008) aims at active demand aspects that achieve real-time interaction among power system participants based on price and volume signals, while delivering technologies to increase the use of distributed generation and renewable resources. It also examined how local intelligence can be used to optimize the real-time responses between the power system participants. This project is also built on the architecture developed for the Fenix project (V. Giordano and I. Papaioannou 2011). This project develops a commercial and technical framework in both the consumer (prosumer) side and the market side, and highlights the role of the aggregator, who acts as an interface between the power system participants and the market. In the attempt of applying these approaches to develop PCGs, the role of aggregator can be adapted and modified as prosumer community coordinator. The aggregator requests each prosumer to trade energy individually; on the other hand, the prosumer community coordinator virtually accumulates energy units from all the members of the PCG and trades them as a single unit.

Moreover, the "CERTS Micro-grid project" (2008) offers an advanced approach to enable the integration of multiple DERs into the utility grid, in the form of a micro-grid, without extensive (and expensive) custom engineering. In addition, the frameworks of the CERTS Micro-grid project provide a high level of system reliability as well as flexibility in the placement of DER within the micro-grid. The peer-to-peer and plug-and-play concepts have been incorporated for each component within the micro-grid, which claims to have reduced the costs. When applied towards the development of PCGs, the similar electrical infrastructure, peer-to-peer and plug-and-play concepts and security mechanisms of the project can be used and further developed to build the technical infrastructure and the security mechanisms for the PCGs.

In the same way, the key focus of the “More Micro-grids” (Camblong, Sarr et al. 2009) project is to develop sophisticated control techniques for distributed micro-generation through micro-grids. It implements the integration of several micro-grids into operation, quantifies the effects of micro-grids on power system operation and planning and conducts field trials to evaluate the strategies. In addition, this project also concerns itself with developing protection and rounding policies to ensure safety of operation. This project develops the “Micro-Grid Controller” to decide the quantity of energy that the micro-grid should draw from the distribution system, load controllers for efficient integration, protocols for technical and commercial integration of multi-micro-grids. Here, the agents are embedded into energy resources to identify the status of the environment to negotiate on how to share the available energy within the micro-grid. When applied to develop the PCGs, the similar electrical infrastructure of micro-grid can be used for the electrical infrastructure of PCGs (although it is not mandatory to provide a dedicated electrical grid among the PCG members). Moreover, the ICT infrastructure of “Micro-Grid Controller” can be adapted and further modified to decide the quantity of power required for each PCG from the distribution system to satisfy the local PCG members’ energy needs.

In addition to the aforementioned projects, there are several research contributions that focus on the same issue of reshaping the energy consumption and generation profile (Table 2.2), which we discuss below.

Table 2-2: Smart grid research studies that focus on influencing the energy profile of users using energy demand and supply shaping

Research Study	Description	Adaptation to develop prosumer community groups
(Ibars, Navarro et al. 2010)	Distributed load management scheme for the smart grid, which is based on the capacity of users to manage their own demand in order to minimize a cost function or price	Similar load management and scheduling algorithm may be further developed to attain effective demand response in community-based energy sharing network These approaches consider the individual prosumer/consumer behaviours; however, if applied to the PCG development, the approaches to be adapted to address the challenges of group behaviours, as well as the PCG characteristics and goals The key aspects of managing prosumers are not addressed
(Pedrasa, Spooner et al. 2010)	Present a coordinated scheduling algorithm to a decision support tool for residential consumers/prosumers that enable them to optimize their acquisition of electrical energy services	
(Bakker, Bosman et al. 2010)	A control algorithms that predicts the consumption and generation profiles of appliances, and use these to achieve goals such as peak shaving and determine optimal times those appliance to be switched on/off, how much energy flow required, etc.	
(Neely, Tehrani et al. 2010)	Efficient algorithms for renewable energy allocation to delay tolerant consumers. This algorithm does not require knowledge of prior statistical information	
(Lagorse, Simoes et al. 2008)	Distributed energy management system using multi-agent systems with bottom-up approach to achieve reliability and simplicity in the energy management	
(Yu, Gatsis et al. 2013)	A power scheduling approach for an energy trading renewable DER-connected micro-grid in order to achieve optimal demand supply balance and low cost	The similar electrical infrastructure of VPP can be used for the electrical infrastructure of prosumer community groups (although it is not mandatory to provide a dedicated electrical grid among the prosumer community group members)
(Block, Neumann et al. 2008)	Market mechanism to facilitate the distributed energy resources (prosumers) and consumers to negotiate and allocate their energy demand and supply	
(Gosh S et al. 2010)	Development of a rebate plan to realize the load reduction responses of diverse customers.	The similar incentive allocation scheme might be used to distribute incentives among the members within the prosumer community group. However, there are many other aspects of managing prosumers in addition to incentive distribution that are not addressed
(Caron and Kesidis 2010)	Dynamic pricing scheme incentivizing consumers to achieve an ideal flat profile	

For instance, a distributed load management scheme to control the power demand at peak hours using dynamic pricing strategies has been proposed by Ibars et al. (Ibars, Navarro et al. 2010). This scheme is developed based on a network congestion game, where the end customers are players, the distribution of the demand across the day is the set of strategies and the cost function is the players' objective in reducing the price of energy, simultaneously considering their preferences. This approach has been evaluated for managing the demand and the grid load in order to demonstrate the load control and the reduction of the signalling burden over the SG network.

Alternatively, Pedrasa et al. (Pedrasa, Spooner et al. 2010) presented a coordinated scheduling algorithm for the energy decision support tool that assists households in making more intelligent decisions when acquiring electrical energy services and operating their power devices. The scheduling algorithm has claimed to enhance the net advantage that the end user gains, where the net advantage was defined as the difference between the total energy service benefit and the costs of energy provision.

On the other hand, a three-step control algorithm to restructure the energy demand profiles of a large group of buildings has been proposed by Bakker et al. (Bakker, Bosman et al. 2010). The first step involves predicting the consumption and generation profiles for all the appliances for the upcoming day, the second step involves usage of these profiles to reach a global objective such as peak shaving, compensating the domestic energy generation with the energy demand, and the third step suggests a real-time control algorithm which determines the optimal times the appliances and generators to be switched on/off, how much energy flows are required, etc.

By contrast, an algorithm to allocate renewable energy resources to fulfil the demand of delay tolerant consumers has been developed by Neely et al. (Neely, Tehrani et al. 2010) . Here, the energy allocation algorithm does not require knowledge of prior statistical information. This algorithm aims to minimize the time-average cost of drawing renewable energy from DERs (prosumers) if the main utility grid fails to serve the required energy demand of consumers within the specified delay window. Moreover, the proposed algorithm facilitates the prosumers (renewable DERs) to dynamically set a price for its service, while maximizing the resultant time average profit. These issues have been solved using the Lyapunov optimization technique.

Going a step further, Lagrose et al. (Lagrose et al 2009) present an application of multi-agent systems to manage the energy generation and storage in a hybrid system connected to the grid. The authors have used the "bottom-up" approach for a more simplified decentralized management solution, instead of the "top–down" approach. This study has illustrated the possibility of developing a system with direct current (DC) bus voltage, which is not controlled by the same element as the concept of dialogue and cooperation among the agents, making the system more reliable. The "bottom-up" approach simplifies the energy management system that enables the designer to look in detail at the problem of each element and manage a single element without confronting with the entire problem. A simulation model has been presented to verify the proposed energy management system.

Accordingly, when applied to the PCGs, similar scheduling algorithms for improving energy consumption/generation profiles of prosumers might be used to assist PCGs to attain optimal supply–demand balance in community-based energy sharing network; however, this requires a major revision. For instance, following the concepts of Pedrasa et al. (Pedrasa, Spooner et al. 2010), the PCGs can optimize their acquisition of electrical energy services; the aspects of Ibars et al. (Ibars, Navarro et al. 2010) might assist to develop a network congestion game considering prosumer or PCGs as players and using relevant set of strategies and a cost function, and the three-step control algorithm proposed by Bakker et al. (Bakker, Bosman et al. 2010) may be further developed to forecast the behaviours of PCGs.

However, the key deficiency of aforementioned research works is that they only consider the individual energy user (consumer/prosumer) behaviour and interactions with other energy market participants. When applied to the PCGs, it is necessary to analyse the individual behaviours of the members of the PCG as well as the PCG behaviours and interactions as a whole.

In addition to the above research contributions that focus on the individual energy users, some research works focus on group of energy prosumers who are connected to each other in the form of VPP or micro-grid.

For instance, Yu et al. (Yu, Gatsis et al. 2013) present a scheduling algorithm for the renewable energy sources-embedded micro-grid to achieve favourable energy management for both demand and supply and to reduce the net cost associated with the micro-grid. The energy management models have been developed for both DERs and adjustable loads to resolve the supply–demand imbalance that can be caused by the unpredictability in renewable energy sources. The power scheduling is done in a distributed fashion, where the original problem was broken into smaller subproblems using a dual-decomposition technique and solved by local controllers of loads, DERs and conventional generators.

Moreover, Block et al. (Block, Neumann et al. 2008), in their demand and supply balance framework for micro-grid, develop a framework that provides a combined heat and power micro energy grids (CHPMEG), which is loosely coupled to the main utility grid, where the energy consumers and prosumers match their demands and distributed resources on local marketplaces. This research work has been carried out as a part of the Self-organization and Spontaneity in Liberalized and Harmonized Markets (SESAM) project.

Overall, one of the key deficiencies found in the aforesaid research efforts is the lack of concentration in the managing prosumers. Generally, there are considerable numbers of management functions that are applicable to energy users (consumers or prosumers). Some of the many such functions are effective incentive distribution, effective communication/negotiation schemes, risk management schemes, user motivation, conflict resolution, etc.

Accordingly, it is noticeable that the existing literature has shown very little attention in addressing the management aspects of energy user; however, there are few research efforts particularly focusing on incentive management. The incentive management is involved in offering benefits to the energy users who achieve specific goals. For instance, incentives are provided to the energy consumers for reducing their energy demand or limiting their energy usage in peak hours.

For instance, Gosh et al. (Ghosh, Kalagnanam et al. 2010) develop an incentive mechanism that offers the energy customers customized, time-varying incentives at distribution and feeder network levels based on their power demand reduction capability, rather than simply shifting their consumption from peak time to off-peak periods. The authors formulate their rebate scheme for a single period, which segments the customers based on their willingness to reduce the energy demand, and for a multi-period, which observe the customers who endeavour to decrease their accumulated energy demand over a period of time. In fact, the customers willing to reduce their demand receive higher incentives than the rest. In addition, in order to attain incentive compensation for load reduction, this framework develops the concept of energy purchases by customers to cover any remaining shortfall.

Moreover, Caron et al. (Caron and Kesidis 2010) also propose a scheme for incentivizing consumers, while allowing them to achieve optimal flat load profiles depending on how much information they share. This scheme is based on the distributed algorithm, which set up as a cooperative game between consumers, which significantly reduces the total cost and peak-to-average ratio (PAR) of the system, when customers can share all their load profiles. In the absence of full information sharing due to privacy issues, this scheme provides distributed stochastic strategies that successfully exploit the limited information on the grid such as instantaneous total load and enable the users to improve the overall load profile.

As a whole, it is duly noted that existing works on influencing energy profiles of users through energy demand and supply shaping require major revision if applied to the PCGs, and particularly should be adapted to improve the group energy behaviours in addition to individual user behaviour. Moreover, the aforementioned literature lacks the aspects of managing the energy users, particularly the prosumers.

2.3.2 Approaches that influence the energy sharing profile of users using energy price optimization

In this section, we discuss influencing the energy behaviours of users by energy price optimization, which provides the users favourable prices for the energy they buy or sell in the energy market. Here, we first provide an overview of energy price optimization.

In the generic energy market, the product traded is energy (kWh) instead of power (kW), which takes place over regular intervals of time. Depending on the availability, demand and price of energy, the energy is bought from or sold to the energy network. The price for selling energy and the price for buying energy is listed in the energy market and the prosumers adjust their set points after negotiation with the other units based on the prices, their operational cost and local demands.

The typical procedure of energy trading is illustrated as follows: the utility provider announces the prices for selling or buying energy. Consequently, the consumers (residential/industrial/commercial) announce their demand, where each consumer has a set of low-priority and high-priority loads. The consumers send separate bids corresponding to each set of low-priority and high-priority loads, where high-priority loads are served irrespective of energy prices and the low-priority loads are served at comparatively lower energy prices. The bids of energy sellers are calculated for a defined regular interval considering the energy prices in the open market, the generating unit operating cost and the hourly payback amount for the investment (Richter and Sheble 1998; Tiansong, Goudarzi et al. 2012). The prosumers and consumers negotiate for a specific time to receive optimal pricing for energy trading, thus maximizing their profits. The price optimization generally depends on the market policy adopted. Moreover, if the consumer bids are lower than the buying price suggested by the grid, the prosumers start selling power to the main utility grid.

However, the key objective of the energy price optimization is the minimization of operational cost, where both prosumers and consumers can share the benefits of reduced operational costs when negotiating among the bids (Richter and Sheble 1998; Tiansong, Goudarzi et al. 2012).

Tables 2.3 and Table 2.4, respectively, provide a brief overview of the commercial SG projects and research works that focus mainly on energy prize optimization and their adaptation to develop PCGs.

First, we look at the literature on SG commercial projects (Table 2.3).

For instance, the Nobel project (2006)provides a market-driven approach to SGs, which develops a service-oriented framework for monitoring and the brokerage system, IPv6 software layer for communication and middleware for data capturing and processing on an SG. Using the proposed energy brokerage system, the consumers could interconnect with both large-scale and small-scale energy producers (prosumers) to communicate their energy requirements directly, thus making energy utilization more efficient. This project was evaluated at a dedicated test site in the town of Alginet (Valencia, Spain). The main advantage of this project was to address the issue of energy optimization in large infrastructures for public use and domestic neighbourhoods, and thus enhance energy efficiency in smart cities. When we apply this project to develop PCGs, the ICT infrastructure that characterizes the energy brokerage system can be adapted and further developed to interchange schedules between participating PCGs and prosumer community coordinator and to maximize the resulting savings.

Table 2-3:Smart-grid commercial projects that focus on influencing the energy profile of users through prize optimization

SG project	Concepts	Adaptation to prosumer community group development
NOBEL Project (2006)	**Objectives**: Energy brokerage system, customized applications at the end-user side **Approach** : Service-oriented framework for monitoring and the brokerage system, IPv6 software layer for communication, middleware for data capturing and processing on a smart grid	The ICT infrastructure that characterizes energy brokerage system can be adapted and further developed to interchange schedules between participating PCGs and prosumer community coordinator and to maximize the resulting savings However, the aspects of managing prosumers are not addressed
S-TEN Project(2006)	**Objectives** : Demand-side bidding techniques **Approach**: Internet-based communications infrastructure, ontologies to publish the information and measurements on the Web and rules for automated network management	Similar demand-side bidding technique which is developed for individual prosumers may be modified and applied for PCG energy sharing that facilitates the PCGs to bid for the accumulated energy units with major revision However, the aspects of managing prosumers are not addressed
EcoGrid (Capodieci, Pagani et al. 2011)	**Objectives** : Energy demand management and market strategy, real-time market concept that presents balancing mechanisms through real time price response **Approach**: ICT platform for real-time markets. prototype solution that would lead to market-driven smart grids	Similar ICT platform can be adapted and further developed for real-time market interaction in PCGs; however, this requires major revision However, the aspects of managing prosumers are not addressed
EU-DEEP (Gehain and Deuse 2005)	**Objectives**: Technical and economic solutions for sustainable DER expansion, promote the interaction among residential, commercial and industrial customers and the market **Approach**: Market assessment methodology, regulatory frameworks, trading mechanisms	A comparable market assessment methodology can be further modified to determine decides on the local trading strategies and grid-market integration appropriate for PCGs
SESAM (2009)	**Objectives**: Electronic energy market platform, security of electricity systems **Approach**: A prototype Decision Support System (DSS) to detect vulnerabilities of the grid, estimate the impact of real or simulated network failures, determine the possible countermeasures and suggest prevention techniques, and a regulatory framework.	A similar Decision Support System (DSS) can be used to improve the security of the community-based energy sharing network with major revision However, the aspects of managing prosumers are not addressed

Going a step further, the S-Ten Project(2006) facilitates a demand-side bidding technique to enable the individual prosumers to adjust their position in market bids and encourage participation of even those prosumers who can supply only small amounts of energy to the grid. It uses semantic web technologies to manage continuously changing self-describing devices such as renewable sources and smart devices, ontology to publish the information and measurements on the Web and rules for automated network management. When we attempt to apply the concepts of this project to develop PCGs, the similar demand-side bidding technique which is developed for individual prosumers may be modified and applied for PCG energy sharing that facilitates the PCGs to bid for the accumulated energy units.

The basic idea of the European initiative, named EcoGrid EU (2011), is to develop market-based techniques close to the power system operation, in order to introduce balancing mechanisms through real-time price response. It proposed an ICT platform for real-time markets that would transmit price signals to the market participants and install automatic end-user smart controllers for DERs (prosumers) as well as smart meters to manage “real-time” price signals. The ultimate task of the project was to make a prototype solution for Europe that would lead to market-driven SGs in Europe. When applied to develop PCGs, a similar ICT platform can be adapted and further developed for real-time market interaction in PCGs.

On the other hand, the European Distributed Energy Partnership (EU-DEEP) project (Gehain and Deuse 2005) has begun a large-scale implementation of DERs in Europe. It has developed a market assessment methodology that determines the demand for DER technologies and decides on the local trading strategies and grid-market integration. This project considers three types of DER technologies – intermittent renewable energy sources, combined heat and power and flexible demand – and determines the links connecting the residential, commercial and industrial customers and the market. Technical and economic solutions have been incorporated in the existing energy system, in order to shape a sustainable DER expansion. When adapted to develop PCGs, a comparable market assessment methodology can be further modified to determine the local trading strategies and grid-market integration appropriate for PCGs.

Similarly, SESAM project (2009) implements an electronic energy market platform. It presents mechanisms for secure communication between the market participants, uses electronic trading agents and an electronic law mediator who supervises the electronic contract making on the platform. In addition, a prototype Decision Support System (DSS) is present to detect vulnerabilities of the grid, estimate the impact of real or simulated network failures, determine the possible countermeasures and suggest prevention techniques and a comprehensive regulatory framework. When applied to PCGs, a similar DSS can be used to improve the security of the community-based energy sharing network.

In addition to the aforesaid commercial SG projects, there are several research contributions in this area (Table 2.4).

For instance, Roozbehani et al. (Roozbehani, Dahleh et al. 2010) argue that direct utilization of wholesale market's prices to the energy users can cause an unstable closed loop system, thus proposes a mathematical model for real-time retail electricity pricing for SGs. Here, the customers (consumers) are considered as autonomous agents who alter their energy usage with respect to the changes in price signals to maximize their utility function, assuming supply follows demand precisely. Simulations results are presented to verify their findings and to show the stabilizing effect and the efficiency of the model.

Additionally, Hatami and Pedram (Hatami and Pedram 2010) propose a "quasi-dynamic pricing" energy pricing method that meets the energy needs of cooperative networked consumers while minimizing their electrical energy bill. Here, the user requests are scheduled for energy consuming device usage at different times during a fixed interval based on the dynamic energy prices during that interval. Two different methods have been utilized for non-interruptible or interruptible tasks to optimize the energy cost. These methods use a quasi-dynamic pricing function to determine the unit of energy consumed that is obtained combining the base price and a penalty term. This method claims not only to minimize the energy cost of the consumers but also to meet the scheduling constraints.

Thomas and Ashok (Thomas, Ashok et al. 2011), on the other hand, propose a uniform pricing scheme for renewable energy generation to determine energy prices, which can be used by power-producing companies, independent power producers such as domestic prosumers and regulatory commissions. The proposed model considers the cost components that depend on the power system performance (such as power quality and reliability issues) and the economic aspects such as capital cost, depreciation, operation and maintenance expenses, taxes, etc. In addition, it incorporates penalties for variations from scheduled energy, a new customer-based reliability index and Clean Development Mechanism (CDM) benefit. The authors claim that this model can be used to ascertain the energy price of different categories of grid-connected or stand-alone generators in any part of the world. This model has been applied and tested to ascertain the electricity price in a 25-MW-powered Hyde energy generator operating in the state of Karnataka, India.

Ramachandran et al. (Ramachandran, Srivastava et al. 2010) propose a risk-based auction strategy for market operation of DERs in an SG using multi-agent systems combined with a hybrid optimization algorithm. This auction process is involved in profit-maximizing adaptive bidding strategy that is based on the risk and competitive equilibrium price forecasting. Here, the prosumer bids are determined considering the minimization of fuel cost; therefore, energy amount offered by the prosumer in the energy market is static before the auctions. The pricing of the energy fluctuates based on the trader attitude (such as risk seeking, risk averse or risk neutral). Thus, the prosumer determines the asking price for the DER based on the minimum fuel cost. The auctioneer manages the utilization of DERs by receiving bids from energy buyers (consumers) and asks from sellers. Consumers are facilitated to choose reduced energy prices during off-load conditions in exchange for shedding their low-priority loads at peak load conditions. The risk-based auction strategy in multi-agent systems enables the agent to assess the risk associated with a bid.

Table 2-4:Smart-grid research studies that focus on influencing the energy profile of users through prize optimization

Literature	Description	Adaptation to develop prosumer community groups
(Roozbehani, Dahleh et al. 2010)	A stabilizing pricing algorithm instead of direct utilization of wholesale market's prices	Similar pricing models can be applied to achieve optimal pricing for energy trading between the PCGs and the external energy buyers; however, this requires major revision to address the PCG characteristics and goals Moreover, the concepts of managing prosumers are not addressed
(Hatami and Pedram 2010)	A "quasi-dynamic pricing" energy pricing method that meets energy needs of cooperative networked consumers while minimizing their electrical energy bill	
(Thomas, Ashok et al. 2011)	A generalized pricing model for determining energy price for renewable energy produced by power companies, distributed producers, regulatory commissions etc.	
(Ramachandran, Srivastava et al. 2010)	A risk-based auction strategy for market operation of a distributed energy resources in a smart grid using multi-agent systems combined with a hybrid optimization algorithm	
(Capodieci, Pagani et al. 2011)	An agent-oriented domestic energy trading modelling for the domestic energy market, whereby the individual prosumers interact with the utility companies and the energy consumers (energy buyers) to achieve their independent goals	The agent-oriented platform might be used with major revision to model prosumer community group interaction with utility grid The similar electrical infrastructure of VPP can be used for the electrical infrastructure of PCGs (although it is not mandatory to provide a dedicated electrical grid among the prosumer community group members) However, most concepts of managing prosumers are not addressed .
(Dimeas and Hatziargyriou 2007)	Multi-agent system technology to enhance the operation of the VPP system	
(Lamparter, Becher et al. 2010)	Highly flexible market platform for coordinating self-interested energy agents representing power suppliers, customers and prosumers. Agent-based structure, market mechanism, local negotiation strategies	
(Block, Neumann et al. 2008)	Market mechanism to facilitate the distributed energy resources (prosumers) and consumers to negotiate and allocate their energy demand and supply in micro-grid	
(Chalkiadakis, Robu et al. 2011)	Development of pricing mechanism, incentive payment technique and uncertainty quantifying tool	

Furthermore, the research by Capodieci and Paganin (Capodieci, Pagani et al. 2011) provides an agent-oriented domestic energy trading modelling for the domestic energy market, whereby the individual prosumers interact with the utility companies and the energy consumers (energy buyers) to achieve their independent goals.

Going a step further, Lamparter et al. (Lamparter, Becher et al. 2010) develop an agent-driven approach for the energy market. A bidding strategy that is governed by local policies was developed, whereby the agent controls the user preferences or constraints of the devices. In addition, efficient coordination among the agents is realized through a market mechanism.

The key deficiency of the aforementioned research works is that they only consider the individual energy user (consumer/prosumer) interactions with other energy market participants. When applied to the PCGs, it is necessary to analyse the individual behaviours of the members of the PCG as well as the PCG behaviours as a whole. A similar agent-oriented platform might be revised and further developed to model PCG interaction with other energy market participants. Moreover, the issues related to the managing prosumers such as incentive distribution schemes, effective communication/negotiation schemes, risk management schemes, user motivation schemes, conflict resolution schemes, etc. are not comprehensively addressed by those research studies.

On the other hand, there are several research studies that aggregate the prosumers in the form of VPPs and micro-grids in the context of energy price optimization. For instance, the decentralized VPP architectures have been investigated in several prior works, like that of Chalkiadakis et al. (Chalkiadakis, Robu et al. 2011), that use the cooperative game theory approach to form the VPP, known as "Cooperative VPP." This framework has enabled even the smallest prosumers to autonomously perform certain communication and decision-making tasks. This project has also developed an energy pricing mechanism to ensure that the competitive rates are allowed in the procurement of Cooperative VPP energy, and also a payment scheme to distribute payments within the cooperative to guarantee that no subgroup has sufficient incentives to establish a new Cooperative VPP.

In the same way, Dimeas (Dimeas and Hatziargyriou 2007) has proposed the use of multi-agent system technology to enhance the operation of the VPP system. As the agents can act independently without the involvement of a central controller, the agent-integrated VPPs can communicate with the power market and also negotiate with other agents that control the micro-sources.

Alternatively, Block et al. (Block, Neumann et al. 2008) in their demand and supply balance framework for micro-grids analyse the varying requirements of the prosumers and customers and accordingly decide the favourable pricing using a combinatorial double auction mechanism. In addition, the authors also introduce an emergency failover procedure to ensure the stability of the micro energy grid, even if the auction mechanism malfunctions.

When applied to the PCGs, the similar electrical infrastructure of VPP can be used for the electrical infrastructure of PCGs (although it is not mandatory to provide a dedicated electrical grid among the PCG members). However, some issues related to the managing prosumers in the VPPs and micro-grids, as well as managing the interactions between VPP/micro-grid and utility grid or other energy buyers, are not comprehensively addressed.

As a whole, Tables 2.1, 2.2, 2.3 and 2.4 show a summarized classification of the existing projects and research works and their adaptation to implement PCGs. In the next section, we comprehensively discuss the shortcomings of existing works on SG commercial projects and research studies, when applied to the managing prosumers in PCGs.

2.3.3 Shortcomings of existing literature on SG when applied to the managing prosumers in the form of PCGs

- **Existing VPPs and micro-grids cannot be directly adapted to form PCGs**

  In most of the existing SG projects, the prosumers individually sell energy, thus no accumulated energy selling, which is a fundamental aspect in PCGs. Moreover, there are several projects that address the issues of VPP and micro-grid, where the prosumers are interconnected under a technically connected infrastructure; however, none has comprehensively addressed the virtual connection among the prosumers in the form of PCGs.

- **Existing approaches do not address inherent features of PCGs**

  The similar demand and supply management schemes, as well as the marketing and pricing mechanisms that are discussed in the existing SG projects, might be applied for PCGs with major revision. For instance, the existing energy pricing stabilization techniques that facilitate prosumers in VPP/micro-grids to optimally trade its energy might be adaptable for PCGs to trade energy in the energy market; however, this is to be revised based on PCG characteristics and goals. None of the existing works addresses the fundamental characteristics of PCGs such as segmenting prosumers having relatively similar energy sharing behaviours and making those groups goal oriented, etc. Therefore, existing schemes require major revision if applied to PCGs.

- **The existing energy user-focused literature does not address several key processes with regard to managing prosumers (such as prosumer motivation, prosumer risk assessment, prosumer evaluation, etc.)**

  The similar ICT architectures (such as service-oriented frameworks, software models and security approaches) that provide different services to the energy sharing prosumers can be adopted and further developed towards facilitating comparable services to the PCGs in the SG. However, the literature has focused on very few aspects of managing energy users that are possibly adaptable to manage prosumers in the form of PCGs. For example Chalkiadakiset et al. (2008) have developed financial incentive distribution techniques for the participants as a return for their commitment, which may possibly be adaptable to PCGs. However, some key aspects of managing prosumers such as prosumer motivation schemes to inspire the prosumers to share more energy, and risk assessment techniques to assess the prosumers' favourable or unfavourable energy sharing behaviours, are heavily overlooked in the existing literature.

- **Existing literature that influence the energy behaviours of users do not comprehensively address the group energy generation behaviour, which is necessary in PCGs**

  Most of the existing research on energy profile shaping has focused on restructuring the distributed energy generation of individual energy users and achieving personalized energy management that is possibly adaptable to individual prosumers within PCGs. However, influencing the behaviours of energy generation of energy user groups is not comprehensively addressed.

- **Limited approaches to address the energy pricing techniques that enable energy user groups to sell/buy energy, which might be adaptable for PCGs**

  Most of the existing research on energy price optimization has addressed the energy pricing and market mechanisms that are developed for single energy user energy trading. However, there are very few researches that facilitate group energy trading; for instance, Chalkiadakis et al. (Chalkiadakis, Robu et al. 2011) have provided an energy pricing mechanism for the prosumers connected to a VPP. Such mechanisms are possible to adapt to build energy pricing mechanisms for PCG energy trading; however, this is to be revised based on PCG behaviours.

Overall, electrical, ICT and marketing platforms that are discussed in existing SG projects are adaptable for PCGs with relevant revisions. However, the socio-technical aspects of managing prosumers, such as profiling prosumers' energy behaviours, prosumer motivation to promote their energy sharing performance or to encourage them to join VPP/micro-grid, incentive distribution and risk assessment have been heavily overlooked in existing SG projects and research studies.

Although the approaches for managing prosumers that can be applied to manage PCGs are lacking in existing SG projects, still one can argue that some aspects related to managing prosumers in PCGs have been implemented in other contexts (e.g. online social network communities); thus, those approaches are adaptable to address the challenges of PCGs. Therefore, in the next section, we study about the adaptability of such management approaches, particularly the methods used in online virtual communities (social network virtual communities) towards the managing PCGs.

2.4 Adaptation of Existing Literature on Online Virtual Communities to Manage PCGs

In this section, we explain the existing literature on online virtual communities and the adaptation of the aspects of online virtual communities to develop PCGs. Table 2.5 briefly discusses the adaptation of the approaches used in the existing research studies on online virtual communities to address the aspects of managing PCGs.

First, we provide a brief overview on the literature on virtual communities. In the literature, the term "virtual community" is defined as a network of individuals who interact through an electronic media, potentially crossing geographical and political boundaries in order to pursue mutual interests or goals (Wren 2006). In literature, the virtual communities have been extensively utilized in diverse areas such as health care, education, peer-to-peer services and more prominently in social network/blog space communities (Armstrong and Hagel III 1996; Ishaya and Mundy 2004; Porter 2004).

In the digital domain, online virtual communities are becoming increasingly prominent due to the growth of social networking sites such as Facebook, MySpace and LiveJournal. There are many benefits of implementing online virtual communities; some of them include encouraging knowledge and idea sharing (Ardichvili 2008), social interaction and advertising products and services (Kosonen and Ellonen 2007). In most scenarios, online virtual communities are informal in nature, and the relationships among the members are established through the involvement of a community administrator. In general, the behaviours of the online virtual community members determine the sustainable existence of the online virtual community, in which the members comply with the norms and procedures, which are determined by the community administrator (Fachrunnisa and Hussain 2013).

Table 2-5: Application of the approaches used by existing online virtual communities in managing prosumer community groups

Literature on online virtual communities	Key focus	Drawbacks when applied to prosumer community group management
(Iriberri and Leroy 2009)	Identify success factors for each stage of the life cycle for a virtual community: inception, creation, growth, maturity and death	Similar success factors can be determined for prosumer community groups. For example, in the success factor “recognition of contribution” of online virtual community, the context of contribution is “online events,” but this is to be changed to “energy generation and sharing capacity” when applied to prosumer community groups. Moreover, this online virtual community research does not provide any frameworks to validate the identified success factors
(Porra and Parks 2006)	Propose a model to address the sustainability issues of online virtual communities, where this model decides the sustainability of online virtual community based on the humanness, the ability to acquire new members and adapt to radical change	A major revision is required for the proposed model if applied to prosumer community groups. For example, the factors that decide the online virtual community sustainability to be altered to make them applicable to prosumer community groups. For instance, the amount of energy the prosumers prefer to share, adapt to adverse climate changes in renewable energy generation, performance of energy sources, etc. to be used to access the sustainability of prosumer community groups
(Ostrom 1990)	Provides a case study of Usenet groups to claim that the low signal-to-noise ratio (a low number of non-active members) in the online virtual community contributes to the sustainability of online virtual community	The non-active members might be analogous to the number of prosumers who breach the initial contract made with the prosumer community group coordinator by offering lower amount of energy than agreed. However, this online virtual community research does not provide comprehensive frameworks to determine the active and non-active members in online virtual community
(Prasarnphanich and Wagner 2009)	Highlights the key factors that sustain the Wikipedia community; some of those factors are the collaboration between authors and readers to create a valuable resource, the contributions from community members and their commitment to improve content quantity	The factors that decide the Wikipedia community sustainability are completely different from those of prosumer community groups. For instance, the amount of energy the prosumers prefer to share, adapt to climate changes, performance of energy sources, etc. to be used to access the sustainability of prosumer community groups

Table 2.5: Continued. Application of the approaches used by existing online virtual communities in managing prosumer community groups

Literature on online virtual communities	Key focus	Drawbacks when applied to prosumer community group management
(Backstrom, Huttenlocher et al. 2006)	Determines the structural features that influence community formation in large social networks (two key features are number of friends a member has within the community and the way these friends are connected to one another)	The features such as the feed-in tariff, other incentives and mutual energy goals will be more prominent factors applicable to prosumer community group formation than the features identified in this social network community research. However, the number of friends a member has within the community group and the way these friends are connected to one another, which are highlighted in this research, may also contribute slightly in prosumer community group formation
(D'ez, Coz et al. 2008)	Algorithm to build groups of people with closely related tastes using clustering techniques	Similar clustering algorithms can be adapted and further developed to form prosumer community groups with similar energy sharing behaviours
(Wagner, Liu et al. 2009)	Suggests the growth rate of online virtual community is influenced not only by the size of readership but also by the sustained contribution from other users, and members' renewal over a certain period of time	The growth rate of prosumer community groups can also be influenced by the similar factors that of generic online virtual community; however, to be analysed based on the energy as the target focus area
(Fachrunnisa and Hussain 2013)	Suggests methodology for maintaining trust in industrial digital ecosystems and multimedia virtual communities. It proposes the use of a third-party agent, an iterative negotiation process, proactive performance monitoring and intelligence metrics recalibration of the trust level	Similar methodologies (such as use of a third-party agent analogous to prosumer community group coordinator, an iterative negotiation process, proactive performance monitoring and intelligence metrics recalibration) can be adapted and further developed for maintaining trust in prosumer community groups

The emergence and existence of online virtual communities have been investigated in several research studies. For instance, Iriberri and Lorey (Iriberri and Leroy 2009) propose a life cycle for a virtual community that follows the five stages, namely inception, creation, growth, maturity and death. The authors identify success factors for each stage; for instance, factors such as regular online events, increased user tools, permeated management and control, recognition of contributions and member satisfaction management are contributed to the mature stage. Similarly, Wegner et al. (Wegner, McDermott et al. 2002) also identify five stages in establishing online communities: potential, coalescing, maturing, stewardship and transformation, whereas Andrews (Andrews 2001.) suggests three stages of community life cycle: starting the online community, encouraging early online interaction and moving to a self-sustained interactive environment (Fachrunnisa and Hussain 2013).

On the other hand, Leimester, Sidiras and Krcmar (Leimester, Sidiras et al. 2006) have analysed the factors necessary to develop successful online virtual communities. The design of the technical platform, which has the ability to manage the virtual community, while handling membership data securely, is considered as one of the most important success factors for a virtual community. Further, the quality of information shared in a virtual community, participation and the existence of subgroups and real-life events are also considered as additional factors that ensure the success of the virtual communities.

On the other hand, several studies explore achieving the sustainability of the online virtual communities in particular. For example, Porra and Parks (Porra and Parks 2006) introduce the virtual community sustainability as an intrinsic longevity over a very long time period and propose a model to address the sustainability issues. This model decides the sustainability of a virtual community based on the humanness, the ability to acquire new members and adapt to radical change. Furthermore, Ostrom (Ostrom 1990) suggests that a virtual community can be sustained if it has low signal-to-noise ratios, using a case study of Usenet groups. Here, a low noise ratio refers to a low number of non-active members in the community. Similarly, Prasarnphanic and Wagner (Prasarnphanich and Wagner 2009) highlight the key factors that are required to sustain the Wikipedia community compared to other Wiki-based information community. Some of those factors are the collaboration between authors and readers to create a valuable resource, the contributions from community members and their commitment to improving content quantity.

Alternatively, some researchers focus on selected tasks and challenges, which a virtual community deals with. The most prominent challenge addressed by existing works is the online virtual community formation. For example, the structural features that influence community formation in large social networks have been determined by Backstrom et al. (Backstrom, Huttenlocher et al. 2006), where some of such features are the number of friends a member has within the community and the way these friends are connected to one another. Moreover, Dı´ez et al. (D'ez, Coz et al. 2008) have presented a new algorithm to build groups of people with closely related tastes using clustering techniques, while Lai and Turban (Lai and Turban 2008) describe how online groups, especially social networks, are formed and operated in the Web 2.0 environment using its tools, applications and characteristics. It also describes various types of online groups, and how these groups, especially social networks, operate in the Web 2.0 environment. Going one step further, Yang and Stephen (Yang and Stephen. 2006) discuss how geographically dispersed learners and providers of knowledge are formed into online virtual learning communities, and how they accomplish the mutual goal of collaborative learning, as well as their individual goals of learning.

Additionally, the growth of virtual communities has been analysed by Wagner et al. (Wagner, Liu et al. 2009), who convey that the growth rate of certain communities like Wikipedia is influenced not only by the size of readership but also by the sustained contribution from other users which provides feedback. Moreover, the authors define the sustainability as a manifestation of the growth rate and members' renewal over a certain period. Moreover, the evaluation of reliability and efficiency of virtual environments has been discussed by Noorian and Ulieru (Noorian and Ulieru 2010), who argue that the virtual community might require the dynamicity and fuzziness qualities of the real world to evaluate the reliability and efficiency.

From the above discussion, it is noticeable that the key focus of the existing literature is a state-of-the-art discussion on achieving a successful virtual community. The primary shortcoming of most of the existing body of literature is that they all provide a comprehensive knowledge of different aspects of online virtual communities, rather than proposing effective methodologies for addressing the challenges associated with those aspects. Additionally, the application of existing community-based approaches in other contexts such as online communities to develop PCGs is difficult due to the complex characteristics of PCGs. In fact, the differences between the PCGs and existing virtual community groups in other contexts make it hard to adopt the existing community-based approaches to PCGs without major revision. In the next section, we further analyse these differences between the PCGs and the online virtual communities, when adapting those existing approaches into PCGs.

2.4.1 Shortcomings of existing literature on online virtual communities when applied to the managing prosumers in the form of PCGs

As discussed above, the complex characteristics of PCGs make it difficult to completely adapt the approaches used in other contexts to develop PCGs. Additionally, the integration of all these services in other contexts has to be accomplished with energy as the target focus area. In this section, we identify several challenges of PCGs that prevent direct adaptation of the community-based approaches in other contexts to address the challenges of PCGs:

- **User restrictions**: In contrast to any Internet user subscription method of joining most of the online communities, the membership of a PCG is limited only to the prosumers having DERs.
- **Difficulty in obtaining inputs from prosumers:** Unlike the simple user inputs such as unique identifier, email address and basic preference information in online communities, a vast number of input parameters are to be captured from prosumers, before assigning them to a particular PCG. Prosumer inputs are obtained either explicitly by directly contacting potential prosumers or implicitly by observing the smart meters in the long term. Some of the many input parameters include average daily power generation and consumption, capacity of smart storage, expected power variation due to the future plans, seasonal power variation (green power variation due to

climate change), prosumer's preferred quantity of energy for future consumption and prosumer's preferred quantity of energy for sharing, etc.

- **Long and complicated process of PCG formation:** Forming PCGs should perform critical evaluation of prosumers' profiles to analyse several influencing factors such as long-term and short-term energy sharing behaviours, government jurisdiction, categories of renewable energy infrastructures, weather forecasts, competitive power market, pricing policies, etc., and systematically segment them to achieve PCGs. Most existing approaches do not evaluate the individuals before assigning the membership; rather they allow any person who shows interest in joining the community. Systematic segmentation of individuals to group the individuals having similar behaviours is absent from most existing online community approaches. In addition, the prospective prosumers' energy profiles should follow the PCG's pre-qualification criteria in order to obtain the membership. Therefore, the subscription to a prosumer community can be a long and complicated process that involves interactions between different authorized agents. However, the research work by Dı´ez et al. (D'ez, Coz et al. 2008) presents an algorithm to build groups of people with closely related tastes using clustering techniques. Such works can be adapted to some degree and further developed to the form PCGs having prosumers with similar energy behaviours.
- **Incentive-based prosumer motivation:** The users in most online communities do not receive tariff for their contributions; thus, the motivational schemes to attract new members are not related to financial enticement. However, the prosumers' motivations behind green energy generation are entirely incentive related, which is mostly financial incentives. Therefore, any motivational schemes to grow or sustain PCGs should be incentive oriented.
- **Prosumers' membership deactivation followed by financial loss**: Unlike the straightforward deactivation for the users in online communities, the member deactivation in PCGs may cause incentive losses to all the members of the PCG and thus should be urgently replaced by a

prosumer having approximately similar behaviours. Therefore, the penalties may be enforced to that member considering the financial loss that could be incurred by other members due to the deactivation of that member.

- **Goal-oriented nature in PCGs:** Most of the existing community groups in the other contexts do not have well-defined mutual goals; thus, the individuals work for their own benefits. However, having a well-defined goal is a crucial requirement for goal-oriented PCGs to attain the energy demand of external energy buyers and thus to achieve long-term sustainability.
- **Some challenges of PCGs have been overlooked in other contexts**: Most existing community-based approaches in different contexts do not comprehensively address some of the fundamental challenges faced by PCGs such as member contribution assessment and ranking, member evaluation, etc.

2.5 Design Requirements of Managing Prosumers in the Form of PCGs

In the previous sections, we have conducted an in-depth literature survey related to the managing prosumers in the form of PCGs in the SG energy sharing process. Following this survey, we have identified the following technical challenges which still need significant attention from the research community. It should be noted that in this chapter, we do not discuss the technical and ICT challenges of creating or operating PCGs, however only focus on the challenges associated with managing prosumers in the form of PCGs:

1. How to define and characterize PCGs
2. How to recruit new prosumers
3. How to manage multiple conflicting goals in community-based energy sharing network
4. How to define and allocate mutual goals to PCGs

5. How to assess the members within the PCGs
6. How to motivate the prosumers to join PCGs
7. How to motivate the members to improve their energy sharing, thus improving the quality of the PCG
8. How to develop effective communication/negotiation schemes
9. How to develop effective standard/ethics definition
10. How to distribute incentives among the PCGs as well as among the members within a PCG
11. How to perform risk assessment in community-based energy sharing network

2.5.1 How to define and characterize PCGs

For sustainable energy exchange among PCGs and energy buyers, creating meaningful PCGs is the foremost step. In order for that, innovative frameworks are required to define PCGs with optimal characteristics, which will then be used as pre-qualification criteria (benchmark) by the new prosumers for joining the relevant PCG.

2.5.2 How to recruit new prosumers to the PCGs

The continuous recruitment of dynamic prosumers to the PCGs is crucial in growing the PCGs. In order to achieve sustainable prosumer recruitment process, it requires analysing the prosumers’ fluctuating energy sharing behaviours over time, thus determining complying and non-complying prosumers. This task becomes more complicated, if that prosumer is new to the entire energy sharing process; thus, no historical energy behaviour data are available to make the decision.

2.5.3 How to manage multiple conflicting goals in community-based energy sharing network, thus defining and allocating mutual goals to PCGs

The community-based energy sharing network comprises multiple irreconcilable objectives such as demand constraints, cost constraints, income maximization, etc. In many cases, one goal may be achievable only at the expense of other goals. This necessitates suitable frameworks to manage multiple goals, while ensuring the satisfactory attainment of the high-priority goals.

Moreover, it is important to assign effective mutual goals to the different PCGs to guarantee the reasonable fulfilment of the goals of the community-based energy sharing network. The key challenge with this regard is that the same PCG that fulfils the defined mutual goal in one time may fail to do so in next time. This leads to the necessity of defining the practically achievable mutual energy goals for PCGs, considering their previous energy behaviour fluctuations in addition to the generic attributes of community.

2.5.4 How to assess the members within the PCGs

Member assessment and ranking frameworks are necessary to identify more influential prosumer profiles that contribute towards long-term sustenance of the PCG. This enables to identify member specificities when granting privileges in equitable manner.

2.5.5 How to motivate the prosumers to join PCGs

Relying on the existing number of prosumers within the PCG in the long term is short sighted, due to the uncertainty involved with climate-dependent green energy sources and uncertain prosumer behaviours. This motivation can take two forms: first, it is necessary to raise awareness about the PCGs amongst prosumers by advertising about the rules and regulation, pre-qualification criteria and the feed-in tariff schemes. Second, the financial and social benefits of energy sharing as a part of PCG should be promoted to attract the attention of prosumers.

2.5.6 How to motivate the members to improve their energy sharing, thus improving the quality of the PCG

If the members are motivated to share higher amounts of energy in the long term, the PCGs can reliably meet the demand of external energy buyers in the long term. One of the key driving forces for improving the performance is the reward, or incentives, which can be tangible or intangible. A tangible reward can be financial like the monetary value given for the additional energy generated and supplied to the grid. Some of the non-financial rewards include social respect, reputation and opportunities for generating and sharing the green energy.

2.5.7 How to develop effective communication/negotiation schemes

Effective communication/negotiation mechanisms between the PCG members and the prosumer community coordinator as well as the other stakeholders in the energy market play an important role to raise awareness, to understand the rules and regulations involved in the energy sharing process, to reach an agreement upon courses of action and to resolve disputes or misunderstandings. Furthermore, it is also critical to build trust among the PCG members.

2.5.8 How to develop effective standard/ethics definition

When the individual prosumers are connected to the PCGs, they deal with the standards and ethics presented by the PCG coordinator as well as other energy market participants. However, defining reasonable standard/ethics will be challenging.

2.5.9 How to distribute incentives among the PCGs as well as among the members within a PCG

Fair incentive distribution scheme is one of the key driving forces to maintain motivated PCG members.

2.5.10 How to perform risk assessment in community-based energy sharing network

Generally, the prosumers exhibit positive as well as negative behaviours. For instance, a positive behaviour is when the prosumer acts in a more beneficial way than what was anticipated, possibly offering more energy than agreed in the initial agreement with the prosumer community coordinator. In order to sustain a PCG in long run, it is necessary to identify different behaviour types, analyse the associated vulnerability and resolve the discrepancies to avoid long-term negative effects.

As mentioned in the earlier sections, existing literature on PCGs has not properly addressed the aforementioned PCG formation issues. In addition, the existing literature on general SG projects only offers technical infrastructure to interconnect DERs as VPP/micro-grid groups; however, creating meaningful groups considering the prosumers' diverse energy sharing behaviours, or inspiring those groups to attain an optimal mutual goal, is not present. Further, the literature on online virtual communities also lacks developing frameworks to address the key issues associated with PCGs.

This thesis focuses on four key challenges of managing prosumers in the form of PCGs selected from the above-mentioned research issues, namely how to define and characterize PCGs, how to recruit new prosumers, how to manage multiple conflicting goals in community-based energy sharing network thus defining and allocating mutual goals to PCGs and how to assess and rank the members within the PCGs.

2.6 Conclusion

This chapter has offered a state-of-the-art review of managing prosumers in the form of PCGs, as well as the literature in the field of SG that focuses on energy consumer/prosumer, and the literature in other contexts such as online virtual communities that might be adaptable to manage prosumers in the form of PCGs. The existing work evidently indicates that slight progress has been made in managing prosumers in the form of PCGs in the SG energy sharing process. However, plenty of key research issues related to this context have not been comprehensively addressed by the current research and require further development.

This thesis focuses on four key challenges of managing prosumers in the form of PCGs, which require further attention in the research community, namely, how to define and characterize PCGs, how to recruit new prosumers, how to manage multiple conflicting goals in community-based energy sharing network thus defining and allocating mutual goals to PCGs and how to assess members within the PCGs.

Based on this review, the next chapter will explicitly define the aforementioned research problems that we address in our thesis.

Chapter 3

Problem Definition

This chapter provides:

- Formal definition for the problems that we address in this research
- The research issues that need to be addressed
- The research methodology that will be adopted in this research to systematically address the identified research issues

3.1 Introduction

Prosumer Community Groups (PCGs) have been one of the most advantageous as well as challenging concepts that have emerged in recent decades in SG energy sharing, which facilitates a more sustainable energy sharing process compared to the individual prosumer involvement in energy sharing, and prosumer groups in the form of VPP/micro-grid involvement in energy sharing.

A comprehensive state-of-the-art review of energy user-focused literature in the SG was discussed in Chapter 2. Accordingly, there has been considerable research and commercial projects in SG that aim to build individual prosumer involvement and VPP/micro-grid prosumer group involvement in the energy sharing process; however, a limited number of SG approaches have implemented PCG involvement in the energy sharing process. In Chapter 2, we particularly emphasized on the literature on PCGs and analyse how existing energy user-focused literature as well as the existing approaches of generic community-based approaches in other contexts such as online virtual communities might be adapted to address the challenges of PCGs. From the surveyed literature, we identified a series of weaknesses in the current approaches and open research issues that require further attention from the research community.

The main contribution of this chapter includes a clear identification of the key problems that we intend to address in this thesis. In Section 3.2, we propose a set of definitions of those terminologies that will be used when defining the problems, as well as in subsequent chapters. Section 3.3 emphasizes the key problems we address in this thesis to be solved to implement sustainable PCGs, namely: PCG definition and characterization, new prosumer recruitment, multiple goal management and mutual goal definition and member contribution assessment and ranking. Finally, this chapter concludes with a brief discussion of research methodologies and a conclusion.

3.2 Key Concepts

In this section, we present a formal definition of terminologies and concepts, which will be used to introduce, elucidate and formally define the problems addressed in this thesis. Table. 3.1concisely illustrates the definitions. The same definitions will be adopted in proceeding chapters as required.

Table 3-1:Key concepts & terminologies

Terminology/Concept	Definition
Prosumer community coordinator	"Prosumer community coordinator" is an entity or a group of entities, who are involved in forming, growing and managing PCGs.
Prosumers' energy sharing profile	Prosumers' energy sharing profile is characterized by the quantity of energy that the individual prosumer is prepared to sell in the energy market to the relevant stakeholders such as retailers, consumers and other prosumers. In general, the prosumer generates green energy in a domestic environment and uses that energy for consumption and storage, and the surplus energy is fed back to the main electricity grid. Such surplus energy is counted as the energy sharing capacity of that prosumer.
Community-based energy sharing network	The community-based energy sharing network refers to the collection of PCGs networked under a single controlling point.

Table 3- 1: Continued: Key concepts & terminologies

Terminology/Concept	Definition
Time slot	"Time slot" is defined as a non-overlapping interval of time in the time space of the interaction. The time slot is obtained by dividing the time space into different equal non-overlapping parts of time.
Energy transaction	"Energy transaction" is defined as any type of energy transfer from prosumer to prosumer community coordinator.
PCG's overall energy sharing capacity	The PCG's energy sharing capacity refers to the combined energy sharing capacities of prosumers in the PCGs.
Local energy demand of the PCG	The local energy demand of the PCG refers to the demand for energy shown by the members of a PCG.
Pre-qualification criteria of the PCG	The pre-qualification criteria of the PCG refer to the basic qualifications that the prosumer might comply with in order to join the PCG.
Eligible energy threshold	"Eligible energy threshold" is the lowest energy boundary required to join the community-based energy sharing network.
Registered prosumer	"Registered prosumer" is any prosumer who shows an interest in joining the community-based energy sharing network.
Eligible prosumer	An "eligible prosumer" is a "registered prosumer" who is capable to meet the "eligible energy threshold.
Evaluation period	The "evaluation period" is characterized by a number of consecutive time slots or energy transactions defined by the prosumer community coordinator agent to evaluate the early behaviours of registered prosumers. The evaluation period of a prosumer is said to be "successful" if that prosumer shows the status of "eligible prosumer" in all the defined energy transactions.
Flexible community group membership	A "flexible community group membership" is assigned to the registered prosumers after each energy transaction within the evaluation period based on their energy contribution. Each "eligible prosumer" gets one of the membership categories at the end of each transaction, in which this category may be fluctuated over the evaluation period. However, their final membership is not decided until the end of the evaluation period.
Stable member	A "stable member" is a "registered prosumer" who keeps the "eligible prosumer" status during all the energy transactions within the evaluation period.

Table 3. 1: Continued: Key concepts & terminologies

Terminology/Concept	Definition
Unstable member	An “unstable member” is a “registered prosumer” who fails to keep the “eligible prosumer” status during one or more energy transactions within the evaluation period.
Fixed community group membership	A “fixed community group membership” is given to “stable members,” provided they have successfully completed the evaluation period.
Energy contract	The energy contract refers to the formal agreement between the prosumer and the prosumer community coordinator that takes place when the prosumer joins the PCG. The purpose of this contract is to set out the terms which allow the virtual connection of the prosumer’s renewable energy resource to a PCG.
Mutual energy goal	The mutual goal refers to the common goal, which is shared among the prosumers within the PCG. The different PCGs may be inspired to achieve different mutual goals; for instance, one community group may want to gain high profits by selling the energy to the utility grid, another group may attempt to reduce emission or energy costs, etc.
Goal management (optimization or negotiation)	The goal management refers to negotiating among the conflicting multiple goals, which transforms the predefined goals of the community-based energy-sharing network into a more favourable set of goals (optimized goals) based on the available resources and limitations.
Goal solution	The goal solution refers to the best satisfying set of goals under a varying amount of resources and limitations that is obtained from goal management/optimization/negotiation.
Sub-goal	When the goal is divided into segments, each segment is referred as a sub-goal.
Degree of attainment of the goals	The degree of attainment of the goals refers to the level of attainment of goals or to what extent the goals are fulfilled.
Static and dynamic characteristics of prosumer community groups	The static characteristics of PCG refers to the attributes that does not change over a considered time-slot, for instance the prequalification criteria is fixed. The dynamic characteristics of PCG refer to the attributes that changes over time-slots, for instance the quantity of energy actually supplied by the PCG.

Table 3 1: Continued: Key concepts & terminologies

Terminology/Concept	Definition
Intra-PCG energy sharing	Intra-PCG energy sharing refers to the energy sharing among members of the same PCG. A member may request energy from the fellow member within the same PCG to fulfil the individual energy shortage.
Inter-PCG energy sharing	Inter-PCG energy sharing refers to the energy sharing among the different PCGs. For instance, a PCG may request energy from another PCG, if its overall energy production does not meet the local energy demand of its members.
External customer energy sharing	External customer energy sharing refers to the energy sharing with external customers such as large-scale power companies, other individual consumers, etc. For instance, a PCG may sell energy to the external customers and receive tariff, or buy energy from external customers to meet its local energy shortfall.
Assessment criteria	Assessment criteria are defined as those criteria from the particular context of the energy sharing, which the prosumer community coordinator uses to assess the prosumers.
Expected outcomes	Expected outcome is defined as the anticipated outcome of those assessment criteria which the prosumer community coordinator wants to achieve from the prosumers.
Actual outcome	Actual outcome is quantitatively expressed as set of functionalities or activities in reality delivered by the prosumer in its energy transaction.
PCG leader	The prosumer community group leader is used to represent the central contact person in a PCG on behalf of its local members.
Relatively influential members	The members who demonstrate a relatively high performance are deemed to be more valuable to the PCG in enhancing the long-term sustenance.
Agent	An "agent" is defined as a specialized intelligent entity which acts autonomously according to the scenario and situation it is currently in, in order to achieve its specified objectives. An agent can be either a software agent or a human agent.

3.3 Problem Definition

The problems and challenges that are addressed in this thesis can be categorized into four sections as follows:

- Problems with defining and characterizing PCGs
- Problems with recruiting new members to the PCGs
- Problems with managing multiple goals in the community-based energy sharing network and defining mutual goals to the PCGs
- Problems with assessing the contribution and ranking of the members within PCGs

For each of these problems, the discussion is carried out from two different perspectives: the existing solutions and the technical problems inherent in these solutions. The technical concerns associated with the problems will form the research issues for the development of the new solution.

3.3.1 Problems with defining and characterizing PCGs

3.3.1.1 Formal definition

Sustainable PCGs strive to achieve sustainable energy sharing, and the very first building block to accomplish that end is effective PCG definition and characterization.

The PCG definition and characterization are to be done by grouping the prosumers' historic energy sharing profiles based on the PCG definition parameters presented by the prosumer community coordinator such as the number of PCGs, minimum number of members per PCG, etc., which output the PCG pre-qualification criteria for each PCG. The generic mathematical formulation for this can be illustrated as follows.

Let P_i be the energy sharing profiles of prosumers, N be the number of prosumers under consideration, A be the PCG definition parameters such as number of prosumers in each PCG and accumulated energy expected from each PCG and *R* represent the PCG pre-qualification criteria. The PCG definition algorithm that relates the inputs *(Pi,A)* and the outputs *(R)*, which is denoted as *f*, is demonstrated in Equation 3.1;

$R \approx f\,(Pi,A),$ Equation 3. 1

where $i=\{1,2,\ldots\ldots N\}$

$A=\{a_1,a_2\ldots..a_t\}$; provided "*t*" number of PCG definition parameters

$R= Cr$; i.e. r^{th} PCG pre-qualification criteria

The overall process of PCG formation is illustrated in Fig. 3.1.

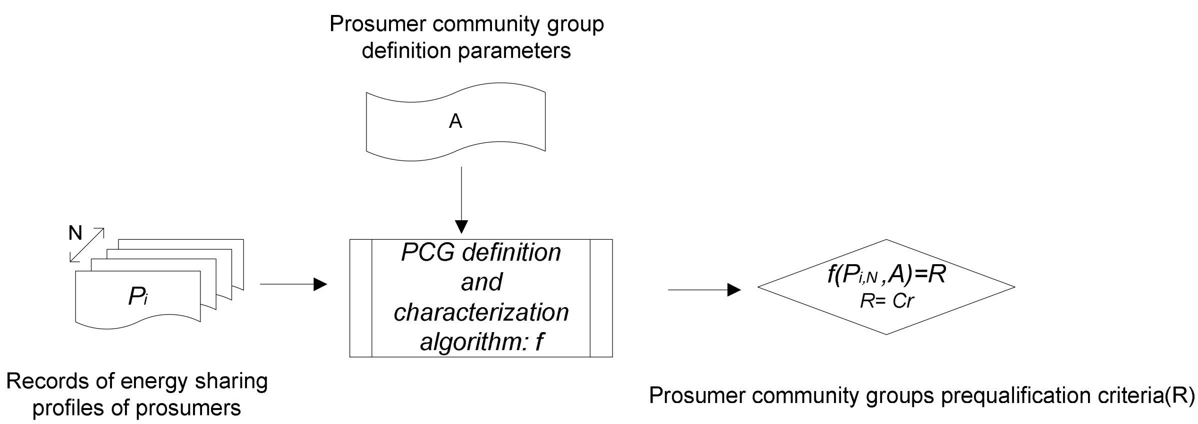

Figure 3. 1: Process of prosumer community group definition

3.3.1.2 Technical concerns

As discussed in the literature in Chapter 2, there is a scant amount of literature that discuss about PCGs, and even those do not focus on the aspects of defining and characterizing PCG in the first place. Moreover, the SG literature has only discussed the operational aspects that can be adapted to the PCGs once it is already formed, and the literature in other contexts such as online virtual communities has shown limitations when applied to the PCG definition and characterization. Accordingly, the main technical drawbacks with the existing approaches are as follows:

1. **Most parameters that influence the energy sharing behaviour profile of prosumers are overlooked.** The literature has several research contributions on analysing the energy consumption and generation behaviours of prosumers. For instance, an extensive set of influential parameters that affect the energy behaviour profiles of prosumers are found in the prior research done by Miller et al. (Miller, Batterberry et al. 2010). However, none of those researches analyse some of the parameters that particularly affect the energy sharing capacity of prosumers, such as energy storage capacities, the performance factors of renewable energy systems, etc.

2. **Inability to present a systematic algorithm to define and characterize PCGs.** Most existing works on PCGs do not present a systematic algorithm when forming PCGs, rather collecting them in unplanned fashion without considering the prosumers' diverse energy sharing capacities, making it ad hoc prosumer groups.

3. **Inability to analyse the prosumers' time-series energy sharing behaviours when defining PCGs**. Due to this variable nature of prosumer's energy sharing profiles over a day as well as in different seasons such as summer and winter, it is short sighted to decide a prosumer's performance in the energy sharing process by observing a single time slot. Therefore, it is necessary to monitor the prosumers' historic energy behaviours over different seasons and measure how well they behave and whether desired energy goals are being achieved. However, none of the research works address the fact of evaluating prosumers' long-term energy behaviours.

4. **Inability to identify prosumers (or users) with inconsistent behaviours (also called outliers) when forming groups.** In general, the prosumers' energy sharing behaviour data set may include the inconsistent data which are further away from the mean than what is deemed reasonable.

Identifying such irregular prosumers at the time of PCG definition and initial formation would be beneficial to the long-term sustenance of the PCGs. In literature, the approaches that identify the prosumers with inconsistent behaviours are lacking; however, in general, there are several studies that attempt to model the data in other contexts such as in computer performance data and in biomedical data, and attempt to find outliers, which might be possible to apply for this purpose.

5. **Absence of approaches to decide the feasible number of PCGs with favourable number of prosumers and sustainable amount of accumulated energy supply.** Literature has shown inadequate attention in deciding the optimal number of PCGs for a community-based energy sharing network. However, addressing this aspect is beneficial; for instance, managing a large number of PCGs, which have a small number of members in each, may not be practical and economical. In addition, if a PCG offers an insufficient quantity of accumulated energy, the longevity of such a group can be doubtful. Therefore, finding the optimal number of PCGs that have a manageable number of prosumers and that provide sufficient quantity of accumulated energy is a challenge.

3.3.2 Problems with recruiting new prosumers to the PCGs

3.3.2.1 Formal Definition

Relying on the PCGs defined and characterized, the subsequent process would be prosumer recruitment. In addition to the initial prosumer subscriptions, the continuous recruitment of new prosumers to the PCGs is crucial in growing the PCGs. However, the prosumers' fluctuating energy sharing behaviours over time make it challenging to identify the complying and non-complying prosumers during the recruitment process. This becomes more complex, if that prosumer is new to the energy sharing process; thus, no historical energy behaviour data are available to make the decision.

In a generic view, the prosumer recruitment requires an ongoing evaluation process of new prosumers, particularly if there are no historical data of energy sharing to make a decision when recruiting them to the relevant PCG. The generic mathematical formulation for prosumer recruitment can be illustrated as follows.

Let E_i be the real-time energy data of the i^{th} prosumers, N be the number of prosumers under consideration, B be the new prosumer evaluation benchmarks, Cr be the r^{th} PCG pre-qualification criteria, which were predefined in the PCG definition and characterization process, M_i be the membership of the i^{th} prosumer and C_f be the most favourable PCG for the i^{th} member. The inputs (Ei, B, Cr) and the output $(M_i \epsilon C_f)$ of the new prosumer recruitment algorithm, which is denoted as α, is demonstrated in Equation 3.2., i.e. the output of the recruitment algorithm would be optimal allocation of prosumers to the most favourable community groups, by evaluating them against the input variables:

$\alpha\ (Ei, B, Cr) \dashrightarrow M_i \epsilon C_f$ Equation 3. 2

The generic process of prosumer recruitment is presented in Fig 3.2.

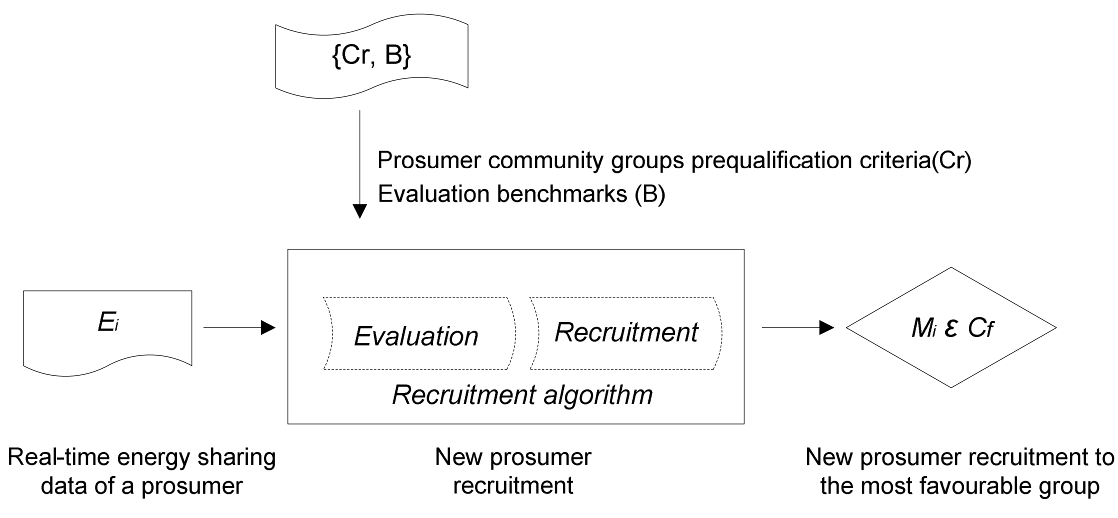

Figure 3. 2: The process followed by prosumer recruitment process

3.3.2.2 Technical concerns

The approaches that exist either in the SG area or in other contexts of online virtual community groups do not adequately address the problem of prosumer recruitment. The main technical problems associated with recruiting new prosumers to the PCGs are as follows:

1. **Limited approaches to continuously monitor the performance of the prosumers.** The recruitment of prosumers to the already-formed PCGs requires continuous monitoring of early adapters to make sure the recruitment of new prosumers does not result adverse effects to the overall performance and the expectations of the PCG. The monitoring of prosumers and even the energy users is absent in literature; however, there are few research works in online virtual communities (Backstrom, Huttenlocher et al. 2006; Fachrunnisa and Hussain 2013) that suggest the continuous monitoring of Internet users to ensure success of the interaction, to enhance trust. However, such methods are difficult to adopt and require major revision when applied to the prosumer recruitment in PCGs.

2. **Lack of approaches to differentiate non-complying members from the rest during recruitment process**. In order to recruit a prosumer to an appropriate PCG, it requires clear differentiation of prosumers based on the community groups' pre-qualification criteria. However, literature has offered very little in differentiating prosumers and identifying non-complying members during the recruitment process.

The state of the prosumer recruitment to PCGs is still subject to the above-mentioned technical concerns and, to date, no study has been able to resolve all of these issues.

3.3.3 Problems with managing goals and defining mutual goals to the PCGs

3.3.3.1 Formal Definition

The community-based energy sharing network has different incompatible objectives such as meeting the local energy demand, meeting the external customers' (utility grid or consumer) demand, achieving higher incentives for the energy auctioned, reduce overall cost, etc. It is necessary to manage and optimize these multiple goals with respect to the given constraints and to realize what alterations are required in constraints to achieve a satisfactory attainment of all the goals. Moreover, it is important to assign effective mutual goals to the different PCGs to guarantee the reasonable fulfilment of overall goals of the community-based energy sharing network.

The generic mathematical formulation for managing goals in the community-based energy sharing network and defining mutual goals to the PCGs can be illustrated as follows.

Let $G_1 \ldots Gv$ be the multiple goals, D be the goal constraints, $G_{1O} \ldots G_{MO}$ be the optimized corresponding goals and the inputs $((G_1 \ldots G_v),Cr)$ and the output $(G_{1O} \ldots G_{vO})$ of goal management algorithm, which is denoted as β, are demonstrated in Equation 3.3:

$$\{G_{1O} \ldots G_{vO}\} \approx \beta\, ((G_1 \ldots G_v),Cr) \qquad \text{Equation 3.3}$$

Let $MG_{1r} \ldots MGv_r$ be the set of mutual goals assigned to the r^{th} PCG, Kr be the PCG attributes, and the inputs $((G_{1O} \ldots G_{vO}),Kr)$ and the output $(MG_{1r} \ldots MGv_r)$ of the mutual goal definition algorithm, which is denoted as λ, are demonstrated in Equation 3.4:

$$\{MG_{1r} \ldots MGv_r\} \approx \lambda\, ((G_{1O} \ldots G_{vO}),Kr) \qquad \text{Equation 3. 4}$$

The generic process used in goal management and mutual goal definition in PCG is presented in Fig. 3.3.

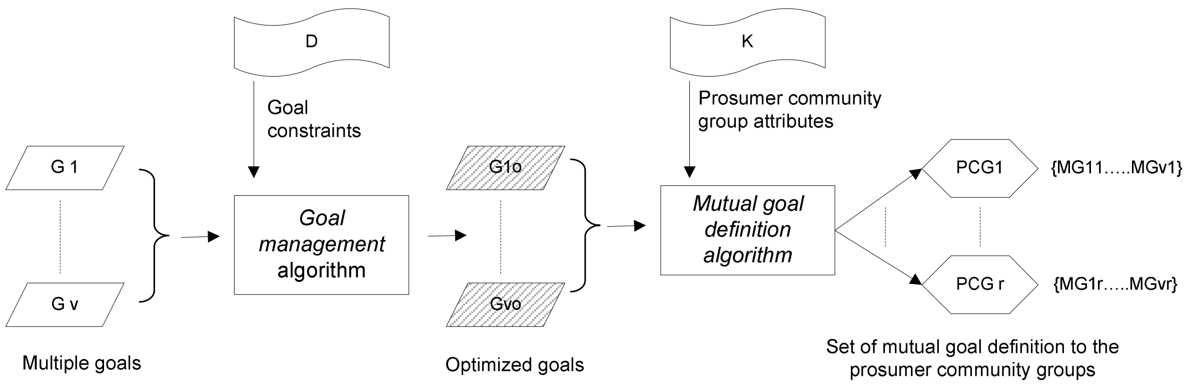

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Figure 3. 3: The process used by goal management and mutual goal definition

3.3.3.2 Technical concerns

Technical concerns associated with goal management and mutual goal definition of PCGs are as follows:

1. **Managing multiple conflicting goals of community-based energy sharing network is heavily overlooked.** In general, one goal of the community-based energy sharing network is realizable by sacrificing the other goal. Furthermore, these goals may be incommensurable, necessitating the establishment of a hierarchy of importance among incompatible goals such that the achievement of the lower-order goals are considered only after the higher-order goals have been satisfied or have reached a point beyond which no further improvements are desirable. However, the existing literature has overlooked the fact of managing conflicting goals within an energy sharing process.

2. **Inability to present a systematic approach to define tailored mutual goals for PCGs.** The different PCGs show different energy attributes from one another, thus not being able to meet the same energy target. Therefore, it is required to define customized mutual energy goals for different PCGs based on the different traits of PCGs. In literature, there are few studies on energy users that offer customized energy consumption schemes (Simonov, Mussetta et al. 2009;

Timmerman and Huitema 2009; Robu, Kota et al. 2012; Yu, Gatsis et al. 2013), however those schemes are difficult to adapt to build customized mutual energy goal definition schemes for PCGs.

3. **Provisions for uncertainties in defining mutual goals are not considered.** In general, the same PCG that fulfils the defined energy target in one time slot may fail to do so in the subsequent time slot, incorporating uncertainties to the satisfactory achievement of goals. This leads to the necessity of defining the practically achievable mutual energy goals for community groups, considering their previous energy behaviour fluctuations in addition to the generic attributes of PCG.

3.3.4 Assessing and ranking the members of PCGs

3.3.4.1 Formal Definition

Assessing and ranking the energy contribution of members within a PCG can be used to differentiate the more influential members whose future behaviour will facilitate the long-term sustainability of the PCG. This can be further beneficial when presenting differential fair incentive distribution schemes to the members, while creating a competitive environment among the members. Typically, the contribution assessment is performed based on the predefined assessment criteria. The generic mathematical formulation for prosumer assessment and ranking can be illustrated as follows.

Let $ac_1 \ldots\ldots ac_z$ be the assessment criteria, $COi_1 \ldots COiz$ be the contribution made by the *i*th member in corresponding criteria, Nr be the number of members in the r^{th} PCG under consideration, PR_i be the rank of the i^{th} member and the inputs $((ac_1 \ldots\ldots ac_z),(COi_1 \ldots COiz))$ and the output (PR_i) of member assessment and ranking algorithm, which is denoted as φ, are demonstrated in Equation 3.5:

$$PR_i \approx \varphi\ ((ac_1 \ldots\ldots ac_z),(COi_1 \ldots COiz));\ i=\{1,2,\ldots Nr\} \qquad \text{Equation 3. 5}$$

The generic process of the contribution assessment and ranking of members within a PCG is illustrated in Fig. 3.4.

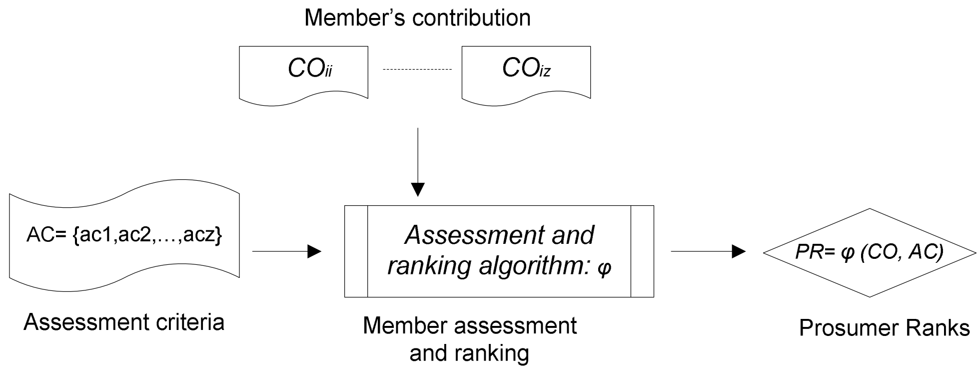


Figure 3. 4: The process used by member assessment and ranking

3.3.4.2 Technical concerns

In the literature, there are no research studies to date that demonstrate contribution assessment and ranking of prosumers, and even of energy users; however, there are several research works in other contexts such as page rank algorithm and buyer rank algorithm that attempt to find ranks to the generic Internet users (Hon Wai and Chen 2009). However, due to the complex attributes of prosumers, it makes it difficult to adapt those techniques to assess the prosumers. Technical concerns associated with member assessment and ranking within a PCG are as follows:

1. **Incapability of presenting a systematic approach to assess and rank the prosumers.** Existing approaches that present the assessment and ranking frameworks for generic Internet users (Hon Wai and Chen 2009; Berry, Chartier et al. 2013) cannot be directly applied to assess and rank the prosumers due to the dissimilar assessment parameters. For instance, in Page rank (Hon Wai and Chen 2009), the ranking is done based on how the Internet users click the particular web page, which is not adoptable for prosumer ranking.

2. **The criteria to assess the individual prosumer's in energy sharing within the PCG are not well understood**. The members of PCG exhibit different behaviours, such that they supply

energy to meet the energy contract, fail to meet the energy contract and participation for inter-PCG energy sharing and intra-PCG energy sharing. These lead introducing different assessment criteria for prosumer assessment. However, the literature has no work on defining suitable criteria and benchmark to assess the prosumers.

3. **Limited approaches to assess the prosumers based on multiple criteria**. Most generic assessment and ranking algorithms (Hon Wai and Chen 2009) assess and rank the users based on a single criteria. However, there are limited approaches that offer solutions to rank the users based on multiple criteria. For example, the edge rank has been calculated for Facebook users, which uses three criteria: affinity between the user and the creator of the item, the type of the interaction among the Facebook users (comments, likes, etc.) and how long the edge was created (Berry, Chartier et al. 2013). However, those available approaches in other contexts are not applicable to assess and rank prosumers in PCGs.

The above list presents issues and weaknesses of the contribution assessment and ranking of prosumers within a PCG. To date, no study has been conducted to resolve all of these issues.

3.4 Research Issues

Using the above knowledge and key concepts, we discussed three areas of problem definitions. For each, we defined the current available solutions and the existing technical problems inherent in these solutions. These technical problems form the basis of our research issues: how can we address them and what are the requirements for the new solution? In this section, we outline the research issues that need to be addressed in any new solution development. We then pursue the solutions from Chapter 4 onwards to target the research issues defined in this chapter and to meet the objectives outlined in Chapter 1.

3.4.1 Research Issue 1: How to define and characterize PCGs by analysing the energy sharing behaviour profiles of prosumers

Based on the survey of current approaches of community group formation that have been discussed in Chapter 2 and problem definitions for definition and characterization of PCGs, it is clear that the concepts of defining and characterizing PCGs are not well understood. Moreover, the literature contains no approaches particularly addressing PCG definition and characterization, and the approaches discussed in other contexts such as online virtual community groups are difficult to adapt to PCGs and may require major revision.

In order to address this problem with defining and characterizing PCGs, a number of research questions need to be investigated:

- **Research Question 1.1: What are the aspects of PCG definition and characterization?**
- **Research Question 1.2: Can we effectively address the varying energy sharing behaviours of prosumers in different seasons such as summer and winter?**
- **Research Question 1.3: Can we differentiate prosumers showing inconsistent energy patterns compared to the typical prosumer behaviours (outlier detection)?**
- **Research Question 1.4: What are the possible methods to segment time-series prosumer data to define the PCGs having relatively similar energy characteristics?**
- **Research Question 1.5: Can we achieve a practically manageable number of PCGs?**

The above research questions will be answered when we design the framework for PCG definition and characterization, which is extensively presented in Chapter 5.

3.4.2 Research Issue 2: How to recruit new prosumers to the PCGs

According to the survey in Chapter 2, the literature has heavily overlooked the aspects of recruiting new prosumers to the PCG. In the previous section, the problem definitions for recruiting prosumers to the PCGs and the associated technical problems are discussed. Those technical problems result in a number of research questions. In order to overcome the problems, the following research questions need to be considered:

- **Research Question 2.1: What are the aspects of recruiting new prosumers to PCGs?**
- **Research Question 2.2: What are the effective methods to monitor the early behaviours of the prosumers?**
- **Research Question 2.3: What are the suitable benchmarks to assess the new prosumers' performance?**
- **Research Question 2.4: How** c**an we differentiate the non-complying members from the rest?**

The above research questions need to be addressed in order to build effective prosumer recruitment and thus sustainable PCG growth. The framework, which will be presented in Chapter 6, presents an approach to continuously monitor the new prosumers waiting to join the PCG, thus recruiting the dynamic prosumers to the PCG.

3.4.3 Research Issue 3: How to manage multiple goals within the community-based energy sharing network and define optimal mutual goal to the PCGs

As mentioned in Research Problem 3, the previous literature has not shown any focus on managing diverse goals in the community-based energy sharing network, thus defining optimal mutual goals for PCGs. Moreover, the goal definition and allocation algorithms in other contexts such as online virtual network community groups also have shown difficulty in adopting their approaches for PCGs due to the complex characteristics inherent by PCGs.

In order to address this problem of managing multiple goals within the community-based energy sharing network and defining mutual goals to PCGs, the following research questions need to be considered:

1. **Research Question 3.1: What are multiple goals within the community-based energy sharing network?**

2. **Research Question 3.2: What is the relative importance of these goals towards the sustenance of the PCG?**

3. **Research Question 3.3: How can we manage the multiple conflicting goals within the community-based energy sharing network to guarantee satisfactory level of attainment of all the goals?**

4. **Research Question 3.4: What are the factors affecting the definition of effective mutual goal for each PCG?**

5. **Research Question 3.5: How can we develop an approach to define tailored mutual goals for PCGs?**

6. **Research Question 3.6: How can we accommodate the factors that deviate the PCGs in achieving the defined mutual goal?**

In this research, we propose a framework for goal management and mutual goal definition that address all the above questions, and it is comprehensively illustrated in Chapter 7.

3.4.4 Research Issue 4: How to assess the contributions made by individual members within the PCG, thus differentiating the more influential members for fair incentive distribution

As discussed above, the contribution assessment and ranking of members have not been discussed in literature to date. In addition, the available approaches in other context cannot be effectively adapted for PCGs.

In order to address this issue, the following research questions need to be considered:

1. **Research Question 4.1: What are the factors affecting long-term and short-term contribution of members of PCG?**

2. **Research Question 4.2: What are the suitable criteria to assess the individual members within the PCG?**

3. **Research Question 4.3: How can we evaluate the importance of different assessment criteria?**

4. **Research Question 4.4: How can we rank the individual members based on the multiple assessment criteria?**

In this research, we propose a framework for member assessment and ranking that address all the above questions, and it is comprehensively illustrated in Chapter 8.

3.5 Research Methodology

The science- and engineering-based research approach is adopted for this research to solve the underlying research problem. Science and engineering research leads to the development of new techniques, architecture, methodologies, devices or a set of concepts, which can be combined to form a new theoretical framework. More specifically, the design science research methodology is adopted that understands the problem domain and designs a solution by creating an application or some design artefacts (Galliers 1994; March and Smith 1995; Hevner, March et al. 2004). To achieve our research aims, we aim to develop algorithms and a prototype system to confirm to the spirit of "making something work" (Nunamaker and Chen 1990).

This methodology consists of problem definition, conceptual solution, implementation, experimentation and testing and validation of prototypes against existing solutions. The aforesaid activities have been divided into three main stages (Nunamaker and Chen 1990):

- Problem definition
- Conceptual solution
- Implementation, testing and evaluation

3.5.1 Problem definition

In the problem definition stage, the aim is to justify the significance of the research questions. It involves the analysis, interpretation, discussion and evaluation based on criteria and perspective. This problem definition stage has been covered in this chapter. Problems for PCGs have been grouped into four categories: problems with defining and characterizing the PCGs, problems with recruiting new prosumers to PCGs, problems with managing multiple goals in the community-based energy sharing network and defining mutual goals to PCGs and the problems with assessing and ranking the contribution of individual members of the PCGs. For each category, the discussion is carried out using a formal definition of the category, and the technical concerns. The problems associated with the technical concerns led to the research issues for the new solution development.

3.5.2 Conceptual solution

The conceptual solution focuses on formulating a new method and approach through the design and building of tools, an environment or system through implementation. In this stage, a conceptual framework is designed for the proposed solution. A system's conceptual framework and system architecture are the key ingredients which provide a research road map for the entire development of a system or system development process. This involves the decomposition of the entire system into leaf or basic functional components and to clearly specify the interaction between these functional components, whose interaction as a whole provides a comprehensive picture of a complete functional system. Here, the design specification is used as a blueprint for the implementation of the system.

3.5.3 Implementation, test and evaluation

In this stage, testing and validation are carried out through experimentation with real-world examples and field testing. The process of testing and validating a working system provides unique insights into the benefits of the proposed concepts, frameworks and alternatives.

By building a prototype system, implementing, testing and evaluating, a better insight into the feasibility and functionality of the conceptual framework as well as the whole solution is provided.

In this dissertation, Chapter 4 provides a conceptual framework for the proposed solution, and Chapters 5–9 carry out implementation and experimentation of the conceptual framework along with verification of the proposed solutions.

3.6 Conclusion

This chapter provides a problem definition for the problems associated with managing prosumers in the form of PCGs in SG energy sharing. Based on the socio-economic and technical problems of existing solutions, four research issues have been defined. For each research issue, a number of research questions have been proposed. These research questions need to be addressed in the development of PCGs in SG energy sharing. To address each research issue, four research frameworks have been proposed. Furthermore, the research methodology for this research has been discussed.

In the next chapter, an overview of the proposed solution along with its conceptual framework will be provided. The conceptual framework is designed to address all the issues that have been discussed in this chapter.

Chapter 4

Solution Overview

This chapter provides:

- An overview of the proposed solutions
- A conceptual framework of the proposed solutions
- A conceptual process adopted in the development of the proposed solutions

4.1 Introduction

As outlined in Chapter 2, there is a very small number of works that directly address the issues of managing prosumers in the form of PCGs and the proposals in other contexts (for example, online virtual community) cannot be directly adapted to the PCGs without major revision. However, the area of PCG research is quite young and it is evident that to date no research has resolved some challenges associated with developing PCGs such as defining and characterizing PCGs, growing PCGs with new member recruitment, managing multiple goals and defining mutual goals, finding influential prosumers within a PCGs, etc. We identified four key research problems that are aimed at addressing the challenges of managing prosumers in the form of PCGs. This chapter provides an overview of the solutions to each of the research issues discussed in Chapter 3. In order to provide a meaningful explanation of how we formulate the solutions, we utilize the same key concepts and definitions, which we briefly explained in Chapter 3.

4.2 Overview of the Solution

In Chapter 3, we presented the problem definition, which listed four main problems in the specific area of managing prosumers in the form of PCGs.

1. Problem with the definition and characterization of PCGs, which requires an analysis of the historic energy sharing profiles of prosumers who have been involved in direct energy supply to the utility grid or retailers as single entities

2. Problem with recruiting new prosumers to the PCGs, who have shown interest to join a PCG

3. Problem with managing multiple goals within the community-based energy sharing network and defining optimal mutual goal to the PCGs

4. Problem with assessing and ranking the individual members within the PCG, thus differentiating the more influential members for fair incentive distribution

In Chapter 3, we identified the research issues for the aforementioned four problems. In this section, the solutions for each of the aforesaid problems are briefly introduced.

In order to address the aforementioned problems of defining and characterizing PCGs, we need to develop a solution which has the following features:

Feature 1: Ability to determine suitable context to analyse the time-series energy sharing behaviour profiles of the prosumers

Feature 2: Ability to detect prosumers showing inconsistent energy sharing patterns (outlier detection)

Feature 3: Ability to create PCGs based on the homogeneity of their energy sharing behaviours

Feature 4: Ability to create a viable number of PCGs with optimal number of prosumers, who generate a satisfactory amount of accumulated energy

Feature 5: Ability to define pre-qualification criteria for each PCG, where new prosumers can use as a benchmark when joining the PCG

The proposed framework that addresses the problem of PCG definition and characterization, which contains these features, is named as "*prosumer community group definition and characterization framework.*"

The next problem that is addressed in this thesis is recruiting new prosumers to the predefined PCGs. In order to address this problem, we need to develop a solution comprising the following features:

Feature 1: Ability to present a proactive mechanism to monitor and evaluate the real-time commitment of the new prosumers

Feature 2: Ability to differentiate the complying and non-complying prosumers before recruiting them to predefined PCGs

The proposed framework that addresses the problem of new prosumer recruitment, which contains these features, is named as "*prosumer recruitment framework.*"

Furthermore, the third problem that is addressed in this thesis is managing diverse goals in the community-based energy sharing network and defining favourable mutual goals for each PCG. In order to address this problem, we need to develop a solution comprising the following features:

Feature 1: Ability to identify multiple conflicting goals within a community-based energy sharing network

Feature 2: Ability to assess and prioritize the goals based on their importance

Feature 3: Ability to negotiate among the diverse goals, thus ensure the satisfactory level of attainment of all the goals

Feature 4: Ability to define tailored mutual goals for PCGs

A framework named "*goal management and mutual goal definition framework*" that contains the aforementioned features is proposed to address the problem of managing multiple goals in the community-based energy sharing network and defining mutual goals for PCG.

The last problem that is addressed in this thesis deals with assessing and ranking the individual members within the PCG, thus differentiating the more influential prosumers for fair incentive distribution. In order to address this problem, we need to develop a solution which has the following features:

Feature 1: Ability to define suitable assessment criteria to evaluate the individual member's energy sharing behaviours within the PCG

Feature 2: Ability to present a mechanism to assess the prosumers and rank them within the PCG

The proposed framework that addresses the problem of prosumer assessment and ranking is named as "*member assessment and ranking framework.*"

Fig. 4.1 shows how the dissertation is organized from this chapter onwards. The conceptual solution is proposed to address the four main problems concerning PCGs, which were outlined in Chapter 3. The figure also shows how each of these problems is addressed in the respective chapters, where Chapters 5, 6, 7 and 8, respectively, present the "*prosumer community group definition framework,*" "*prosumer recruitment framework,*" "*goal management framework*" and "*prosumer assessment and ranking framework.*"

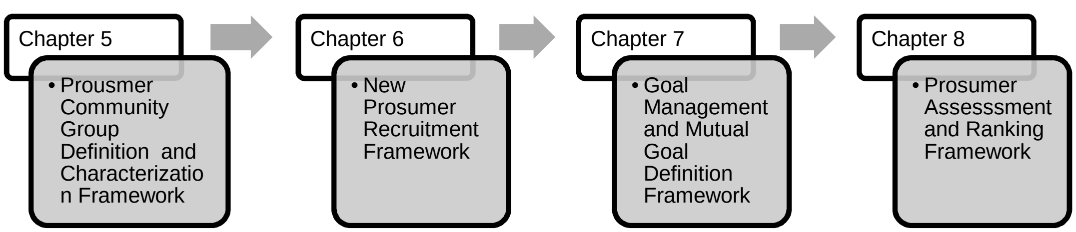


Figure 4. 1: Overview of the conceptual solution

In the next section, the details of each proposed solution are discussed.

4.3 Solution Description

In this section, we describe the solutions, which have been developed to address the issues highlighted earlier in this chapter.

In Fig. 4.2, we present a broad overview of the methodologies that we will propose in this thesis, which involves the solutions for four different key research problems we identified in forming and evolving PCGs in the domain of SG energy sharing. Furthermore, Figs. 4.3, 4.4, 4.5 and 4.6 illustrate the solutions for four different key research problems separately. It should be noted here that the relationships shown between the different entities in the figures represent just the flow of control in the proposed methodology, and they do not represent the relationships from the object modelling language.

The four solutions presented in this thesis to address the identified research issues are as follows:

1. *Solution for the prosumer community group definition and characterization framework*: In order to form and evolve PCGs in the domain of SG energy sharing, the foremost task would be the definition and characterization of PCGs with appropriate attributes; in other words, define suitable pre-qualification criteria to represent PCGs. The prosumers interested in joining the PCGs can use the predefined pre-qualification criteria of the PCG when choosing the preferred PCG.

2. *Solution for the prosumer recruitment framework:* In order to recruit the new prosumers to the PCGs, it is required to evaluate their real-time energy sharing behaviours and determine the complying and non-complying prosumers in prosumer recruitment.

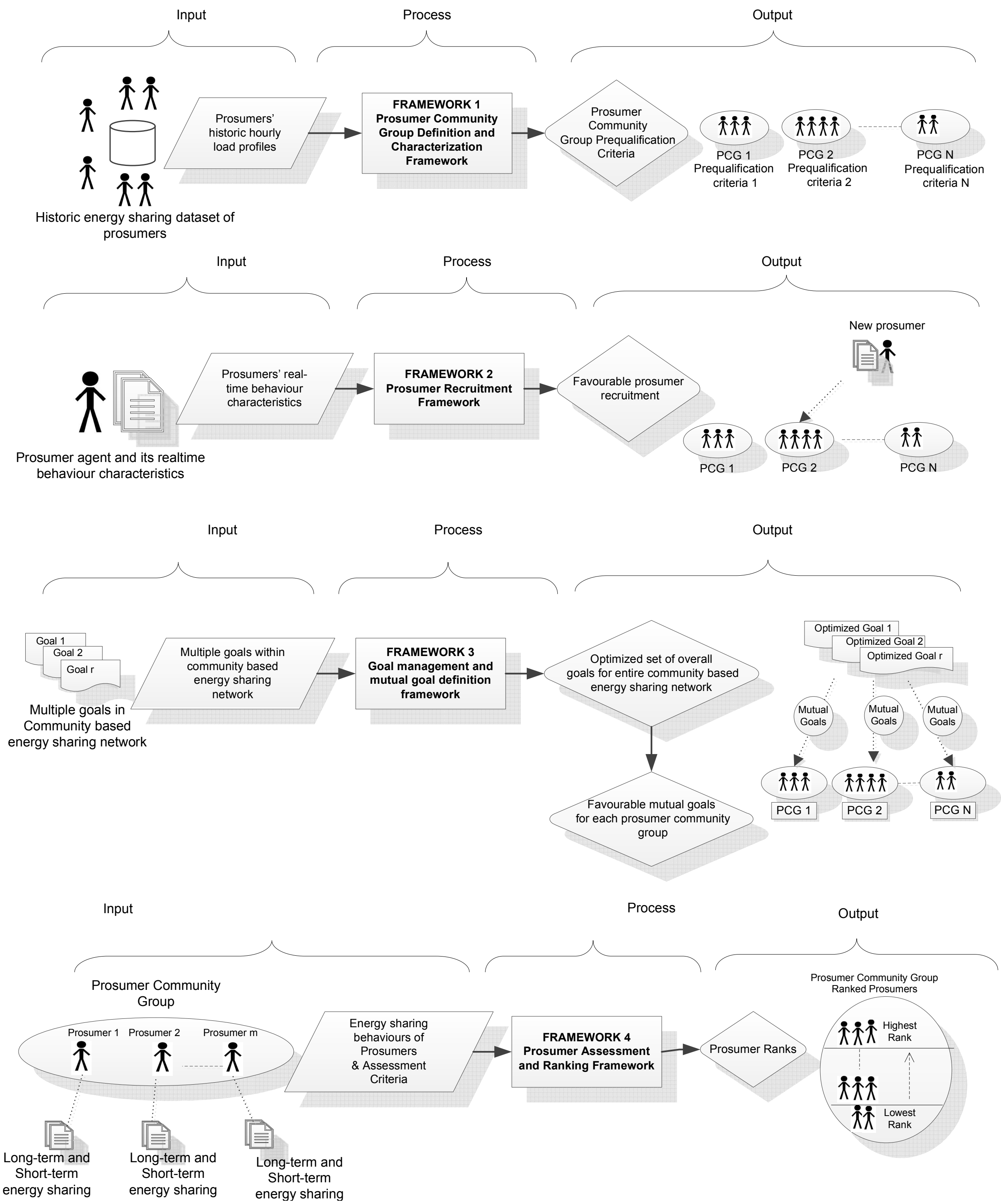


Figure 4. 2: Broad overview of the methodologies

3. *Solution for the goal management and mutual goal definition framework:* In order for the satisfactory attainment of multiple goals that lie in community-based energy sharing network, the management/negotiation among the conflicting multiple goals is required. In addition, to promote the achievement of each PCG's mutual goals, the definition of the most favourable mutual goal for each PCG is required.

4. *Solution for the prosumer assessment and ranking framework:* In order to find the more influential members within a PCG, it is required to assess and rank the members within a PCG.

In the next sections, we will explain each of the aforementioned solutions, which are formulated to solve the research issues mentioned in Chapter 3.

4.3.1 Solution for the PCG definition and characterization framework

In this section, we present an overview of the solution to define and characterize PCGs, thus defining suitable PCG pre-qualification criteria for different PCGs. In order to attain this, we utilize the time-series clustering technique. The main aspects of the proposed methodology are illustrated in Fig. 4.3, and are briefly highlighted as follows:

1. The prosumer community coordinator analyses the historic behaviours of the set of prosumers registered to the community-based energy sharing network and estimates their energy sharing nature based on their hourly energy load profiles over different climatic conditions, which quantify the time-series data set.
2. These sets of prosumers are assumed to have shared energy as single entities directly with the utility grid or energy retailer, and the time-series data set is assumed to contain hourly energy load profiles to represent both summer and winter (extreme) climatic conditions.
3. The PCGs are defined on the basis of relative homogeneity of energy sharing behaviours of prosumers using time-series clustering techniques.

4. The proposed clustering system has the ability to determine the energy sharing behaviour observations that are numerically distant from the rest of the data (usually named outliers), thus deciding the prosumers further away from the mean behaviour than what is deemed reasonable.
5. Based on the clustering analysis, it recommends to the prosumer community coordinator the level of similarity among the prosumers within the same PCGs and the level of difference among the prosumers within the different PCGs.
6. The number of prosumer clusters obtained via the clustering system is optimized to ensure each PCG supplies a sufficient quantity of energy as well as includes a viable number of prosumers.
7. The community coordinator can consider the output from the overall system in order to define and characterize the PCGs. The identified characteristics of PCGs can be represented as pre-qualification criteria for each PCG.
8. The community group coordinator can utilize the defined pre-qualification criteria for each PCG as a benchmark to attract and recruit new prosumers to the relevant PCGs in the future.

In Chapter 5, we present in detail the steps of the methodology and explain how it is utilized in defining the PCGs.

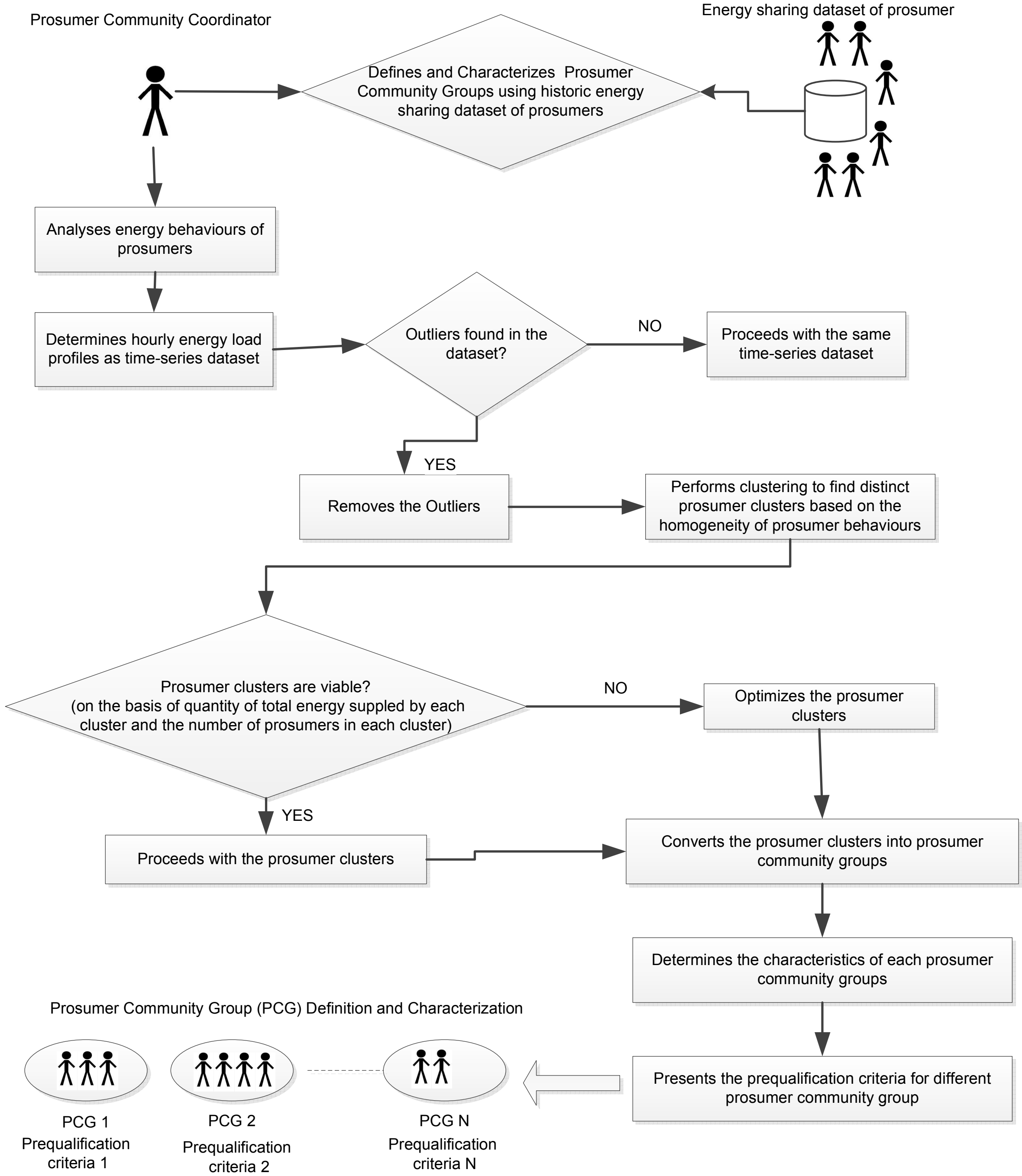


Figure 4. 3: Prosumer community group definition and characterization framework

4.3.2 Solution for the new prosumer recruitment framework

In this section, we will give an overview of the solution by which the prosumer community coordinator evaluates the performance of the new prosumers and recruits them to the predefined PCGs. In order to achieve this, we develop an evaluation scheme that reflects the proactive monitoring of prosumers over a period of time, rather than recruiting the prosumers based on the performance in a single energy sharing transaction. Utilizing this type of performance evaluation is beneficial, as the prosumer community coordinator can predict the level of success or failure of the prosumers within the boundaries of different PCGs and attach them to the most appropriate PCG. The main aspects of the proposed methodology are illustrated in Fig. 4.4 and are briefly highlighted as follows:

1. The prosumer community coordinator evaluates the behaviours of the new prosumer according to the pre-qualification criteria of the preferred PCG over a period of time before recruiting that prosumer permanently to that PCG.
2. To evaluate the early adaptors, the prosumer community coordinator has to first determine the duration of the time space, which it wants to evaluate the prosumer before deciding their final PCG. This time duration is named the "evaluation period."
3. The prosumer community coordinator identifies the prosumers' eligibility on a scale in each time slot of the evaluation period and determines their suitability for the different PCGs.
4. At the end of the complete evaluation period, the prosumer community coordinator combines the overall performance of the prosumer and assigns the complying members to a fixed community membership level.

In Chapter 6, we explain the proposed methodology in detail by which the prosumer community coordinator achieves the aforementioned steps by which it can manage the new prosumers and assign them to the most beneficial PCG.

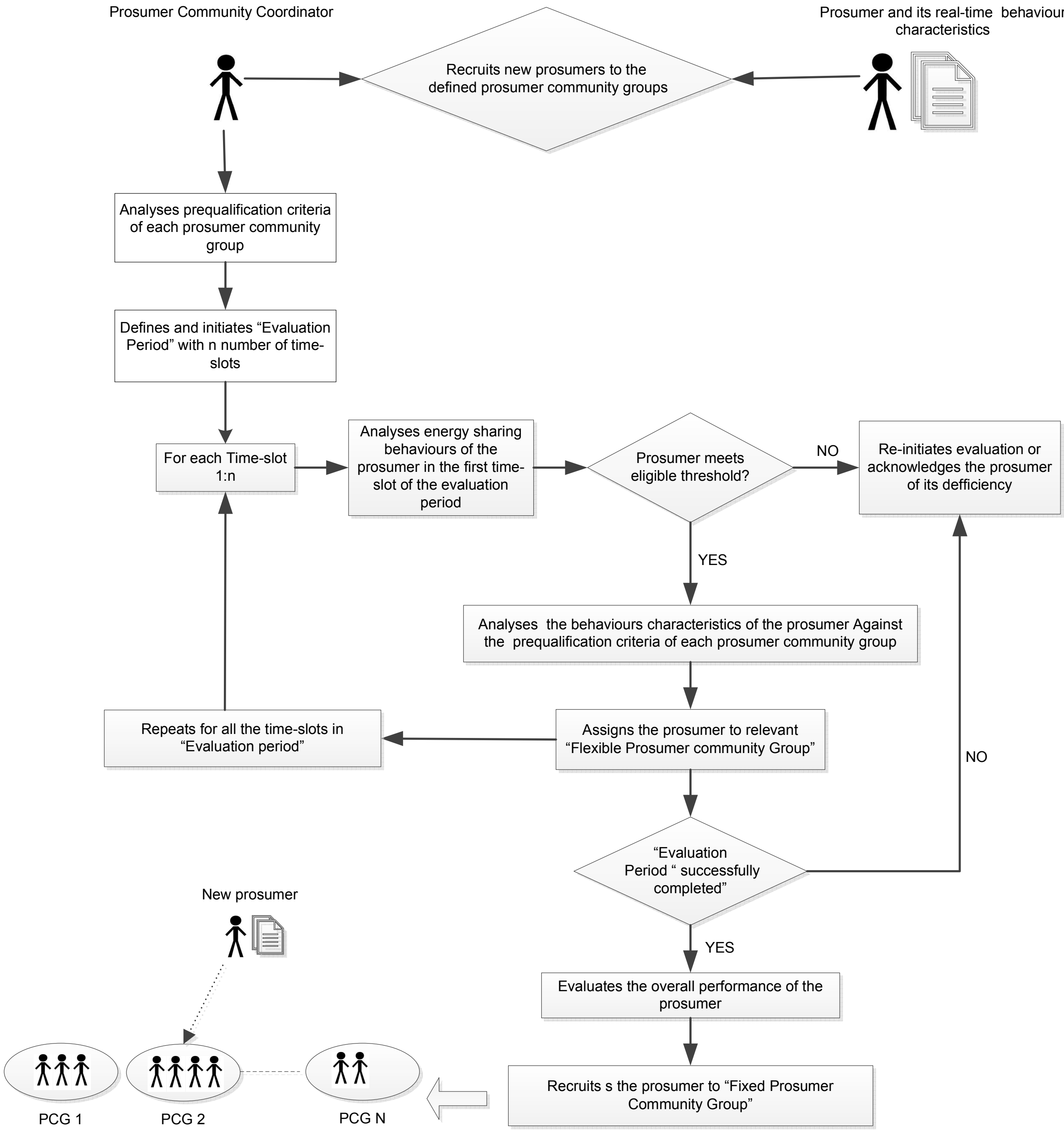


Figure 4. 4: New prosumer recruitment framework

4.3.3 Solution for the goal management and mutual goal definition framework

In this section, we will present an overview of the solution for managing the multiple goals in community-based energy sharing network followed by allocating optimal mutual goals to the PCGs. The significance of solving this problem can be illustrated as follows: the community-based energy sharing network encompasses different incompatible objectives such as meeting the PCG members' energy demand, meeting the external customers' (utility grid or consumer) demand, achieving higher income for the energy auctioned, reduce overall cost, etc. In many cases, one goal may be achievable only at the expense of other goal. For example, in order to reduce the overall cost associated with PCGs, the overhead of managing prosumers in PCGs is to be reduced by reducing the number of active prosumer participations. However, reducing the number of participating prosumers will reduce the total energy production and sharing, while reducing the total income (feed-in tariff). Therefore, it is necessary to reach a favourable compromise among these multiple diverse goals with respect to the given constraints and priorities. Moreover, these goals are to be effectively broken down into customized mutual goals for different PCGs, where the prosumers of each PCG are inspired to achieve the respective mutual goal. In order to achieve this, we use MCDM and goal programming techniques. The main aspects of the proposed methodology are illustrated in Fig. 4.5 and are briefly highlighted as follows:

1. The prosumer community coordinator determines the multiple objectives of a community-based energy sharing network that a PCG may come across during its evolution and progression.
2. The prosumer community coordinator assesses and prioritizes the goals based on their importance.
3. The goal programming theory is utilized in order to negotiate among the multiple goals and find out the degree of attainment of the goals subjected to the resource availability.

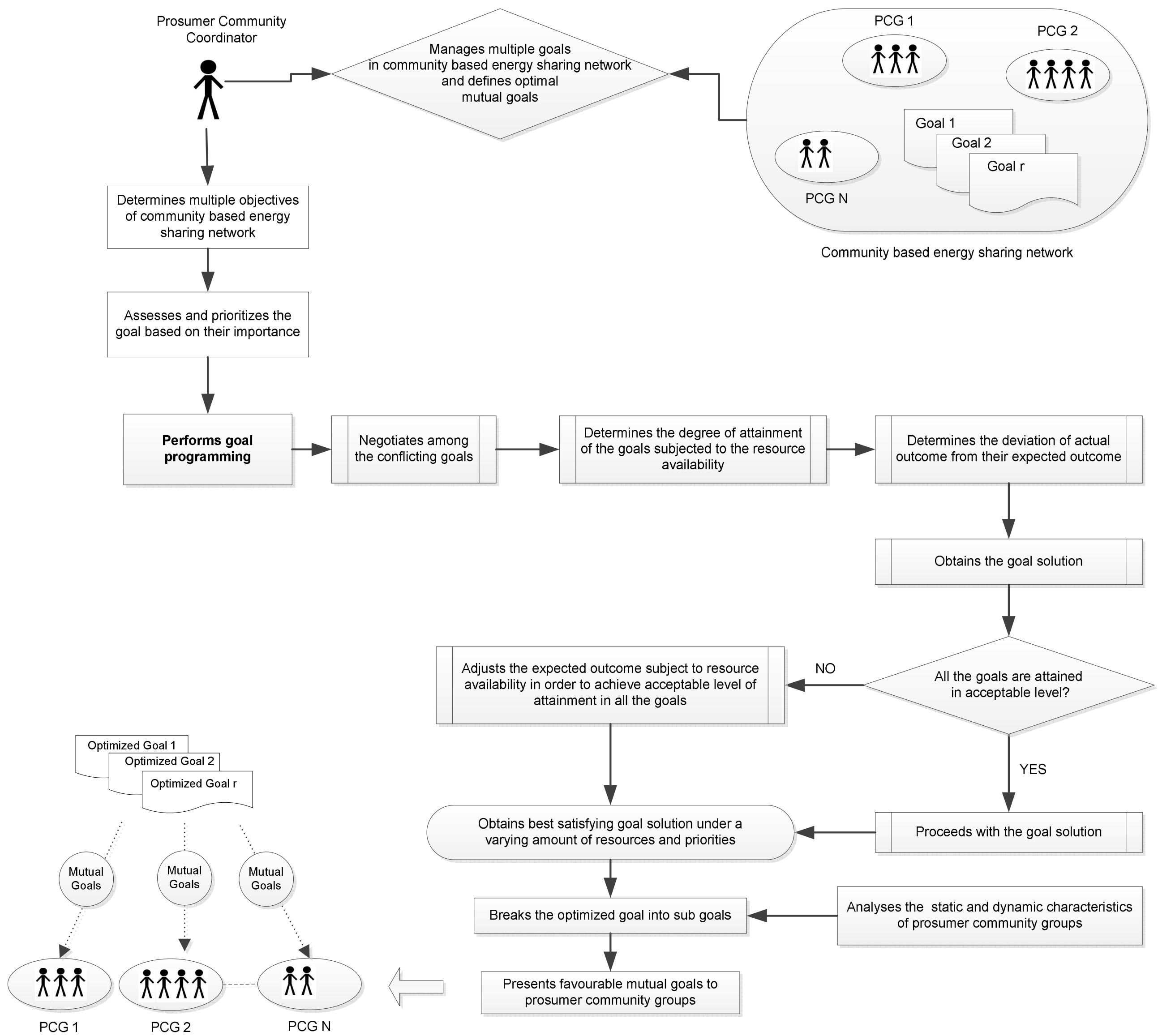


Figure 4. 5: Goal management and mutual goal definition framework

4. The goal-programming model develops an objective function for each goal and then seeks a solution that minimizes the deviations of these objective functions from their respective goals.
5. If there is any deviation in the observed goal attainment levels and the expected level of goal attainment, then the goal to be adjusted in order to achieve an acceptable degree of attainment in all the goals.

6. The goal-programming model facilitates the prosumer community coordinator to identify what alterations are necessary in parameters to attain all the goals in an acceptable degree and finally to provide the best satisfying solution under a varying amount of resources and priorities.
7. The goal solution is broken down into sub-goals, which is then assigned to different PCGs. The community coordinator analyses the static as well as dynamic characteristics of prosumer groups when defining the customized mutual sub-goals.

In Chapter 7, we explain in detail the proposed methodology by which the prosumer community coordinator manages the multiple goals in a community-based energy sharing network and decides the mutual sub-goals for each PCG.

4.3.4 Solution for the prosumer assessment and ranking

In this section, we present an overview of the solution that assesses and ranks the prosumers within a PCG. As discussed in the last chapter, even though the PCGs are formed with favourable members, there is a possible risk of failure when those prosumers supply energy to the community-based energy sharing network in the long term under unpredictable climatic conditions. Therefore, the continuous assessment and ranking of members within each PCG is important. Here, we discuss the significance of addressing the aforementioned issue from different perspectives: from the prosumer community coordinator's viewpoint, this concept can be used to differentiate the more influential members whose future behaviour will facilitate the long-term sustainability of the PCG. Thus, the prosumer community coordinator can take appropriate actions to make these influential members feel privileged within the community group (by offering differential incentives). On the other hand, from the prosumers' perspective, being influential members who generate and share higher amount of energy, they will receive special incentives (financial benefits and social responsibility). This will create a competitive environment among the prosumers, which will further encourage all the prosumers to invest in additional energy resources (e.g. putting more solar panels), knowing that the cost will be recovered within a specific time frame, and they will be getting greater profits as their energy generation capacity increases. From the perspective of the society, the identification of influential prosumers, followed by higher incentives, motivates prosumers to generate green energy within their domestic environments, which is crucial to combat the problem of electricity shortage in the society, which is currently heavily dependent on non-renewable energy sources.

In order to achieve this solution, we use MCDM techniques. The main aspects of the proposed methodology for the prosumer assessment and ranking are shown in Fig. 4.6 and demonstrated as follows:

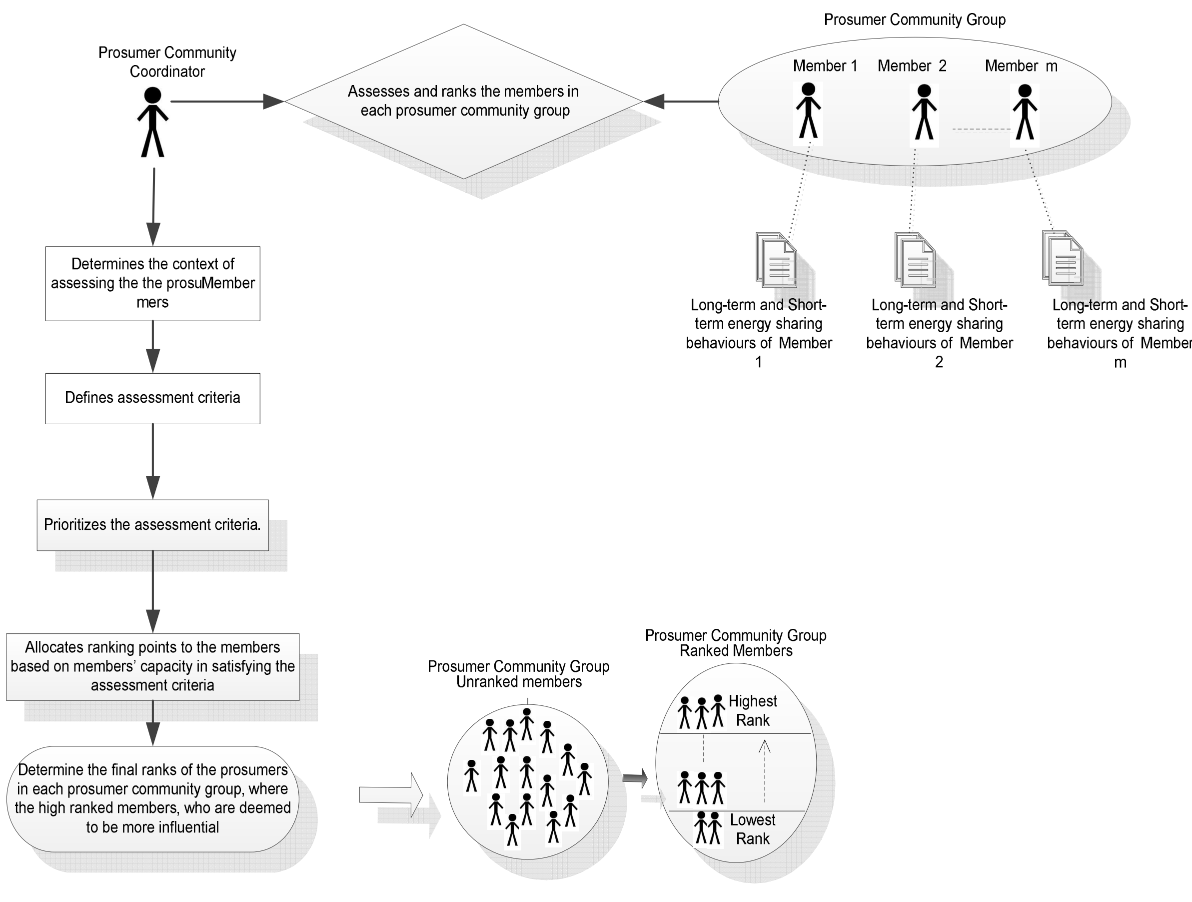


Figure 4. 6: Prosumer ranking and assessment framework

1. The prosumer community coordinator needs to first determine the context in which it wants to assess the members. Further, within that context, it should identify the specific assessment criteria that it wants to achieve based on the desired outcomes and the expectations.

2. The assessment criteria are defined in order to highlight the short-term performance of the members as well as the long-term performance over their tenure.
3. Based on the importance of different assessment criteria, the prosumer community coordinator prioritizes the assessment criteria.
4. By analysing each member's capacity in satisfying the assessment criteria, the prosumer community coordinator allocates ranking points to the members.
5. The ranking points allocated to members are weighed against the significance of the assessment criterion to determine the final ranking points of each member.
6. Based on the ranking points allocated to the members, the final ranks are decided.
7. By determining the ranks of the members, the prosumer community coordinator can identify higher-ranked members, who are deemed to be more influential in enhancing the long-term sustenance of the PCG.

In Chapter 8, we explain in detail the proposed methodology by which the community coordinator assesses and ranks the members.

This concludes the overview of the proposed solutions presented in this dissertation. In the next section, we highlight the conceptual process.

4.4 Conceptual Process

In the above-mentioned subsection, we provide an overview of solutions that we develop in this thesis. In order to develop these solutions, we have to strictly follow a conceptual process that includes the following stages: clearly elicit the requirements and the design rationale, propose a theoretical foundation to address the requirements, build a prototype system to verify the theoretical foundation, set up a simulation environment to test the prototype and, finally, validate and verify the proposed solution. The flow of the main steps in the conceptual process is demonstrated in Fig. 4.7.

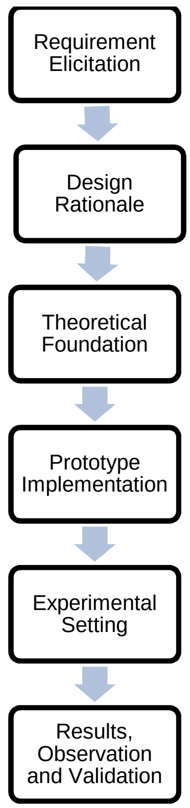


Figure 4. 7: Main steps in the conceptual process

In this section, we discuss the conceptual process that is consistently applied throughout all the four research frameworks covered in this thesis. As described in Chapter 3, for the development of the advanced technology solution, the thesis follows the science- and engineering-based approach and system design and development methodology which is consistent with Fig. 4.7. We now explain each of the main stages in detail and list the activities that are carried out at each stage.

4.4.1 Requirements elicitation and prioritization

This stage starts with a survey of existing solutions and identification of main issues relevant to these solutions. The issues are then prioritized according to their importance. The prioritized issues act as a framework for the proposed solution. For example, the main issues of the aforementioned four different frameworks are analysed and prioritized according to their design precedence and the top of the list would be given high designing priority.

4.4.2 Design rationale

This is the second stage in the conceptual process. Once the requirement elicitation and prioritization stage is completed, the next stage (i.e. design rationale) describes the basic design decisions that should be undertaken in order to meet the requirement elicited in Stage 1. Each and every listed requirement contributes to the design process. We relate each and every requirement to a design decision, thereby ensuring that all the requirements are considered when finalizing the design process.

4.4.3 Theoretical foundation

The third stage in the conceptual process is theoretical foundation. This stage is based on the design rationale which comes from Stage 2. This stage provides a solution to address all the requirements elicited in Stage 1 by analysing the design rationale in Stage 2. A detailed algorithm is proposed in this stage to cover all the needs.

The final algorithm needs to be tested for functionality purposes. To test the algorithm, it needs to be implemented which is described in the next stage.

4.4.4 Prototype implementation

The fourth stage in the conceptual process is prototype implementation. This stage provides an implementation of the theoretical foundation and prototype algorithm. The prototype is used to test and experiment and validate the theoretical foundation. The prototype can be designed in any suitable development environment. For example, the theoretical concepts used for the aforementioned research frameworks are verified using MATLAB, and a realistic model of complete community-based energy sharing network is developed as multi-agent systems using JADE.

MATLAB is a numerical computing environment that allows matrix manipulations, plotting of functions and data, implementation of algorithms and interfacing with programs written in other languages.

On the other hand, JADE is implemented in Java language and simplifies the implementation of multi-agent systems through a middleware that complies with the Foundation for Intelligent Physical Agents (FIPA) specifications and through a set of graphical tools that supports the debugging and deployment phases. The JADE prototype is used to utilize the proposed methodologies in a single platform.

However, before conducting the experiments or simulations using the prototype, the experimental or the simulation setting should be finalized first. This stage is explained next.

4.4.5 Experimental setting

The fifth stage in the conceptual process is experimental setting. This stage provides simulation or experiment parameters to examine the prototype.

4.4.6 Results, observation, and validation

The sixth stage in the conceptual process is concerned with results and observation. This stage discusses the experiments of running the prototype. It also analyses the experiments and describes the observations. These observations are then cross-related with the theoretical foundation to validate the results. Validation compares the result from the experiments (actual results) with the theoretical model (expected results). The expected results might be similar to or quite different from actual results. In the case of difference, the theoretical model needs to be adjusted and all the steps from stages 1 to 6 might need to be amended.

4.5 Conclusion

This chapter provides an overview to the solutions that are proposed in this dissertation. These solutions are proposed to address research issues that have been discussed in Chapter 3. In the next chapters, we will give a detailed solution of four research frameworks mentioned in this chapter.

Chapter 5

Prosumer Community Group Definition and Characterization

This chapter provides:

- An introduction to the PCG definition and characterization
- An innovative framework to define and characterize PCGs
- A study of design requirements, design rationale and theoretical framework of the proposed framework for PCG definition and characterization
- Experimentation and testing of the proposed framework for PCG definition and characterization

5.1 Introduction

As mentioned earlier in this dissertation, the current literature lacks a comprehensive understanding of PCG definition and characterization. This chapter addresses those problems by providing a framework by which the prosumer community coordinator categorizes the prosumers' energy profiles in order to define PCGs and characterizes the suitable pre-qualification criteria for each of those PCGs.

As discussed in the last chapter, in order for a goal-oriented PCG to work sustainably, significant initial pull-in efforts are needed by the prosumer community coordinators. These efforts should start from defining and characterizing the PCGs. However, these efforts are lacking in the burgeoning literature and, accordingly, this gap has motivated us to propose a new paradigm for PCG definition and characterization in this chapter. It is necessary to define and characterize PCGs because the clear definition of PCGs with suitable pre-qualification criteria presents unique characteristics for each PCG, where these characteristics can be used as benchmarks when recruiting new prosumers to the PCGs in future.

The methodology that we propose in this chapter will assist the prosumer community coordinator to determine the suitable PCGs and their pre-qualification criteria. The preliminary point for achieving this methodology would be the energy profile analysis of prosumers and cluster them in order to create different PCGs. Moreover, the pre-qualification criteria of each PCG that includes the commitment to be achieved by the members of each PCG should be clearly defined.

This chapter is organized as follows. A general overview of the PCG definition and characterization framework is presented in Section 5.2. The requirements and design rationale of the framework development are presented in Sections 5.3 and 5.4, respectively. The theoretical foundation of the proposed framework along with its algorithms is covered in Section 5.5, followed by the verification of the framework in Section 5.6. Chapter 5 is concluded in Section 5.7.

5.2 Overview of PCG Definition and Characterization

The key objective of this framework is to define the PCGs and characterize them with suitable pre-qualification criteria. For a better understanding, we give an overview of PCG definition and characterization in this section.

The abstract overview of the PCG definition and characterization is illustrated in Fig. 5.1. As mentioned in the last chapter, the key input for the PCG definition and characterization framework is the prosumers' energy profiles. The energy profiles of prosumers are selected to represent the different climate conditions, particularly the key seasons like summer and winter, because the prosumers' green energy generation as well as the energy consumption heavily depend on the weather condition. The key output of the framework is the pre-qualification criteria of different PCGs. The pre-qualification criteria defined for each PCG using this framework can be utilized by the new prosumers as a benchmark when obtaining the membership.

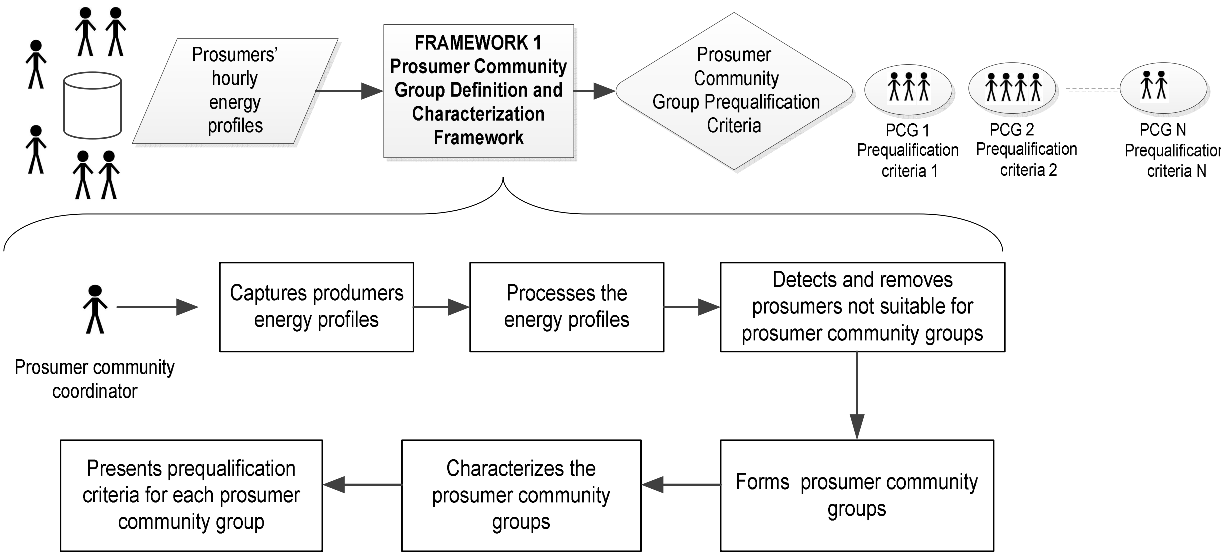


Figure 5. 1: The prosumer community group definition and characterization

The fundamental processes identified in the PCG definition and characterization framework is illustrated as follows: the prosumer community coordinator obtains prosumers' energy profiles and processes them to identify which energy profiles are more suitable for further processing and to define PCGs, thereby removing the energy profiles that are not suitable. By processing the remaining energy profiles, the prosumer community coordinator defines different PCGs based on the homogeneity of the energy profiles of diverse prosumers. Afterwards, the distinct characteristics of different PCGs are presented as the pre-qualification criteria of each community group, which comprise the commitment to be expected from each member of the group.

The key attributes that uniquely identify the pre-qualification criteria of each PCG is the highest and lowest energy sharing commitments accepted from a member. Thus, each PCG is associated with two key boundaries: "*lower threshold*" and the "*upper threshold*" (as shown in Fig. 5.2). For example, the "*lower threshold*" of a PCG is the least quantity of energy, which a new prosumer may generally share to receive the membership of the corresponding PCG. On the other hand, the "*upper threshold*" of a PCG is the highest quantity of energy that the new prosumer may generally share when obtaining the membership of the corresponding community group. Moreover, the different PCGs can be represented by different grades based on its "*lower thresholds*" and "*upper thresholds*," for instance, when the grade of the community group is higher, and more benefits the members receive.

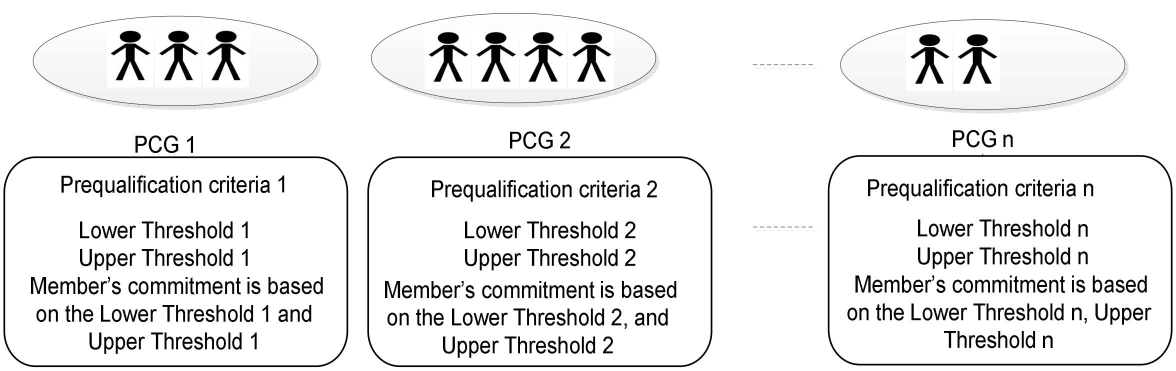


Figure 5. 2: Pre-qualification criteria of prosumer community groups

Given the brief insight into the research conducted in this chapter, the following section discusses the requirements for this research.

5.3 Requirements

This section represents the *first* stage of the conceptual process where requirements are elicited and prioritized. The following requirements are laid down for the proposed solution:

1. **Determine the energy behaviour profile**: The solution should process the prosumers' energy consumption and generation profiles over a period of time. In fact, prosumers' daily energy

profiles that show hourly energy variations are the most effective option to capture the characteristics of the prosumers for creating meaningful PCGs and enabling meaningful energy exchanges among them.

2. **Determine the suitable energy profiles for PCGs**: The solution should determine the suitable energy profiles that can be used to define and characterize possible PCGs. For instance, the observations that are numerically distant from the rest of the data (usually named outliers) can occur in any distribution. For example, in an energy behaviour data set, there may be particular prosumer behaviour profiles, which are further away from the mean behaviour, and are deemed unreasonable. Retaining such irregular profiles in the data set would adversely affect the definition of PCGs' pre-qualification criteria.

3. **Create PCGs based on the homogeneity of the prosumer behaviours:** The framework should ensure that the energy profiles with similar energy behaviours fall in the same PCG. Making PCGs with homogeneous energy profiles will make it easy for the prosumer community coordinator to manage such groups rather than managing the groups having extremely diverse prosumers.

4. **Achieve feasible number of PCGs**: The framework should determine the most favourable number of PCGs with a manageable number of prosumers who provide sufficient quantities of accumulated energy. For instance, having a large number of PCGs makes the management of PCGs much harder, as the prosumer community coordinator would have to bear additional overheads, interacting with several numbers of PCGs. In addition, if there are PCGs with a very small number of prosumers, it may reduce the reliability of the group's energy supply as, when some prosumers are unable to produce, there may not be a sufficient number of prosumers to make up the shortfall. Therefore, finding the optimal number of PCGs with a manageable number of prosumers who provide sufficient quantities of accumulated energy is also a key requisite.

5. **Define pre-qualification criteria of PCGs:** The solution should clearly categorize different energy profiles into PCGs and identify their exclusive pre-qualification criteria. This predefined pre-qualification criteria of each PCG are to be used as a benchmark by the new prosumers when joining the relevant PCG in the future.

This concludes stage 1 of the conceptual process. The design rationale which is discussed in the following section is based on the above-mentioned requirements. A design decision for each requirement is made in the design rationale accompanied by a discussion of how the requirement is fulfilled.

5.4 Design Rationale

This section provides a design rationale to fulfil the requirements that are outlined in Section 5.3. This is the *second* stage of the conceptual process. The following design decisions are proposed in order to address each requirement. The concise overview of the design decisions are shown in Fig. 5.3.

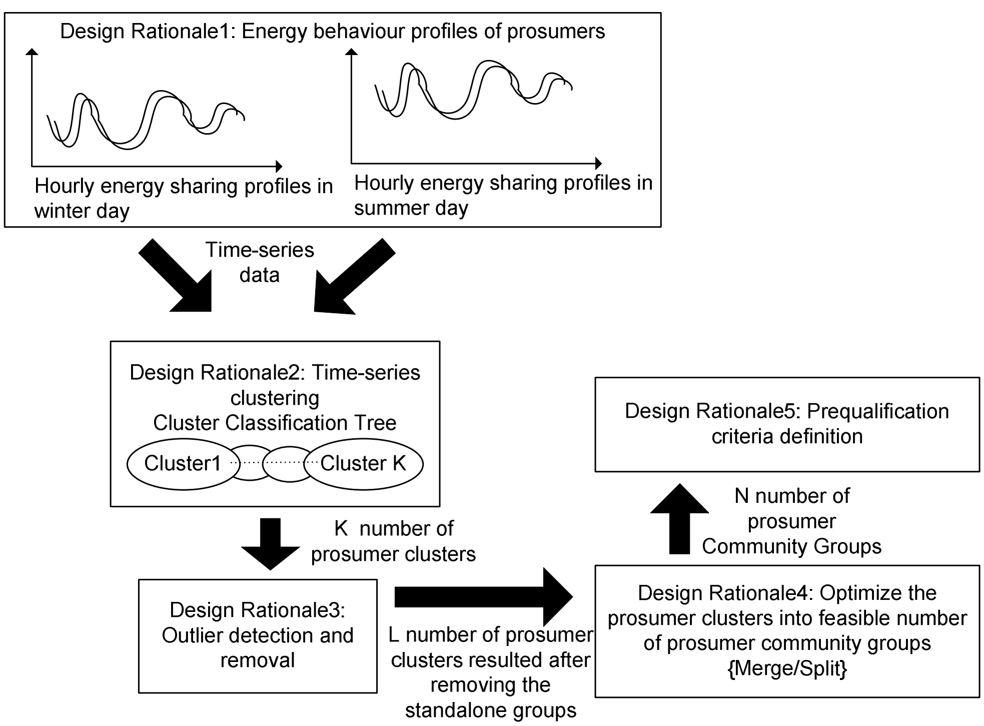


Figure 5. 3: Abstract view of the proposed framework

1. **Design rationale 1:** Individual prosumer's energy behaviour profiles are obtained in the form of time-series data. In fact, in order to obtain comprehensive characteristics of prosumers' energy sharing, we use hourly energy sharing behaviours. Each prosumer is defined with 48-time series data profiles for their energy sharing for two key climate conditions as follows (Table 5.1): (i) hourly energy sharing profile for average winter day and (ii) hourly energy sharing profile for average summer day. This would satisfy the requirement for determining the energy behaviour profile (Req. 1).

Table 5-1: Time-series energy profile of the prosumer

	Energy sharing behaviours
Average winter day	Hourly time-series data <24 time-series>
Average summer day	Hourly time-series data <24 time-series>

2. **Design rationale 2**: In order to determine suitable energy profiles to define the PCGs, we use general data mining techniques (clustering). The first stage of clustering would be the creation of a CCT, which adapts the concepts of the BIRCH algorithm developed by Guojun et al. (Guojun, Chaoqun et al. 2007). As shown in Fig. 5.2, we cluster the time-series profiles of prosumers using the CCT, where we use the symbol "*K*" to represent the number of clusters obtained. The outlier detection, which identifies and removes the energy profiles that show unreasonable energy profiles from the data set, is carried out, by determining the prosumer profiles who do not make groups with any other profiles, i.e. the time series data which are further away from the rest, and

make them isolated entities in the cluster tree. This would satisfy the requirement for determining the suitable prosumers for the PCGs (Req. 2).

3. **Design rationale 3**: The time-series clustering based on the CCT is performed to group the energy profiles having similar profiles. As shown in Fig. 5.2, the framework output “L” number of non-overlapping prosumer clusters will then be further processed to create PCGs. This would satisfy the requirement for creating prosumer clusters (later will be modified as PCGs) based on the homogeneity of the prosumer behaviours (Req. 3).

4. **Design rationale 4**: Optimizing the obtained clusters into a viable number of PCGs is done by merging the neighbouring clusters (if the originally formed clusters are too small) or splitting the large clusters (if the originally formed clusters are too large). This guarantees that each PCG supplies a sufficient amount of energy and has a sufficient number of prosumer profiles. This would satisfy the requirement for obtaining a feasible number of PCGs (Req. 4).

5. **Design rationale 5**: The pre-qualification criteria of each PCG are defined by analysing the traits of the PCGs defined in the previous design decision. As discussed earlier, we identify two key quantitative parameters in the pre-qualification criteria: the “lower threshold” of a PCG, which is the least commitment expected from a prosumer of the corresponding PCG, and the “upper threshold” of a PCG, which is the highest commitment expected from a prosumer of the corresponding PCG. This would fulfil the requirement of the PCG pre-qualification criteria (Req. 5).

In the development of the proposed solution framework for PCG definition and characterization, the above design decisions are considered. This concludes stage 2 of the conceptual process. The following stage is the theoretical foundation for the proposed solution.

5.5 Theoretical Foundation

The theoretical foundation for the PCG definition and characterization framework is discussed in this section, which represents the *third* stage of the conceptual process. The theoretical foundation of this framework has two main parts (Fig. 5.4): (i) Phase 1: time-series clustering and outlier detection and (ii) Phase 2: optimization of prosumer clusters and pre-qualification criteria definition. Figure 5.4 illustrates a concise flowchart of the PCG definition and characterization algorithm.

The first part of the framework is designed for the *time-series clustering and outlier detection* mechanism. The input for this part of the system is the prosumers' energy sharing for an average summer day and winter day.

The time-series clustering data mining technique (based on CCT) is used to detect outliers and make prosumer clusters based on the homogeneity of energy profiles. The output of this part of the system is the non-overlapping prosumer clusters.

Optimization of prosumer clusters and pre-qualification criteria definition is the subsequent and last part of the proposed solution. The output of the previous part of the system would be used as the input for this part, where the prosumer clusters obtained in the first part are optimized to achieve a feasible number of PCGs and the attributes of identified PCGs are used as pre-qualification criteria of PCGs.

The proposed solution explained above addresses all of the requirements described in Section 5.3 . The next sections provide a detailed description of the theoretical development.

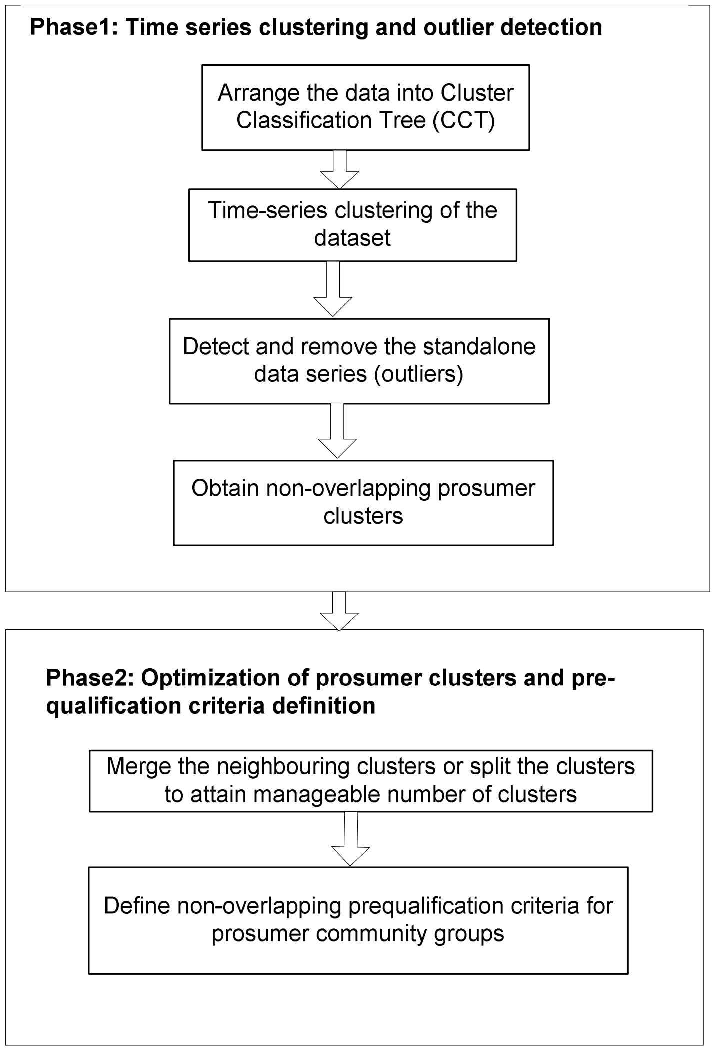


Figure 5. 4: Theoretical foundation of prosumer community group formation

5.5.1 Phase 1: Time-series clustering and outlier detection

This phase involves time-series clustering and the outlier detection of the prosumers' profiles using a CCT. The input for this phase is the time-series data of the energy profiles representing 48 time series as shown in Fig. 5.5.

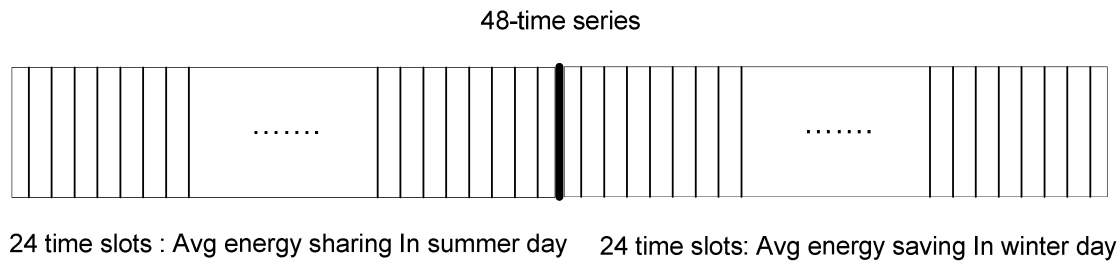


Figure 5. 5: Time series for each prosumer

This phase can be broken down into two main steps: (i) Step 1: building CCT and (ii) Step 2: outlier detection.

5.5.1.1 Step 1: Building CCT

In this phase, the CCT is built dynamically as objects are inserted (Fig. 5.6); thus, the method is incremental. The optimal CCT is made by scanning all the time slots of the time series (prosumer profiles) and arranging them as groups, through an iterative process. The first prosumer profile is used as the reference group. We denote the Euclidean distance between two adjacent groups as "*threshold distance*" ($Dist_{th}$) which is set to the radius of the data set at the first iteration (Equation 1). This threshold distance is reduced iteratively stepwise. In each iteration step, the Euclidean distance (d_{euc}) measure between the centres of the existing groups and the datapoint is calculated (Equation 2). The object is inserted to the closest group, and if the diameter of the object and the existing groups after insertion is larger than the threshold distance, that group cannot contain the corresponding object and that object forms a new group. In fact, the size of the CCT can be changed by modifying the threshold distance. If the size of the memory that is needed for storing the CCT is larger than the size of the main memory, the CCT should be made smaller, and a larger threshold value can be specified and the CCT is rebuilt.

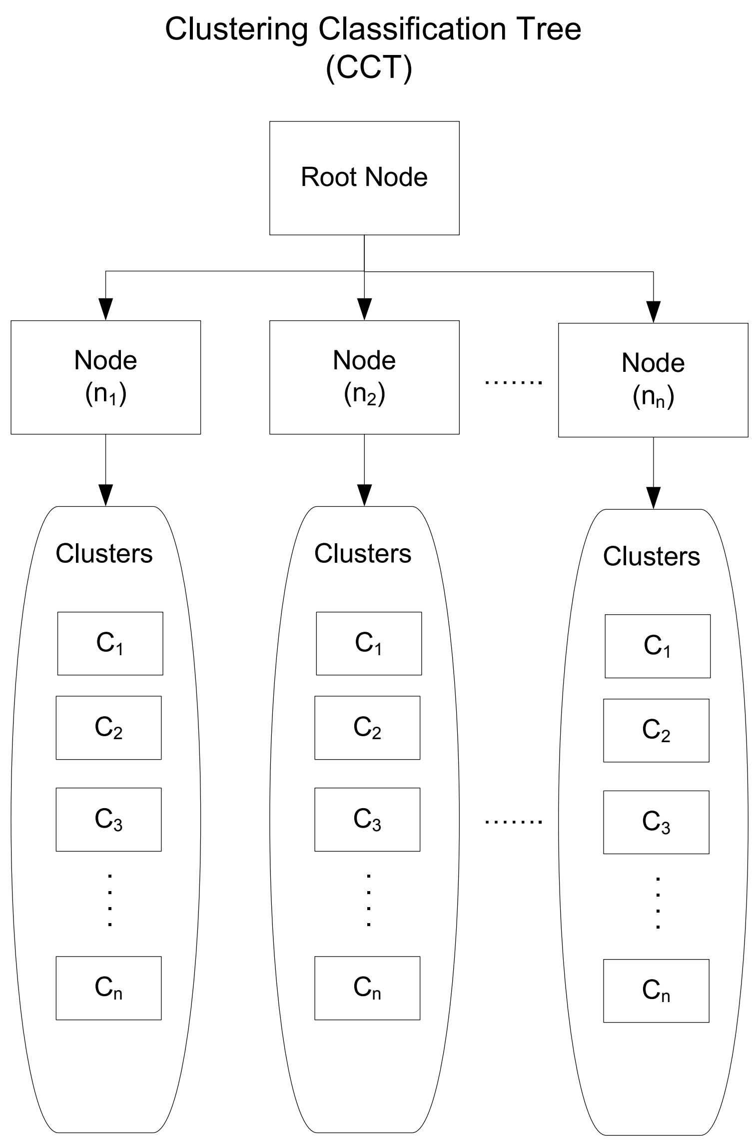


Figure 5. 6: Cluster classification tree

The generic model for CCT is illustrated by following equations (1–3):

$$R_m = \left(\frac{\sum_{i=1}^{N_c}(x_i - C_c)^2}{N_c}\right)^{1/2} \qquad \text{Equation 5. 1}$$

where x_i is a datapoint, N_c is the number of energy profiles of the data set and C_c is the cluster centroid of the data set in which x_i exists.

$$Euclidean\ Distance = d_{euc}(E_{ij}, M_r) = \left\{(E_{ij} - \mathrm{M_r})^2\right\}^{1/2} \quad ; 1 \le j \le d;\ 1 \le i \le N;\ 1 \le r \qquad \text{Equation 5. 2}$$

$$if\ minimum\ of\ \left\{(d_{euc}(E_{ij}, M_r)\right\} < \ Dist_{\mathrm{th}} \rightarrow allocate\ E_{ij}\ to\ r^{th}\ \ group \qquad \text{Equation 5. 3}$$

where $Dist_{th}$ denotes the threshold distance, E_{ij} the time-series datapoint (energy behaviour of the *i*th profile in the *j*th time slot), M_r the centre of the group *r* in the CCT, d_{euc} (E_{ij}, M_r) the Euclidean distance measure between M_r and E_{ij}, *d* is the number of time slots in each time-series and *N* the total number of energy profiles.

5.5.1.2 Step 2: Outlier Detection

Analysis of CCT results presents clusters with homogeneous energy profiles, as well as the individual prosumer profiles, which are stand-alone, or not grouped with any other data-points (as shown in Fig. 5.7). If we further analyse those prosumer profiles, such profiles are distant from other observations, thus being further away from the sample mean. At this stage, we remove such outliers, because in this framework our key objective is to define and characterize optimal PCGs with suitable pre-qualification, whereby these pre-qualification criteria would be used as standard rules to recruit new prosumers in the future. Thus, having such inconsistent energy profiles can adversely affect the definition of standard rules of PCG pre-qualification criteria. Therefore, this phase involves in determining the energy profiles that do not make groups with any other prosumers due to their extremely different energy profiles, i.e. the time-series data which are further away from the rest, thus making them isolated entities in the time-series clustering process.

The output from this phase, which is the non-overlapping prosumer clusters obtained from CCT, after removing the outliers, will become the input to Phase 2: optimization of prosumer clusters and pre-qualification criteria definition.

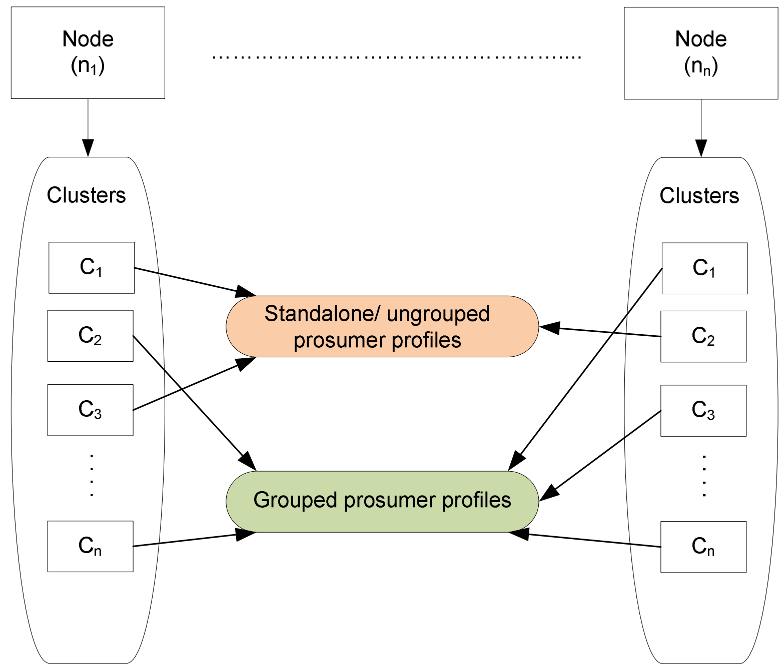


Figure 5. 7: Differentiation of stand-alone and grouped prosumers

5.5.2 Phase 2: Optimization of prosumer clusters and pre-qualification criteria definition

This phase involves optimization of prosumer clusters and pre-qualification criteria definition, which includes two main steps: (i) Step 1: optimization of prosumer clusters and (ii) Step 2: PCG pre-qualification criteria definition. We further illustrate the aforementioned steps in this section.

5.5.2.1 Step 1: Optimization of prosumer clusters

In this step, the number of prosumer clusters created via CCT (without outliers) are optimized into a manageable number of prosumer clusters which will then be represented as PCGs (as shown in Fig. 5.8).

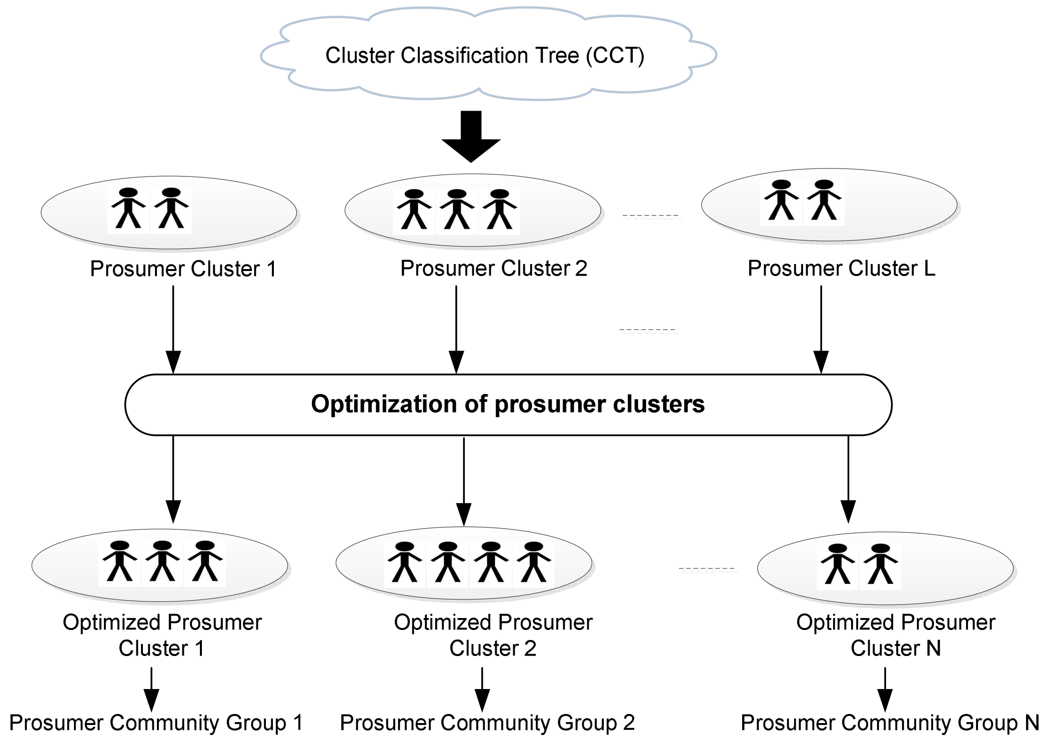


Figure 5. 8: Optimization of prosumer clusters

The number of clusters created via CCT depends on the diversity of the prosumers' energy sharing behaviour data set. If the diversity is high, a large number of prosumer clusters can be presented. In such a case, if these prosumer clusters directly represent the PCGs, having a large number of PCGs may not be economically feasible. Therefore, this stage involves optimizing the obtained prosumer clusters into a viable number of PCGs. In this stage, rebuilding the CCT is done (as shown in Fig. 5.9) by merging two adjacent clusters into one, or splitting the larger clusters (re-clustering into required number of partitions); thus, we endeavour to attain feasible PCGs. This optimal number of clusters can be decided by the user (the community group coordinator) based on the minimum and maximum number of prosumers possible in each PCG, and the minimum and maximum commitment (accumulated energy sharing) expected from each PCG.

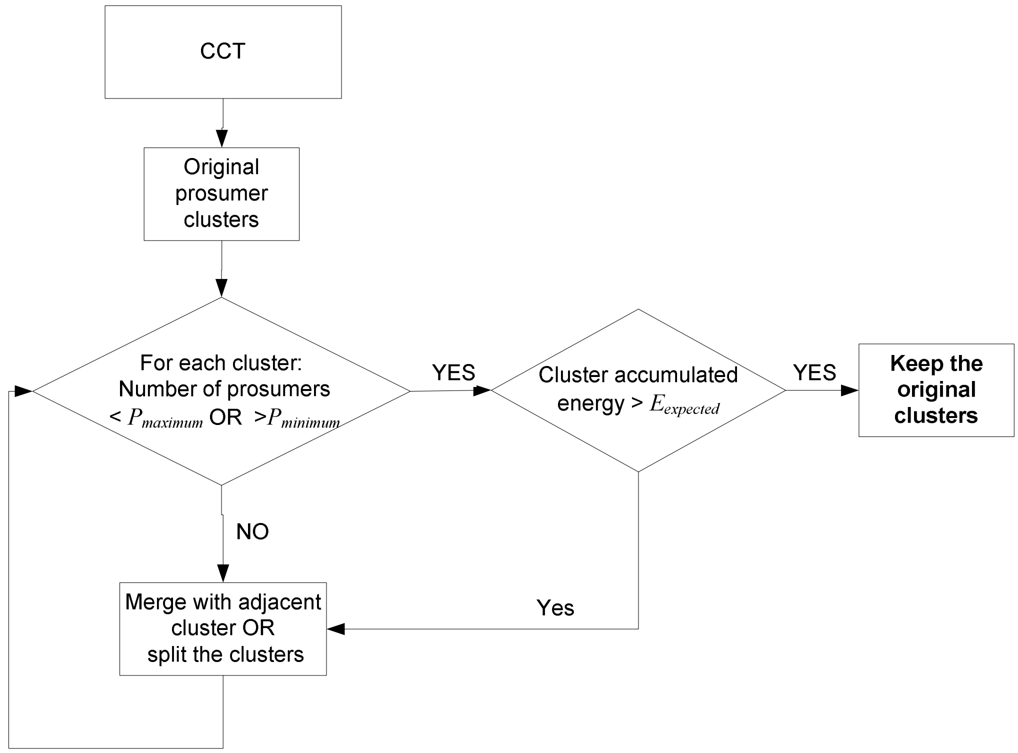


Figure 5. 9: Flowchart for optimizing the clusters

Let $P_{minimum}$ and $P_{maximum}$, respectively, be the minimum and the maximum number of prosumers (energy profiles) expected in each PCG. Let $E_{expected}$ be the minimum accumulated energy expected from each PCG. The number of prosumers (energy profiles) (P_{num}) and the quantity of accumulated energy ($E_{obtained}$) obtained from a considered prosumer cluster is constrained as shown in Equations 5.4 and 5.5:

$P_{minimum} < P_{num} < P_{maximum}$ Equation 5. 4

$E_{obtained} > E_{expected}$ Equation 5. 5

If the accumulated energy expected from the prosumer cluster is less than the expected ($E_{obtained} < E_{expected}$) or the number of prosumers are lower than the optimal number of prosumers ($P_{minimum} > P_{num}$), that prosumer cluster is merged with the most adjacent prosumer cluster and the same process continues until the prosumer cluster meets the requirements for total accumulated energy ($E_{obtained} > E_{expected}$) and the number of prosumers ($P_{minimum} < P_{num} < P_{maximum}$) defined for the PCG.

If the prosumer clusters created by CCT consists of a significantly large number of prosumers, such clusters are split into the prosumer clusters having an optimal number of prosumers adhering the requirements for total accumulated energy ($E_{obtained} > E_{expected}$) and the number of prosumers ($P_{minimum} < P_{num} < P_{maximum}$) defined for the PCG (Fig. 5.10). In order to split the large prosumer clusters, we use global clustering technique *K*-means, the initial number of clusters is defined as 2 (K =2) and the clustering process continues by incrementing the number of clusters (K = 3, 4,…) until both requirements for total accumulated energy ($E_{obtained} > E_{expected}$) and the number of prosumers ($P_{minimum} < P_{num} < P_{maximum}$) are met.

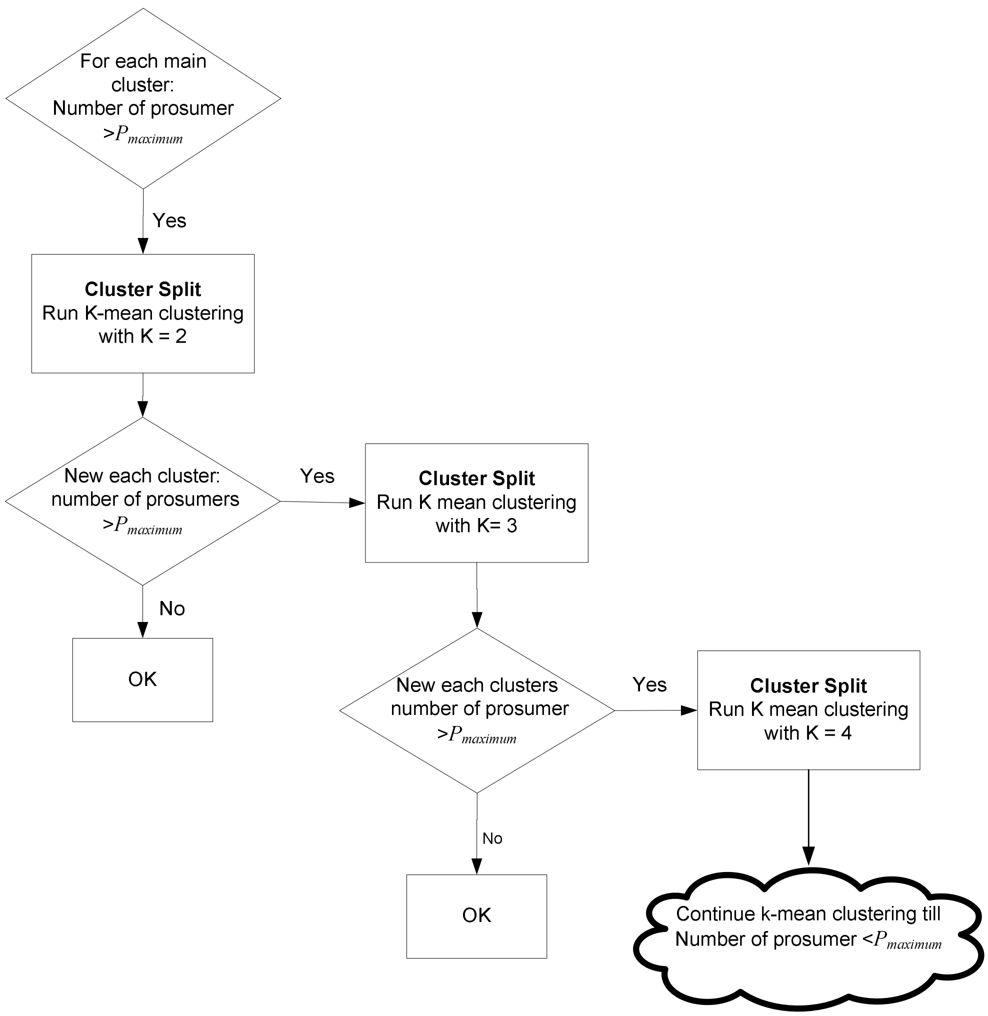


Figure 5. 10: Cluster splitting process

The final outcome of the optimization of prosumer clusters is the optimized prosumer clusters, which are represented as PCGs. In the next phase, each PCGs is analysed to identify its set of characteristics, which is denoted as the PCG's pre-qualification criteria.

5.5.2.2 Step 2: Pre-qualification criteria definition

Once the PCGs are defined, it is necessary to identify their non-overlapping pre-qualification criteria. As mentioned in the earlier sections, the two fundamental characteristics of pre-qualification criteria to identify the prosumers' commitment are the "lower threshold" (L) and the "upper threshold" (U). The two energy thresholds are further categorized based on the two key climate conditions: commitment during an average winter day and the commitment during an average summer day. Accordingly, the following thresholds are defined:

- Upper threshold for expected daily energy commitment during average summer day: U_s
- Upper threshold for expected daily energy commitment during average winter day: U_w
- Lower threshold for expected daily energy commitment during average summer day: L_s
- Lower threshold for expected daily energy commitment during average winter day: L_w

Each PCG defined in Step 1 is characterized with the aforementioned upper and lower thresholds (Fig. 5.11). As shown in Fig. 5.11, the expected member commitment is defined for warm and cool months; for instance, if a prosumer prefers to join Prosumer Community Group 1 (PCG 1) during warm months, his net energy sharing capacity may lie in between or closer to $U_{s,1}$ and $L_{s,1}$. When defining the upper and lower energy thresholds for pre-qualification criteria, we ensure that there is a PCG for any prosumer whose energy commitment is higher than the lowest "lower threshold." For instance, if PCG 1 and PCG 2 are adjacent PCGs, the gap between the upper threshold of PCG 1 and the lower threshold of PCG 2 is zeroed, in which no prosumers can fall within this gap.

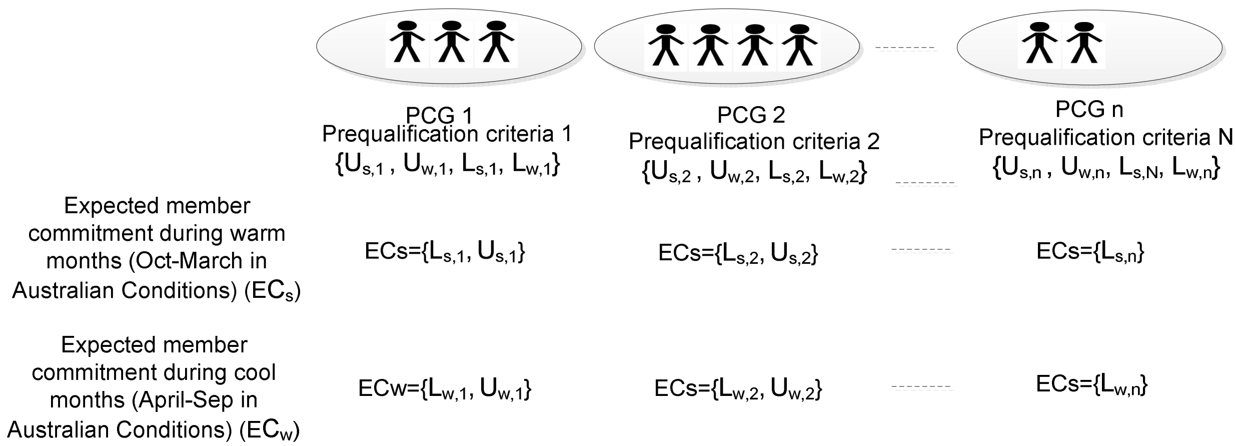


Figure 5. 11: Prosumer community group characterization with pre-qualification criteria

In this section, we have gained a theoretical understanding of how PCGs are defined and characterized with suitable pre-qualification criteria. In the subsequent section, we verify the theoretical concepts we used.

5.6 Verification of the Concepts Used in PCG Definition and Characterization Framework

In this section, we verify the aspects of proposed framework for PCG definition and characterization by conducting a series of simulations.

In this verification, we extensively used MATLAB to verify the concepts we used in developing PCG definition and characterization framework. We use MATLAB statistics toolbox, which is a well-known tool for data processing. MATLAB is a high-level language that provides an interactive environment for numerical computation, visualization and programming. MATLAB has been successfully utilized to analyse data, develop algorithms and create models and applications. The key advantage of MATLAB over spreadsheets or traditional programming languages, such as C/C++ or Java, is that MATLAB has built-in tools and math functions that enable to explore multiple approaches and reach a solution faster.

We first discuss the simulation set-up (experimental setting) used to test the proposed framework.

5.6.1 Simulation set-up

In this section, we illustrate the simulation parameters we used for the verification. We used the following parameters in simulating the PCG definition and characterization framework.

Table 5-2: Simulation parameters to verify prosumer community group definition and characterization framework

Simulation Parameter	Value
Number of prosumers' energy profiles	550
Maximum and minimum threshold distance for outlier detection	1.8–0.1 kW
Minimum number of prosumers expected in each prosumer community group Maximum number of prosumers expected in each prosumer community group	80 200
Minimum accumulated energy expected from each prosumer community group Maximum accumulated energy expected from each prosumer community group	500 kWh 1000 kWh

As shown in Table 5.2, one of the key simulation parameters of the verification is the prosumer energy data set. Obtaining a prosumer energy data set is challenging as actual energy data are publicly inaccessible. Therefore, in order to produce the prosumer energy data set, we model the average prosumers' energy generation and consumption curves during two main weather conditions (summer and winter periods) in Australia. Here, our concern is only on the solar energy generation profiles which are prominent in the Australian domestic environments compared to the other renewable energy sources. In this section, we first discuss about the generation of prosumer energy data set.

5.6.1.1 Generation of Prosumer Energy Data Set

In this section, we develop the solar energy generation curve and the energy consumption curves that we further utilized to generate the prosumer energy data set.

Prosumer's solar energy generation curve

In this section, we model the PV energy generation curve for an average prosumer. Here, the realistic energy profile is developed by capturing the energy generation data from PvWatt Calculator (2014).

We first briefly illustrate the grid-connected solar-electric system parameters that control the parameters of PvWatt Calculator. The output of the solar PV system is influenced by the several fixed parameters of the PV module such as DC rating, array type, the orientation of the panels on the customer's roof (assuming its orientation is preset) and the derate factor (derate factor may slightly change in long-term operation), as well as by the other variable factors like the extent to which the panels are shaded by surrounding trees or infrastructures, the weather conditions, the level of solar radiation in the area in which it is located and the temperature. Theoretically, the following influencing factors are to be considered when we utilize the PvWatt Calculator:

- DC rating of the PV system: This rating is the expected amount of power production from the solar panel in one peak sun hour (power listed on the nameplates of the PV modules). Usually, the PV module power ratings are for standard test conditions of 1000 W/m^2 solar irradiance and 25 °C PV module temperature (Rathnayaka, Potdar et al. 2012). In Australia, the commonly used small-scale PV systems range from 1.5 kW to 5 kW DC ratings.
- Array type: The PV array may be fixed, adjustable or tracking, which the fixed type is the most common type. The tilt angle of the fixed frames cannot be changed and are set at the optimum tilt angle for the system by system designers, whereas adjustable frames allow manually changing the tilt angle throughout the year to enhance the solar output. On the other hand, tracking arrays are autonomously controlled to follow the sun as its path across the sky changes over the day and year. To attain this autonomous operation, an electric motor or refrigerant gas in the frame that uses the heat of the sun is used (Rathnayaka, Potdar et al. 2012).

- Orientation: The amount of power produced by the solar module heavily depends on the amount of sunlight it receives. Thus, if directly pointed at the sun, much power is generated. In Australian conditions, the highest solar output is obtained by facing the solar panels north with a tilt angle of 32° for fixed arrays. However, the tilt angles between 20° and 40° will usually provide 90% effective results.

- Derate factor: However, the average solar system will generate and export approximately 75–80% of its DC-rated power to the grid, since there are losses (around 25% of rated value) involved with mainly cleaning, inverting and transforming power from the solar cells to a usable form. Some of the many other causes that contribute to this factor are the age of the system, wear and tear in components like AC and DC wiring, diodes and connections, etc. (Rathnayaka, Potdar et al. 2012).

We use these factors based on the Australian conditions, in obtaining the data set of solar-electricity generation via PvWatt. Table 5.3 illustrates the parameters used in PvWatt Calculator in obtaining the data set.

Table 5-3: Parameters for PvWatt Calculator

Parameter	Value
Country/city	AUS/NSW[a]
Array type	Fixed Tilt
Array tilt (deg)	32^{o}
DC rating (kW)	1–5kW
DC to AC derate factor	0.77

a. Please note that in developing the energy behaviour profiles of prosumers, we consider the data obtained from NSW.

Figure 5.12 illustrates the prosumers' average hourly solar-electricity generation profile on a summer day and on a winter day for 1.5 kW and 3 kW PV systems (please note that for clarity we present only 1.5 kW and 3 kW in Fig. 5.12). These profiles are obtained by analysing and averaging the data in an entire month of winter (July) and summer (January) in Australia. As illustrated in Fig. 5.12, the solar-electricity power curves have not reached the respective rated power levels of the systems (1.5 kW and 3 kW) even in the summer due to the associated losses. It is obvious that the power curve for the summer shows higher figures than the respective curve for winter due to the higher level of sunlight in the summer.

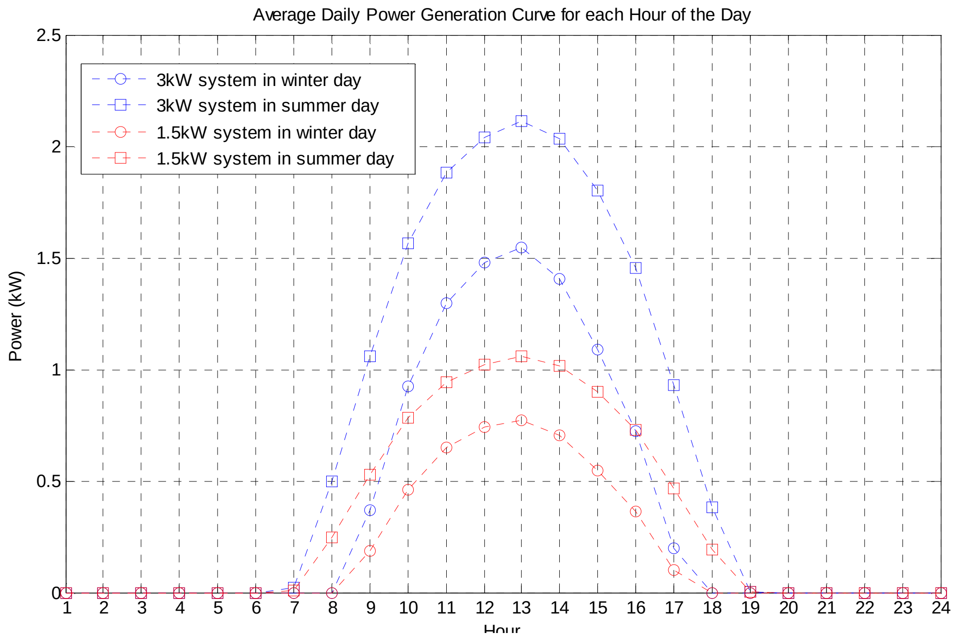


Figure 5. 12: Hourly energy generation over a day

Energy consumption curve

In this section, we briefly describe the energy consumption curve for an average prosumer. Unlike the analysis of energy generation profiles, there are several studies on developing energy consumption profiles for different domestic and commercial environments. The energy consumption pattern in the household is influenced by the power loads operating in the prosumer's premises, which are activated or deactivated, based on the regular and irregular energy requirements of different energy users living in the premises. In addition, the energy profile also fluctuates according to the weather condition, the number of members within the household, occupancy status, etc. Figure 5.13 shows the hourly energy consumption profiles for 24 hours during the summer and winter day in NSW, Australia.

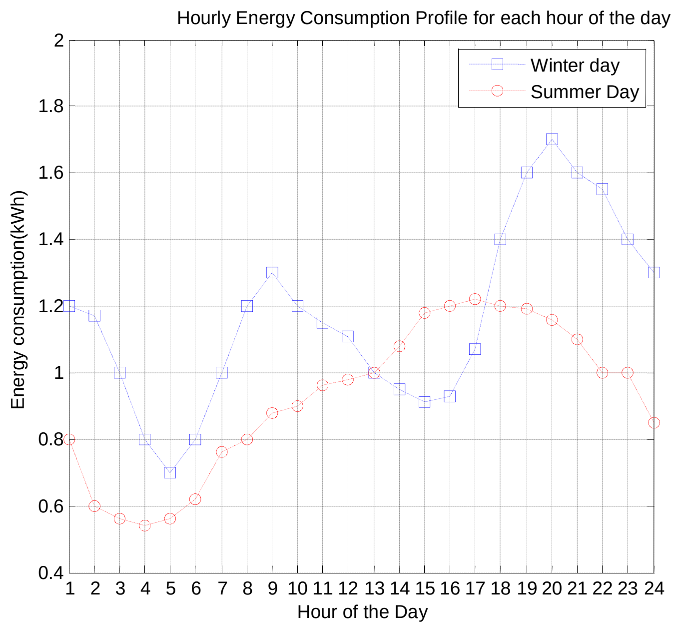


Figure 5. 13: Hourly energy consumption over a day

Following the above illustrated realistic energy consumption, and generation models in Australian conditions, we develop the energy sharing curve for an average prosumer on winter and summer days. In hourly energy profiles, we assume that the prosumers share the energy during the period they have excess energy (i.e. energy generation – energy consumption) and will rely on the energy supplied by the main utility grid during the night to meet their energy shortage.

Energy sharing curve

In this section, we interpret a prosumer's energy sharing curves based on the energy generation and energy consumption profiles we identified in the previous sections. In obtaining the energy sharing profiles, we assume that the prosumers export all the excessive green energy (energy saving) to the grid.

Figure 5.14 shows the hourly energy saving for each hour of a usual winter day and a summer day when utilizing 1.5 kW and 3 kW PV system for solar-electricity generation. According to Fig. 5.14, it is clearly seen that if there is no sufficient solar radiation (early morning and night) to produce adequate electricity to fulfil the energy demand, the prosumer has to depend on the energy supplied by the main grid. This situation becomes worse during the winter season. However, if there is excess solar energy, the prosumer can exchange it with the main grid for feed-in tariff.

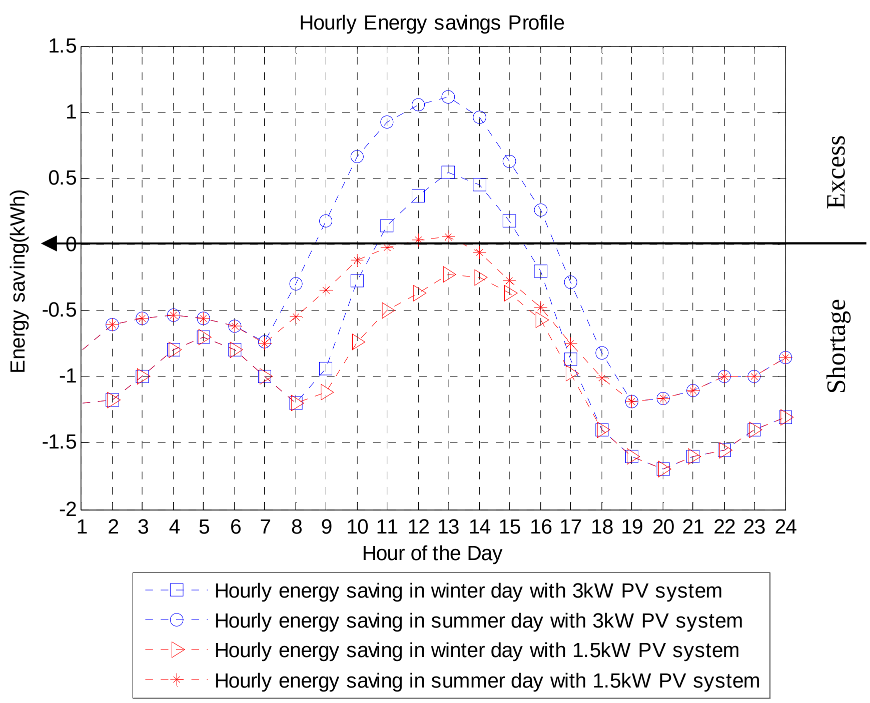


Figure 5. 14: Hourly energy consumption over a day

Following this energy sharing curve, we randomly generate 550 energy sharing profiles (Rathnayaka, Potdar et al. 2012), which are used in verifying the proposed framework for PCG definition and characterization. The results, observations and discussion are presented in the next section.

5.6.2 Results, observation, validation and discussion

In this section, the theoretical aspects used by the proposed framework are evaluated. As mentioned in Section 5.5, the theoretical foundation of the proposed framework was discussed in two sections: (i) time-series clustering and outlier detection and (ii) optimization of prosumer clusters and pre-qualification criteria definition.

We first verify the time-series clustering and the outlier detection of the hourly energy sharing behaviours of 550 energy behaviour profiles that we detect the prosumers with unreasonable energy sharing behaviours (outliers). As mentioned earlier, we use CCT to achieve time-series clustering and remove the unreasonable behaviours. As shown in Table 5.2 (simulation set-up), we use the initial maximum threshold distance ($Dist_{th}$) (the radius of the data set as shown in Equation 1 in Section 5.5) at 1.8 kWh and minimum $Dist_{th}$ at 0.1 kWh. The threshold distance $Dist_{th}$ is reduced iteratively until all the outliers (stand-alone) energy profiles are detected subject to the minimum $Dist_{th}$ at 0.1 kWh. Figure 5.15 illustrates the identification of outliers in the energy sharing data set.

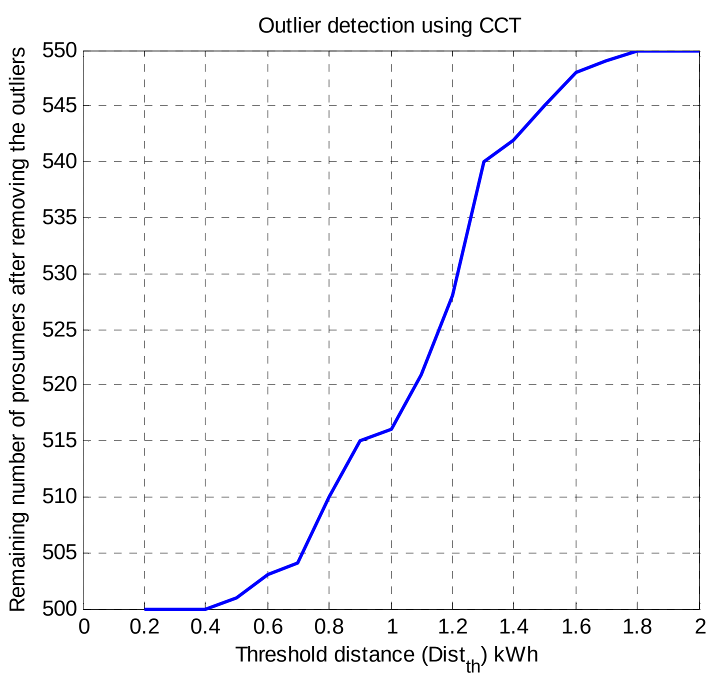


Figure 5. 15: Identification of stand-alone energy behaviours with the change of threshold distance

As shown in Fig. 5.15, the threshold distance ($Dist_{th}$) is illustrated in the *X* axis, which is reduced from 1.8 kWh to 0.1 kWh and, accordingly, more stand-alone energy sharing profiles (outliers) are identified, thus reducing the number of reasonable energy profiles for clustering (*Y* axis). All the outliers have been identified at $Dist_{th} = 0.4\ kWh$ in which the number of preferred energy sharing profiles remains constant afterwards. In the considered data set of 550 energy profiles, 50 profiles are identified as stand-alone (outliers), resulting in 500 acceptable energy profiles to be used for further processing to define and characterize PCG definition and characterization.

The resulting 500 time-series energy profiles that are obtained after removing the outliers are clustered into different prosumer clusters using CCT (Guojun, Chaoqun et al. 2007) described in Section 5.5. The time-series data set that we used results in eight clusters. Figure 5.16 illustrates the number of energy profiles allocated to each cluster where C1 to C8 denote the prosumer clusters produced in an eight-cluster set-up. Figure 5.17 illustrates the accumulated daily energy that each cluster is able to share on an average winter day and average summer day.

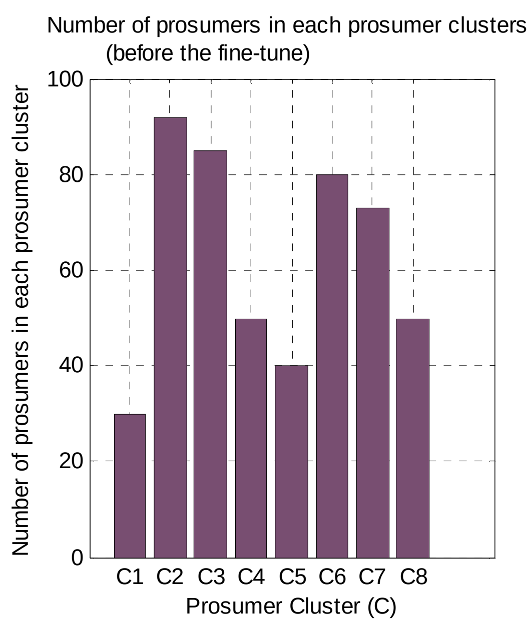


Figure 5. 16: Number of prosumers in each prosumer cluster in eight-prosumer cluster set-up

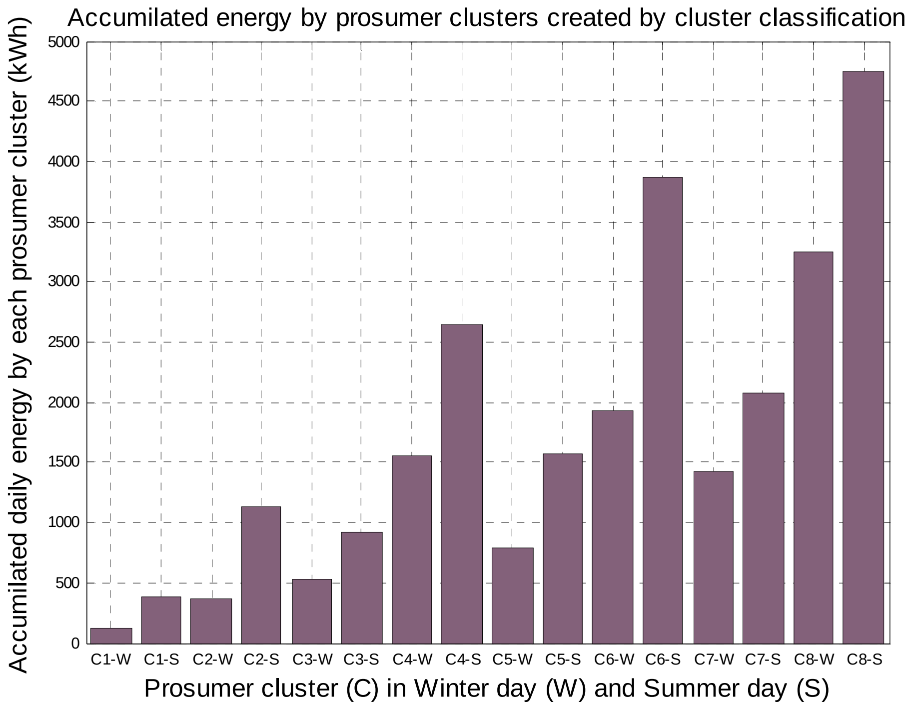


Figure 5. 17: Amount of daily energy supplied by each prosumer cluster in eight-prosumer cluster set-up on winter day and summer day

However, as shown in Fig. 5.16, with eight prosumer clusters, there are some clusters with a small number of energy profiles allocated; for instance, prosumer clusters C1 and C5 have even less than 50 energy profiles allocated to each. However, having many PCGs with a small number of prosumers may cause unnecessary overheads and inefficiency. In fact, having an effective number of members in each PCG makes the process of managing prosumers much more efficient as the prosumer community coordinator does not have to worry about interacting with many small PCGs. Therefore, in this scenario, the optimization of the number of clusters by merging the adjacent prosumer clusters is done in order to meet the expected number of members in the PCGs (100–200 prosumers in each PCG).

Moreover, according to Fig. 5.17, it is visible that with the eight prosumer clusters, some prosumer clusters do not share sufficient accumulated energy per day as expected particularly in winter days; for instance, as shown in Fig. 5.17, the prosumer cluster 1 and prosumer cluster 3 offer less than 500 kWh per day as opposed to the expectations of the PCG. In fact, if the PCGs fail to supply adequate amount of energy to the energy buyers, such PCGs may not enjoy a stronger bargaining power in the long term and even cause unreliable energy transfer in the energy sharing marketplace followed by unsustainable PCGs. Therefore, in this scenario, the optimization of the number of clusters is done by merging the adjacent prosumer clusters in order to meet the expected accumulated energy requirement from the members of PCGs (>500 kWh), while meeting the expected number of members in each PCG at the same time.

We optimize the originally obtained prosumer clusters into an optimal number of PCGs in order to reach the maximum and minimum number of members expected in each PCG and the minimum number of accumulated energy from each PCG.

For this data set, we reduce the number of clusters into four PCGs by merging the neighbouring two clusters into one to ensure each cluster includes a manageable number of prosumers (we assume at least 100 prosumers) in each PCG, and each cluster produces an adequate quantity of accumulated energy (at least 500 kWh per day). These finalized clusters were presented as PCGs.

Figure 5.18 illustrates the total number of energy profiles allocated to each PCG once optimized with four PCGs. Similarly, Fig. 5.19 demonstrates the accumulated daily energy that each PCG can share in the community-based energy sharing network.

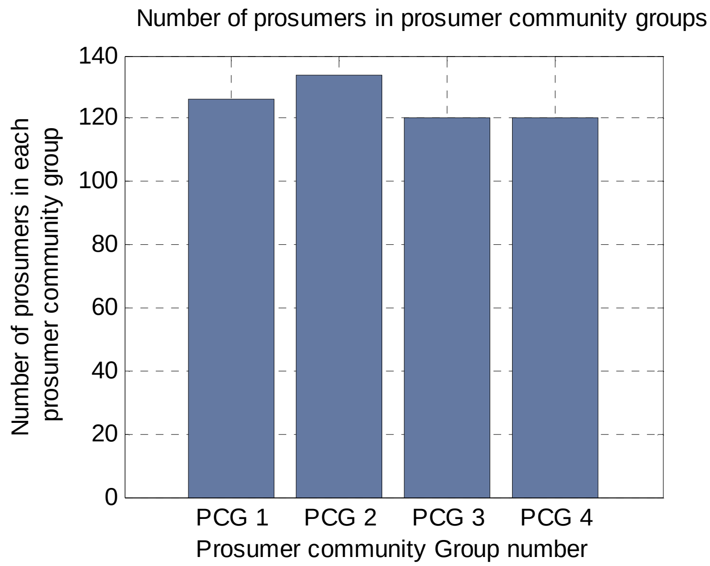


Figure 5. 18: Number of prosumers in each prosumer cluster in four-prosumer cluster set-up

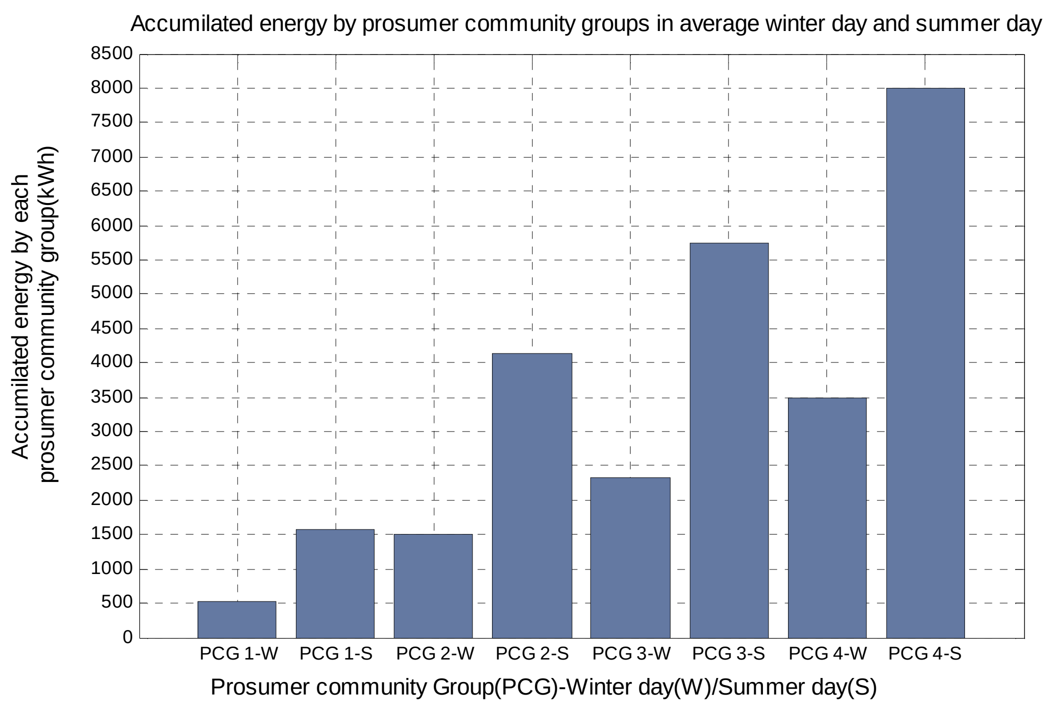


Figure 5. 19: Amount of daily energy supplied by the four prosumer community groups onn average winter and summer day

Figure 5.20 illustrates the basic view of how prosumers' energy profiles are distrusted in four PCGs. Accordingly, it is certain that during daytime the average energy level mostly shows positive energy sharing figures, in which prosumers share the excess solar energy, and during the late evening, night and the early morning, the energy level becomes negative as there is no solar energy generation; thus, prosumers show solar energy shortage (thus, they rely on the energy supplied by the main utility grid to meet their energy shortage). Therefore, the prosumers' effective energy sharing occurs only during the daytime. When defining daily energy thresholds (upper threshold and lower threshold) for PCGs, we only consider the time duration of the day in which effective energy sharing occurs. For this simulation, we consider the energy sharing (excess energy) between 7 a.m. and 7 p.m. for an average summer day and 8 a.m. and 4 p.m. for an average winter day.

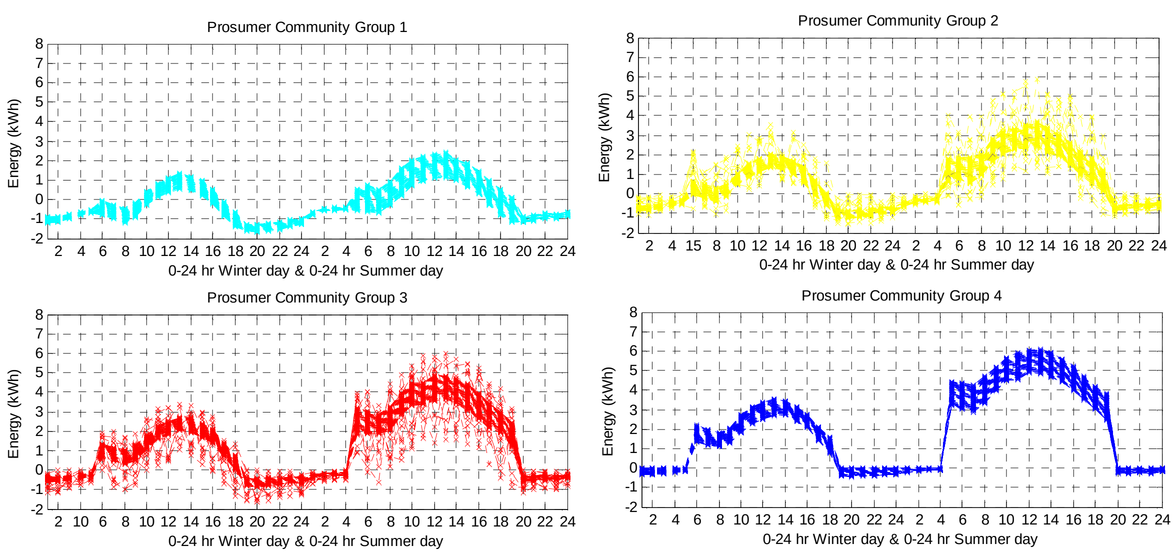


Figure. 5.20. Distribution of prosumers' energy sharing profiles in four prosumer community groups

Based on those energy boundaries, the upper and lower energy thresholds of PCGs are defined as shown in Table 5.4.

Table 5-4: Prosumer community group pre-qualification criteria

Prosumer community group	Season	Average energy (kWh)	Pre-qualification criteria	
			Lower energy threshold	Upper energy threshold
Prosumer Community Group 1	Summer	10.9998 kWh	5	17
	Winter	2.5156 kWh	2	3
Prosumer Community Group 2	Summer	26.7195 kWh	17	36
	Winter	9.3584 kWh	3	16
Prosumer Community Group 3	Summer	41.7607 kWh	36	47
	Winter	15.3171 kWh	16	15
Prosumer Community Group 4	Summer	59.0678 kWh	47	71
	Winter	22.4479 kWh	15	30

These upper and lower energy thresholds characterize the PCGs' entry requirements (or pre-qualification criteria). Table 5.4 illustrates the pre-qualification criteria for different PCGs on an average winter day and summer day. The pre-qualification criteria are advertised among the interested prosumers in order for them to obtain a better understanding about the entry requirements to the community-based energy sharing network.

5.7 Conclusion

In this chapter, a PCG definition and characterization framework was proposed to categorize the prosumer profiles into feasible PCGs, while defining the pre-qualification criteria for each PCG. The pre-qualification criteria defined for each PCG can be utilized when recruiting new prosumers, i.e. the new prosumers may be required fulfil the upper and lower thresholds defined for a PCG in order to receive the membership of the corresponding PCG.

Moreover, MATLAB simulations are present to verify the PCG definition and characterization framework.

This proposed framework has been published in a peer-reviewed international journal(Rathnayaka, Potdar et al. 2014), wherein we have attached a complete list of all the publications arising as a result of the research study carried out in this thesis at the beginning of the thesis.

The following chapter provides the detailed framework for new prosumer recruitment for predefined PCGs.

Chapter 6

Prosumer Recruitment Framework

This chapter provides:

- Introduction to prosumer recruitment to predefined PCGs
- Presentation of a framework to recruit prosumers to the PCGs
- Analysis of proactive mechanism to monitor and evaluate the real-time commitment of new prosumers and differentiate the complying (stable) and non-complying (unstable) prosumers before recruiting them to a predefined PCGs
- Verification of the proposed framework for prosumer recruitment

6.1 Introduction

In the last chapter, we instigated the framework for the PCG definition and characterization, where the prosumer community coordinator analyses a set of energy profiles and categorizes them into different groups, thus defining and characterizing PCGs with appropriate pre-qualification criteria. On that framework for PCG definition and characterization, the prosumer community coordinator relies on the prosumers' historic energy behaviour profiles when deciding the pre-qualification criteria for each PCG. However, it is important to evaluate the prosumer's real-time energy profiles before offering them the membership in the corresponding desired PCG, particularly if a prosumer has recently started green energy generation and showed an interest in joining a PCG. In addition, even if the prosumer has a record of historic energy generation profiles, assigning their memberships based on their real-time energy profiles would allow the prosumer community coordinator to obtain a better understanding of the prosumers' commitment towards the sustenance of the PCGs in an up-to-date environment, rather than merely relying on their historic energy behaviours.

In this chapter, we propose an approach for new prosumer recruitment to the predefined PCGs by which the prosumer community coordinator evaluates the new prosumers' real-time commitment over a period and assigns them to appropriate PCGs.

In Section 6.2, we explain the aspects of framework of recruiting prosumers to the PCGs. In Section 6.3, we discuss the requirements for this framework followed by the design rationale in Section 6.4. In Section 6.5, we discuss the theoretical foundation of this framework, followed by verification of the framework in Section 6.6. Section 6.7 concludes the chapter.

6.2 Overview of the Prosumer Recruitment Framework

This framework presents an innovative solution to recruit the new prosumers to the predefined PCGs. In this section, we provide an overview of prosumer recruitment framework in detail.

Figure 6.1 illustrates the concise overview of the prosumer recruitment framework. The input for this framework is the real-time energy behaviour profiles of the new prosumers who have shown interest in joining the PCGs. We call these prosumers "*Registered Prosumers,*" who have registered their interest towards the community-based energy sharing network. In this framework, we assume these registered prosumers are new to the green energy sharing process; thus, there are no previous energy sharing profiles to come up with conclusions, therefore have to rely on the real-time energy sharing behaviours. The ultimate output of this framework is recruiting the registered prosumers to suitable PCGs and assigning them suitable membership levels. We use the term "*fixed prosumer community group*" to denote the finalized PCG of the prosumers.

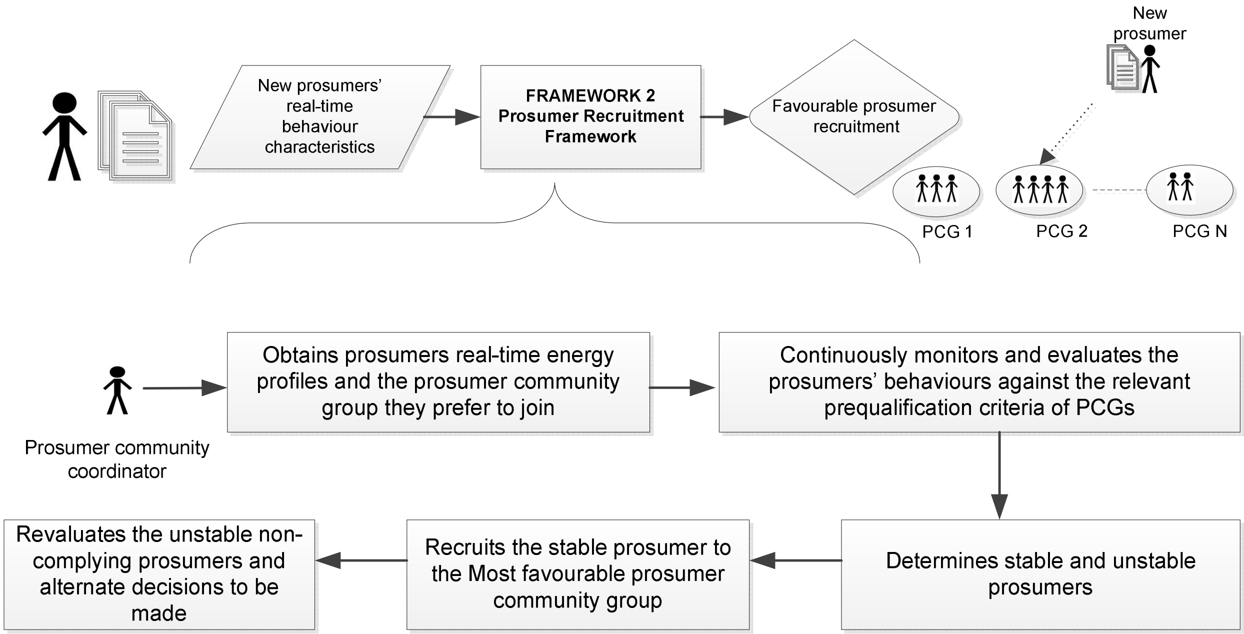


Figure 6. 1: Concise overview of the prosumer recruitment framework

Figure 6.2 illustrates the flow of interactions that can occur between the new prosumer and the prosumer community coordinator when recruiting them to the fixed PCGs. As shown in Fig. 6.2, the prosumers can register their interest towards the community-based energy sharing network. Then the prosumer community coordinator notifies the different PCG pre-qualification criteria, which include a range of activities that need to be delivered by the prosumer to become a member of available PCG. As discussed in the last chapter, the two key attributes of the pre-qualification criteria of a PCG is the "*upper threshold*" and the "*lower threshold*," where the "*lower threshold*" of a PCG is the least quantity of energy, which a new prosumer may agree to share to receive the membership of the corresponding PCG, and the "*upper threshold*" of a PCG is the highest quantity of energy that the new prosumer may agree to share when obtaining the membership of the corresponding community group.

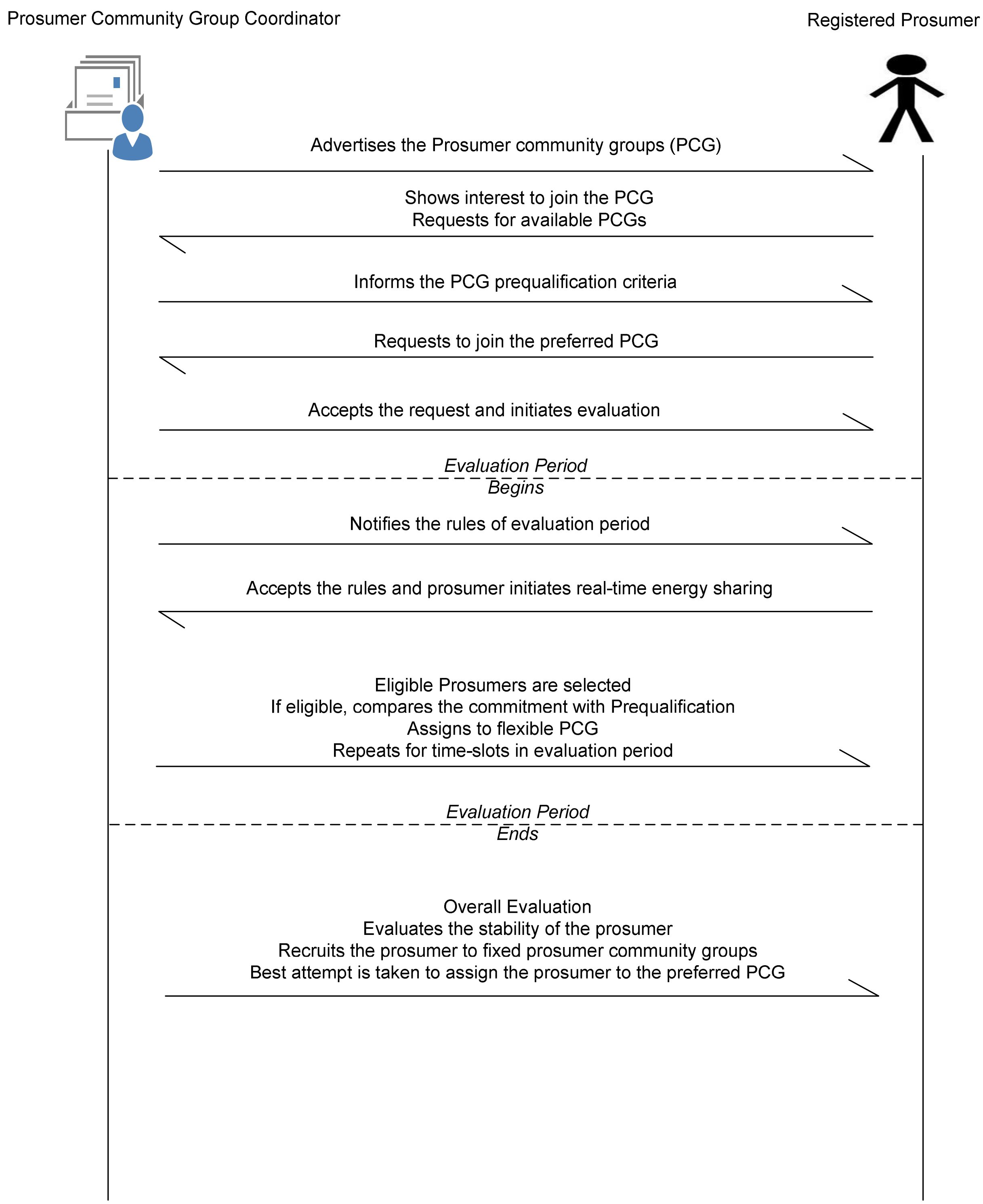


Figure 6. 2: Abstract flow of prosumer evaluation (evaluation period)

The prosumer chooses the PCG that he is interested to join, which we termed as "*preferred prosumer community group*." The prosumer community coordinator initiates the "*evaluation period*," which is denoted as the defined period of time which involves the evaluation of prosumers before assigning them to the fixed PCG. Accordingly, the prosumers are notified the evaluation rules and governance with which prosumer must comply during the evaluation period. The fundamental benefit of introducing an evaluation period with a number of time slots to evaluate the prosumers, rather than relying on the prosumers' behaviours in a single time slot, is that the community coordinator can get a better understanding of the behaviours of registered prosumers before recruiting them permanently to the PCGs.

The key processes involved during the evaluation period are illustrated as follows: the *prosumer community coordinator* requests the registered prosumer to share the energy for a specific number of time slots. The prosumer's real-time energy sharing performances are assessed in each time slot, and if that prosumer's performances meet the lowest commitment expected to join any of the PCG, that prosumer is termed as an "*eligible prosumer*." This lowest commitment expected to join any of the PCG is termed as "*eligible energy threshold*." The prosumer's performances are then evaluated based on the pre-qualification criteria of the preferred PCG and if that prosumer's performances are acceptable for that PCG, he is assigned to the corresponding preferred PCG in temporary basis. If the prosumer's performances do not meet the expectations of his preferred PCG, but meets the expectations of other PCG, he is given a recommendation to join other PCGs. The PCG where the prosumers are assigned in each time slot over the evaluation period in temporary basis is termed as "*flexible prosumer community group*." At the end of the complete evaluation period, the prosumer community coordinator evaluates the overall performance of the prosumers and differentiates the "*stable prosumers*" and "*unstable prosumers*,". The "*stable prosumers*" denote the complying prosumers who meets the expectations of any PCG to the acceptable level and has successfully completed the evaluation period and the "*unstable prosumers*" denote the non-complying prosumers who fails to meet the expectations of any PCG at the end of the evaluation period. The "*stable prosumers*" are recruited to the most suitable PCG on a permanent basis; the best attempt is made to recruit the prosumers to their preferred PCG. As mentioned above, this permanent PCG is termed as "*fixed community group membership*." Finally, the prosumer community coordinator initiates the "*energy contract*" with the prosumers recruited to the fixed community group membership, where this energy contract refers to the formal agreement between the prosumer and the prosumer community coordinator that takes place when the prosumer is recruited to a fixed PCG, and it sets out the terms which allow the virtual connection of the prosumer's renewable energy resource to a PCG's accumulated energy pool.

In the following section, we discuss the requirements for this research.

6.3 Requirements

This section represents the *first* stage of the conceptual process where requirements are elicited and prioritised. The following requirements are laid down for the proposed solution:

1. **Determine an approach for prosumer evaluation:** The prosumer monitoring and evaluation scheme should clearly define how these new prosumers are evaluated, for instance, the duration of the time space, which the new prosumers are evaluated before allocating them to the PCGs, the scale of evaluating the prosumers' commitment and the expectations from the prosumers.

2. **Continuous monitoring and evaluation of the prosumers' real-time energy behaviours:** The solution should facilitate monitoring and evaluation of the new prosumers' real-time energy sharing profiles over a specified period of time before recruiting them to the PCGs. An ongoing evaluation process of real-time energy sharing is essential, particularly if there are no historical data of energy sharing to make a predictive decision when recruiting them to the relevant PCG.

3. **Determine stable prosumers before assigning them to the fixed membership in PCGs:** The solution should identify the prosumers' fluctuating energy behaviours over time, thus clearly differentiating the complying stable prosumers from the rest during the recruitment process. This

process becomes more challenging, when the prosumer is new to the energy sharing/green energy generation process; thus, no historical energy sharing/energy generation behaviour data are available to make the decision.

This concludes stage 1 of the conceptual process. The design rationale which is discussed in the following section is based on the above-mentioned requirements. A design decision for each requirement is made in the design rationale accompanied by a discussion of how the requirement is fulfilled.

6.4 Design Rationale

This section provides a design rationale to meet all the requirements listed above. This is the *second* stage of the conceptual process. The following design decisions are proposed in order to address each requirement. The concise overview of the design decisions are shown in Fig. 6.3

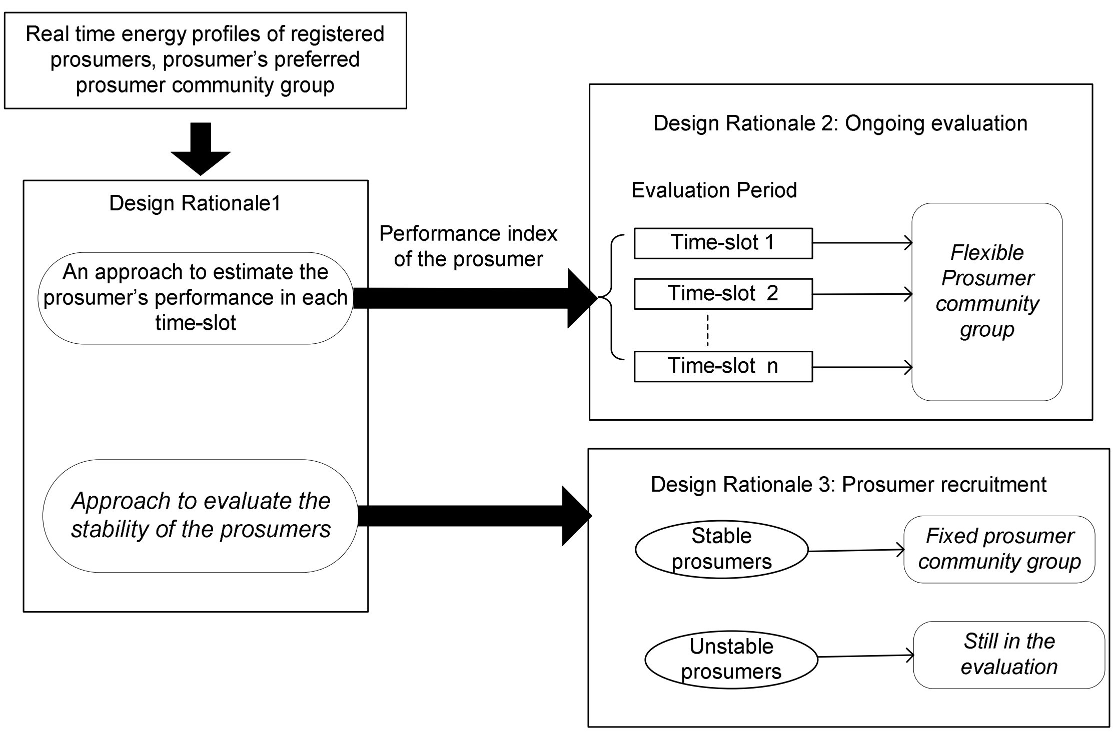


Figure 6. 3: Concise overview of the design decisions

1. **Design rationale 1:** In order to recruit a prosumer to the preferred PCG, it is necessary to evaluate his energy contribution against the pre-qualification criteria of the preferred PCG. The evaluation technique we suggested in this chapter is the key backbone of this prosumer recruitment framework. The prosumers' real-time energy behaviours involve chance of variation and we propose performance indices to measure the prosumers' likelihood of meeting the pre-qualification criteria of the preferred PCG (*approach to determine the prosumer's performance in each time slot of the evaluation period*). Moreover, we propose an approach to recruit the prosumers to the suitable PCG (*approach to recruit the prosumer to the most favourable PCG*). This would satisfy the requirement for determining an approach to evaluate the prosumers' real-time energy sharing behaviours (Req. 1).

2. **Design rationale 2:** In order to evaluate the new prosumers continuously over a period before recruiting the prosumers to the finalized PCG, we propose an ongoing evaluation using an "evaluation period," where the evaluation period includes several predefined consecutive time slots. This would satisfy the requirement for continuous monitoring of prosumers (Req. 2).

3. **Design rationale 3:** In order to identify the stable prosumers, we introduce the stability index (SI), which analyses the prosumer's overall performance at the end of the evaluation period. This would satisfy the requirement for differentiating stable and unstable prosumers (Req. 2).

In the development of the solution for prosumer recruitment, the above design decisions should be considered. All these design decisions are included in the proposed method to recruit new prosumers to the predefined PCGs. This concludes stage 2 of the conceptual process. The next stage is the theoretical foundation for the proposed solution.

6.5 Theoretical Foundation

In this section, we discuss the theoretical foundation for the prosumer recruitment framework, which represents the *third* stage of the conceptual process. The theoretical foundation of this framework is discussed with four components, which we briefly illustrate as follows.

The key backbone of the framework includes four processes: (i) development of an approach to evaluate the prosumer's energy sharing performance (Section 6.5.1), (ii) process of evaluating the prosumers energy sharing transactions during the evaluation period (Section 6.5.2), (iii) development of an approach to evaluate the stability of the prosumers (Section 6.5.3) and (iv) recruitment of the prosumers to the fixed PCGs after the evaluation period (Section 6.5.4). The conceptual method presented in the processes evaluates the variable nature of prosumers' real-time energy behaviours in every time slot of the evaluation period and allocates them to the flexible PCGs (which is temporary basis). Afterwards, the prosumer's overall behaviours in the complete evaluation period are evaluated and recruited to the fixed PCGs (which is under a permanent basis). The proposed solution, which is explained above, addresses all of the requirements described in Section 5.3 . The next sections provide a detailed description of the aforementioned parts of the theoretical development.

6.5.1 An approach to estimate the prosumer's energy sharing performance in each time slot

The first component of the evaluation technique is evaluating the prosumer's energy sharing performance. For a better understanding, we first explain the aspects of the evaluation period as follows.

6.5.1.1 Evaluation period

As discussed in the previous chapters, the "*Evaluation Period*" is characterized by a finite period of time defined by the prosumer community coordinator to evaluate the early behaviours of the prosumers, who has shown interest in joining the community-based energy sharing network.

This evaluation period is divided into non-overlapping, mutually exclusive time slots, and each time slot is assigned with an energy transaction between the prosumer and the prosumer community coordinator. Here, the prosumer community coordinator analyses the prosumers' real-time energy behaviours in a set of consecutive predefined number of energy transactions (analogous to time slots) over that given finite period of time, i.e. evaluation period.

The community group coordinator evaluates the performance of the prosumers in each energy transaction (or each time slot) within the evaluation period, as well as evaluates the prosumer's stability at the end of the evaluation period. In the subsequent section, we explain the approach used to determine the prosumer's performance in each time slot of the evaluation period.

6.5.1.2 The proposed approach

The concise overview of the approach is shown in Fig. 6.4.

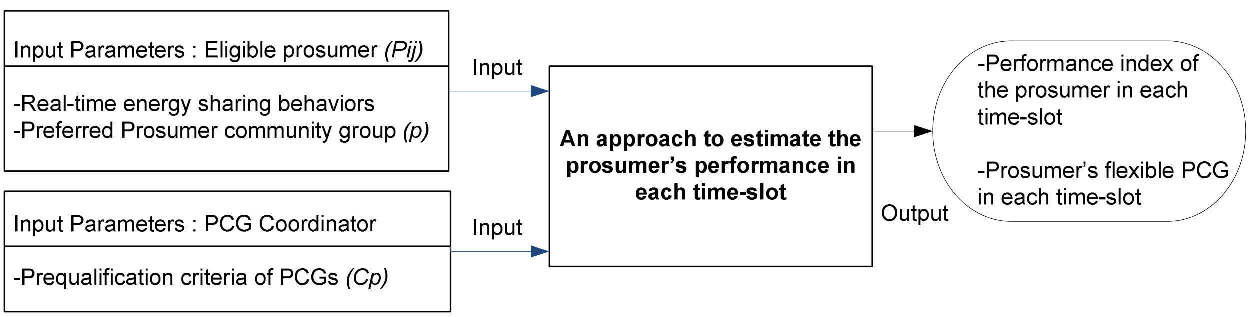


Figure 6. 4: A concise overview of the approach to evaluate prosumers in each time slot

As shown in Fig. 6.4, the key inputs to this approach can be categorized into two components: the input from the eligible prosumer and inputs from the prosumer community coordinator. The input parameters from the eligible prosumer include the prosumer's real-time energy sharing behaviours in a time slot and the prosumer's preferred PCG (the PCG which the prosumer is interested to join). Inputs from the prosumer community coordinator comprise the pre-qualification criteria of the available PCGs.

In this approach, the prosumer's energy sharing performances are evaluated based on the pre-qualification criteria of the preferred PCG using a probabilistic approach.

The main outputs of this approach are the "performance index" and the flexible PCG of the prosumer in each time slot. For a better understanding, we first introduce the term "performance index" that we use in this approach. The "performance index" visualizes the rate of success and failure of a prosumer in fulfilling the pre-qualification criteria of the preferred PCG. To identify and represent semantically the different levels of success and failure, we propose and define the "semantics of performance indices" (as shown in Table 6.1). In fact, each performance index value quantifies and represents a different magnitude or success rate of performance in the energy sharing behaviour.

Table 6-1: Semantics of performance indices

Semantics of performance index	Rate of success/failure	Performance index
Total success	100% (Certain)	3
Medium success	90%-99.99%	2
Low success	80%-89.99%	1
Failure	0-79.99%	−1

The performance indices range from [−1, 3], where 3 represents the total success and the performance index increases with the increase in rate of success. Here, we assume the prosumers should at least exhibit 80% of success in meeting the pre-qualification criteria of the preferred PCG in order to be obtain positive (+) performance index with respect to the preferred PCG. If the rate is less than 79% in meeting the predefined pre-qualification criteria of a preferred PCG, we use the term "failure."

We choose to have a single integer representing each performance index, for the range of success/failure rate covered by it. Using such a domain is more expressive and can represent different levels of performance according to their success/failure rate. In fact, various indices of performance present in prosumer behaviours cannot be modelled accurately when they are determined or expressed by using just two superlatives or extremes, such as "high" or "low." Hence, in order to determine and model the performance of the prosumers more accurately, the various levels of performance should be identified first according to their semantics.

Moreover, we also express semantically each value of the performance index, as it would be advantageous and beneficial for the prosumer community coordinator to assimilate performance of the prosumer in energy sharing.

The semantics corresponding to different performance indices are illustrated as follows.

- **Total success**

The first level of the semantics is termed the "total success" and its corresponding performance index is 3. This level suggests that the rate of success in interacting with the prosumer in energy sharing process is 100%. This level on the performance index suggests that at a given point in time and with respect to pre-qualification criteria of the preferred PCG, the prosumer is extremely reliable to meet the desired pre-qualification criteria of the corresponding PCG. The performance index of 3 expresses the highest level of success possible in an energy sharing transaction.

- **Medium success**

Medium success is the second level on the performance level with the corresponding performance index value of 2. This level denotes that there is a 90–99.99 % rate of success in interacting with that prosumer in energy sharing process. This level on the performance index depicts that at a given time slot and with respect to the defined pre-qualification criteria, the prosumer's reliability in meeting the pre-qualification criteria is significantly high. In other words, a performance index of 2 indicates that there is a significant level of success in the energy transaction, as the prosumer at that given time slot will commit to a large extent to the expectations of the pre-qualification criteria.

- **Low success**

The third performance level is termed as low success, and it is represented by a performance index of 1. This level outlines that there is 80–89.99 % rate of success in a time slot in energy sharing. A performance index of 3 assigned to a prosumer under evaluation suggests that at that particular time slot, the prosumer slightly meets the expectations in pre-qualification criteria, possibly resulting in a low success in the energy sharing.

- **Failure**

The fourth performance level on the performance index is defined as failure with a corresponding performance index value of −1. This level depicts that there is 0–79.99% rate of success that the prosumer meets the pre-qualification criteria of the preferred PCG. This performance level suggests that at a given time slot of the evaluation period, the prosumer does not meet at least 79.99% of commitment defined at the pre-qualification criteria of the preferred PCG, and indicates that the prosumer assigned with this value cannot be fully relied upon for the corresponding PCG, thus requiring the selection of a different PCG that is more suitable to him.

The mathematical formulation of the aforementioned performance indices is illustrated in Equation 6.1. For any time slot *(j)* of the evaluation period, the rate of success (*Rate*) of the prosumer (P_{ij}) being allocated to preferred flexible PCG (C_p):

$$\mathrm{Rate}(\mathrm{P_{ij}} \in \mathrm{C_p}) \begin{cases} 100\%: \text{if } \mathrm{E_{ij}} \geq \mathrm{L_p} \\ \frac{\mathrm{E_{ij}}}{\mathrm{L_p}}: \text{if } \mathrm{E_{ij}} < \mathrm{L_p} \end{cases} \qquad \text{Equation 6. 1}$$

$Rate(P_{ij} \in C_p)$ = 100% → Performance index of prosumer P_{ij} = 3, Semantic= Total success

89.99% < $Rate(P_{ij} \in C_p)$ < 99.99% → Performance index of prosumer P_{ij} = 2, Semantic= Medium success

80% < $Rate(P_{ij} \in C_p)$ < 89.99% → Performance index of prosumer P_{ij} = 1, Semantic= Low success

$Rate(P_{ij} \in C_p)$ < 79.99% → Performance index of prosumer P_{ij} = −1, Semantic= Failure where P_{ij} is an i^{th} prosumer's performance in the j^{th} time slot, C_p is the preferred PCG, E_{ij} is the real-time energy commitment of the i^{th} prosumer's performance in the j^{th} time slot and L_p is the lowest energy threshold of the preferred PCG.

6.5.2 The evaluation of prosumers' real-time energy sharing behaviours during the evaluation period

The involved process of ongoing evaluation during the evaluation period is illustrated in Fig. 6.5. In this process, the prosumer community coordinator attempts to assign the prosumer into his preferred PCG in each time slot of the evaluation period.

The key steps involved in this process can be described as follows: The prosumer community coordinator requests the registered prosumer to supply the energy in real time for n number of time slots in the evaluation period (analogous to n number of energy transactions). For each time slot, real-time energy measurement is compared with the eligible energy threshold (E_{th}), which is the minimum energy requirement to join any PCG. If that prosumer's supplied energy is equal or greater than the eligible energy threshold (E_{th}), this prosumer is considered as an eligible prosumer (as shown in Equation 6.2):

$$P_{rij} \xrightarrow{yields} P_{eij} = \{E_{ij} | \, E_{ij} \geq E_{th} \}, \quad ,1 \leq j \leq n \ ,1 \leq i \leq N \qquad \text{Equation 6. 2}$$

where N is the number of prosumers registered with the community-based energy sharing network, P_{rij} is the registered i^{th} prosumer in the j^{th} time slot. P_{eij} is the eligible i^{th} prosumer, E_{ij} is the amount of energy supplied in the j^{th} time slot and n is the number of transactions in the evaluation period.

On the other hand, if the new prosumer fails to achieve eligible energy threshold (E_{th}), that prosumer's evaluation period is added with new time slots (energy transactions) and that prosumer remains under evaluation until he succeeds the n number of predefined consecutive energy transactions.

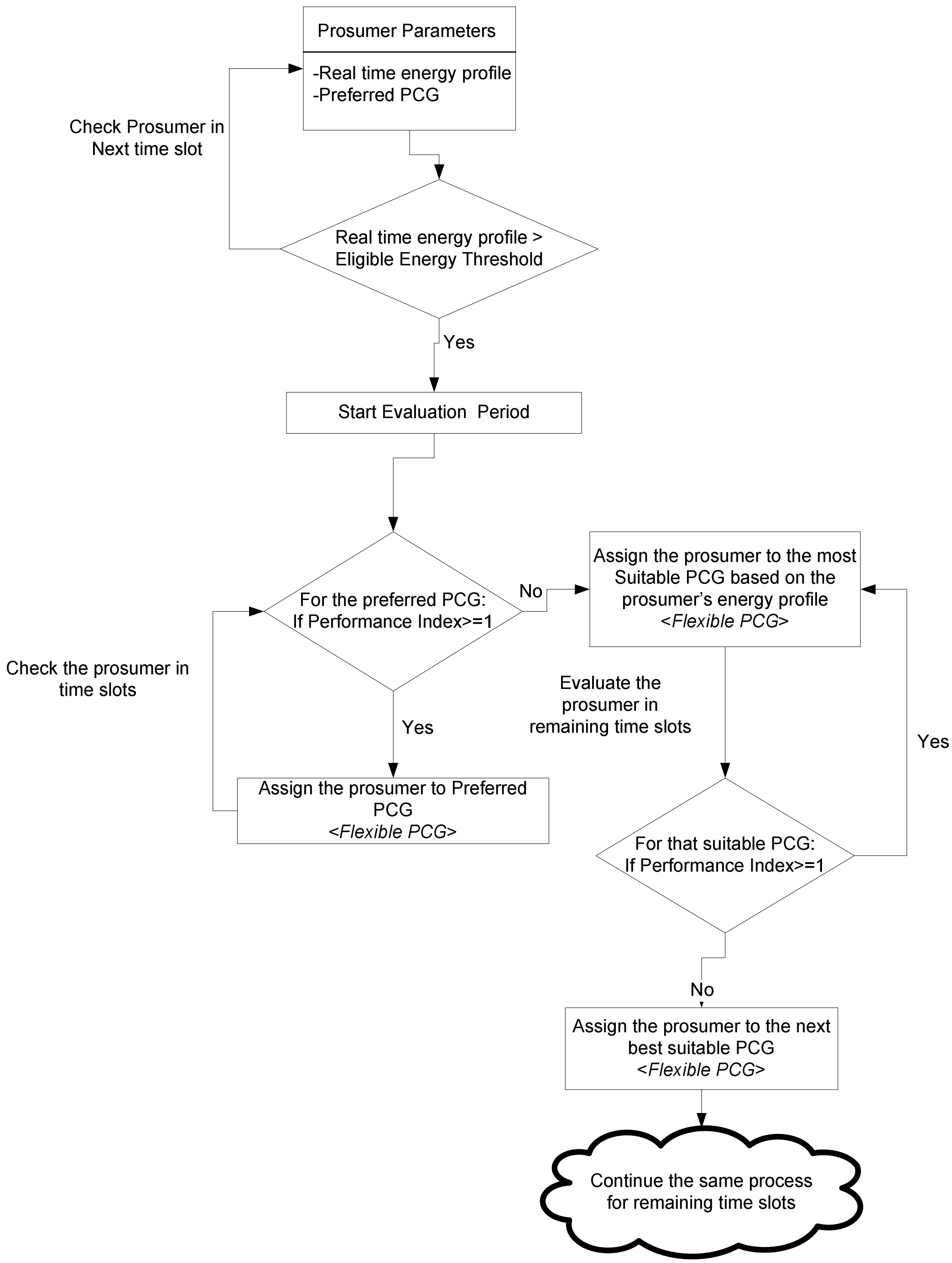


Figure 6. 5: The process of prosumer evaluation

In simple terms, only if the registered prosumer receives the status of an eligible prosumer after the first time slot, he will be transferred to the second time slot and so on. If the new prosumer fails to become an eligible prosumer at least in one energy transaction within the predefined number of time slots, he has extended the evaluation period with more time slots.

In each time slot, the eligible prosumer's real-time energy is evaluated based on their performance index and the corresponding PCG's pre-qualification criteria. The approach that evaluates the prosumer's performance in each time slot has been discussed in Equation 6.1 in above section.

The new prosumer is allocated to the prosumer's preferred PCG (*flexible prosumer community group*) if he meets the predefined performance index 1, 2 and 3, else he will be given an option of selecting another PCG, which is more suitable for his energy contribution. The suitable PCG is decided based on how close that prosumer's energy contribution to the centroid of the PCG. In order for that, the distance measures between the eligible prosumers' supplied energy amount (E_{ij}) and the centroid energy value of the m^{th} community groups ($\mu\ (C_m)$) and is calculated via Equation 6.3:

$$dist\left(E_{ij}, \mu(C_m)\right) = \left|E_{ij} - \mu(C_m)\right|; \quad ,1 \le j \le n \ ,1 \le i \le N \qquad \text{Equation 6. 3}$$

Let the upper energy threshold of the m^{th} PCG be U_m and the lower energy threshold of the m^{th} community group be L_m; then $\mu\ (C_m) = (U_m - L_m) / 2$.

The ultimate outcome of this step is the assignment of eligible prosumers to the flexible PCGs in each time slot of the evaluation period. After the completion of the evaluation period, each prosumer can be identified with different performance indices and different flexible PCGs, which are obtained in different time slots.

After completion of the evaluation period, the prosumers are recruited to the fixed PCGs by analysing their stability in different flexible PCGs. In the next section, we illustrate the approach that we use to determine the prosumer's stability in a PCG.

6.5.2.1 An approach to determine the prosumer's stability in a PCG

When recruiting the prosumers to the fixed PCGs, the prosumer community coordinator estimates the prosumer's stability in his preferred PCG, as well as the other PCGs that they have been assigned to throughout the evaluation period. Figure 6.6 illustrates the approach that we develop to obtain the prosumer's stability in his preferred PCG.

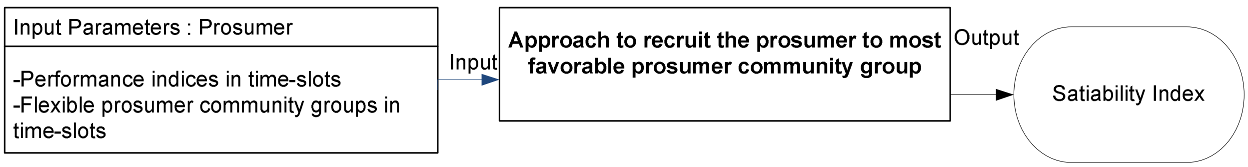


Figure 6. 6: Overview of the approach to determine the prosumer's stability in a prosumer community group

As shown in Fig. 6.6, the key inputs for this approach are the performance indices of prosumers in each time slot of the evaluation period and the flexible PCGs that the prosumers have been assigned to. The mathematical formulation of the approach to determine the prosumer's stability in a PCG is illustrated in Equations (6.4–6.5). For better understanding, we define the term "stability index" (SI) of prosumer, which represents the prosumer's likelihood to stay in his preferred PCG. The output for SI always takes an integer between "—1" to "3," and a higher SI shows higher likelihood of sustaining in the preferred PCG:

$$SI_{p_i} = \frac{\sum_{j=1}^{np} PX_{ij}}{np} \qquad \text{Equation 6. 4}$$

where SI_{pi} is the SI of the i^{th} prosumer with respect to preferred PCG *(Cp)*, PX_{ij} is an i^{th} prosumer's performance index in the j^{th} time slot and *np* is the number of time slots, where the prosumer is assigned to the preferred PCG.

Moreover, the rate of getting recruited to a specific PCG (*Rate*) is estimated using Equation 6.5. For instance, if the rate of the prosumer to stay in a preferred PCG is higher than the rate of staying in other

PCGs, the preferred PCG is considered as the most suitable PCG for that prosumer's energy sharing capability.

$$Rate(P_i \in PCG_r) = \frac{Count\ of\ (PCG_{Fr})}{n} \qquad \text{Equation 6. 5}$$

where P_i is the i^{th} prosumer, PCG_{Fr} is the r^{th} flexible PCG, *Count of* (PCG_r) is the number of time slots that the prosumer is selected to r^{th} flexible PCG throughout the evaluation period and n is the number of time slots.

In the next section, we discuss the process of prosumer recruitment to the fixed PCGs based on the aforementioned method.

6.5.3 Recruitment of the prosumers to the fixed PCGs after the evaluation period

This step involves recruiting the prosumers to the most suitable PCGs. The prosumer community coordinator performs the overall appraisal of the registered prosumer after the completion of the evaluation period. Figure 6.7 illustrates the concise flow chart of this process.

As discussed earlier, the Stability Index of the prosumer is calculated based on the prosumer's performance indices throughout the evaluation period. On the other hand, the prosumer's rate of staying in different flexible PCGs over the entire evaluation period is calculated. The combined index of the prosumer being allocated to the fixed PCG (IPr) is obtained as shown in Equation 6.6. The corresponding PCG, which shows the highest combined index for a specific prosumer when formulated in Equation 6.6, is chosen as that prosumer's finalized fixed PCG:

$$IPr(P_i \in PCG_r) = SI_{p_i} \times Rate(P_i \in PCG_{Flr}) \qquad \text{Equation 6. 6}$$

$IPr\ (P_i \epsilon\ PCG_r) = \{\ Rate\ (P_i \epsilon\ PCG_1), Rate\ (P_i \epsilon\ PCG_2), \ldots, Rate(P_i \epsilon\ PCG_N)\}$ for N number of PCGs.

If $(IPr\ (P_i \epsilon\ PCG_k) > IPr\ (P_i \epsilon\ PCG_r)) \rightarrow P_i$ is recruited to the kth fixed PCG.

where PCG_r is the r^{th} fixed PCG, P_i is the i^{th} prosumer, SI_{pj} is the Stability Index of the i^{th} prosumer and PCG_{Flr} is the r^{th} flexible PCG.

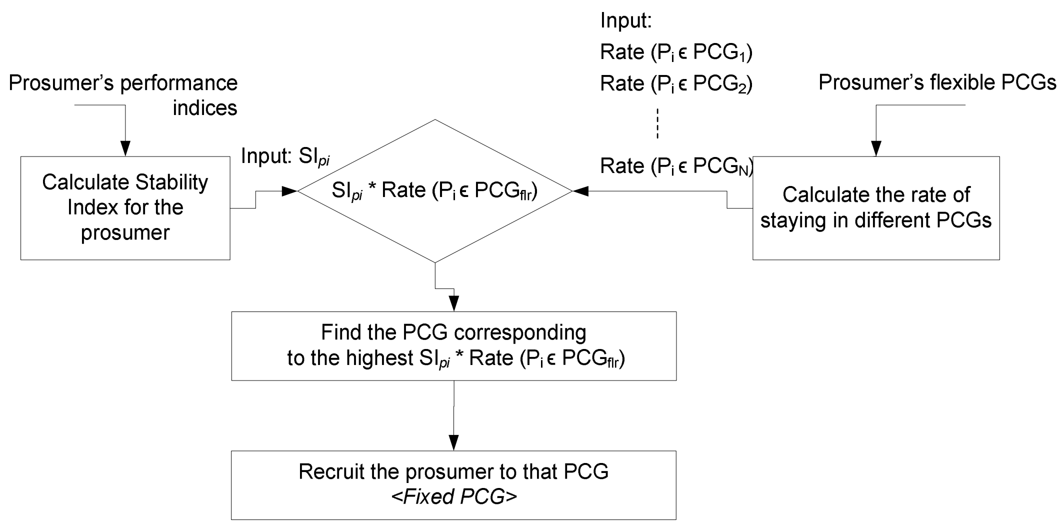


Figure 6. 7: The process of prosumer recruitment

In this section, we have discussed the concepts of the prosumer recruitment framework. The subsequent section discusses the verification of the proposed framework.

6.6 Verification of the Prosumer Recruitment Framework

In this section, we verify and validate the solution framework for prosumer recruitment by conducting simulations using MATLAB. As mentioned in Chapter 5, MATLAB is a well-known tool for data processing and data analysis.

We first discuss the experimental settings used for testing the proposed framework.

6.6.1 Experimental setting

This represents the basic set-up to examine the proposed framework for prosumer recruitment. In order to verify the proposed algorithm, we generate an energy behaviour dataset of 100 prosumers, assuming 100 prosumers have shown interest in joining the PCGs. The dataset is generated following energy generation and consumption models discussed in Chapter 5. Further information of this dataset can be found on our previous work (Rathnayaka, Potdar et al. 2012). In this verification, we use the data obtained for a summer season and four PCGs that are defined and characterized in Chapter 5. Furthermore, we assume the time-slot equivalent to a day, and thus evaluation period as 30 days. In other words, the prosumer is evaluated for 30 consecutive days or 30 consecutive time slots, where energy transfer is possible in each time slot.

The required simulation parameters are illustrated in Table 6.2.

Table 6-2: Simulation parameters

Simulation parameters	Value
Eligible energy threshold	2 kWh
Registered prosumers (interested to join the community-based energy sharing network)	100
Evaluation period	30 days (30 daily energy transactions in summer)
Prosumer Community Group 1 < Lower boundary–Upper boundary>	5–17 kWh
Prosumer Community Group 2 <Lower boundary–Upper boundary>	17.01–36kWh
Prosumer Community Group 3 <Lower boundary–Upper boundary>	36.01–47kWh
Prosumer Community Group 4 <Lower boundary–Upper boundary>	>47.01 kWh

In the next section, we apply the proposed framework to the 100 prosumers and present the results.

6.6.2 Observation, results and discussion

In this section, we illustrate the observation and results we obtained when the prosumer recruitment framework is applied to the aforementioned data set.

As discussed in Section 6.5, the evaluation technique plays the most critical role in the prosumer recruitment framework. We conduct simulations to verify the evaluation techniques, which demonstrate evaluating the registered prosumer's energy sharing performance during the "evaluation period."

As mentioned in Section 6.5, eligible prosumers are identified by the community coordinator during each time slot of the evaluation period. Therefore, only eligible prosumers who meet the "*eligible energy threshold* (E_{th})" in each time slot can proceed in the evaluation period. As mentioned earlier, the eligible prosumer has chosen their preferred PCG. Here, we assume that the registered prosumers cannot change their selection of preferred PCG throughout the evaluation period; thus, the prosumer's preferred PCG remains fixed over 30 time slots.

However, the eligible prosumers' ability in meeting the preferred PCG's pre-qualification criteria may be fluctuating over the time slots in the evaluation period. As discussed in Section 6.5, we consider the fundamental evaluation parameter of the PCG pre-qualification criteria is the registered prosumer's capability in meeting the lower threshold of the prosumer's preferred PCG. In order to determine to what extent the registered prosumer attains the pre-qualification criteria of the preferred PCG, we have introduced four semantics of performance: "total success," "medium success," "low success" and "failure," with respective performance indices of "3," "2," "1" and "−1".

In this simulation, we first assess the registered prosumer's capability in meeting the pre-qualification criteria of the preferred PCG. Figures 6.8, 6.9, 6.10 and 6.11 illustrate the percentage prosumers who are allocated to different performance indices over the 30 time slots, where that prosumers' preferred PCG is, respectively, PCG 1, PCG 2, PCG 3 and PCG 4.

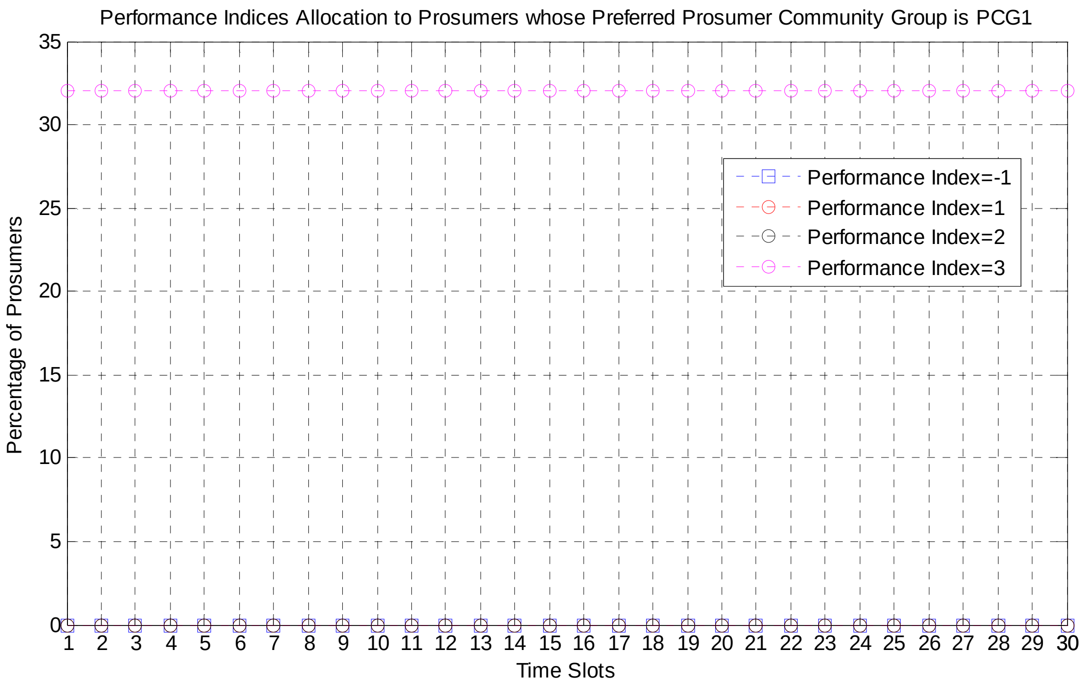


Figure 6. 8: Performance indices allocation to prosumers whose preferred prosumer community group is PCG 1

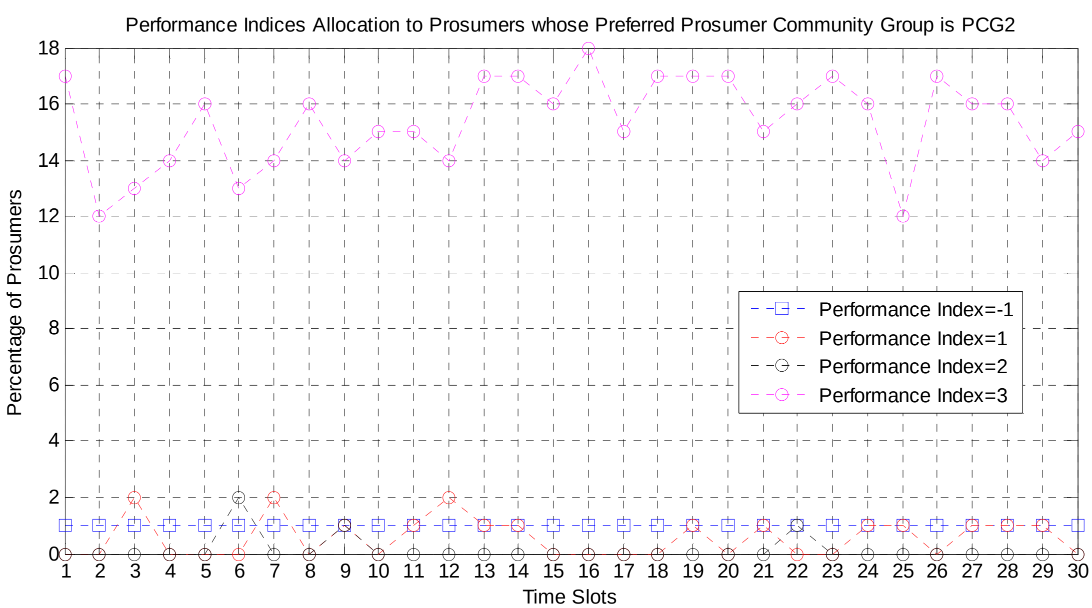


Figure 6. 9: Performance indices allocation to prosumers whose preferred prosumer community group is PCG 2

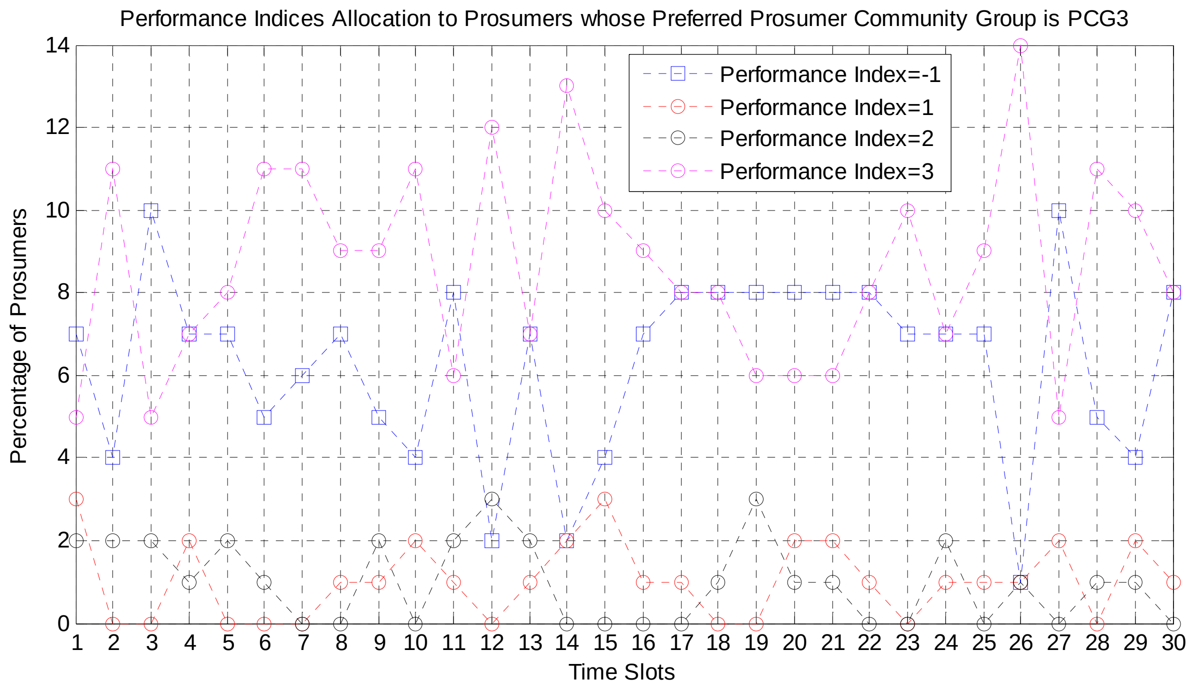


Figure 6. 10: Performance indices allocation to prosumers whose preferred prosumer community group is PCG 3

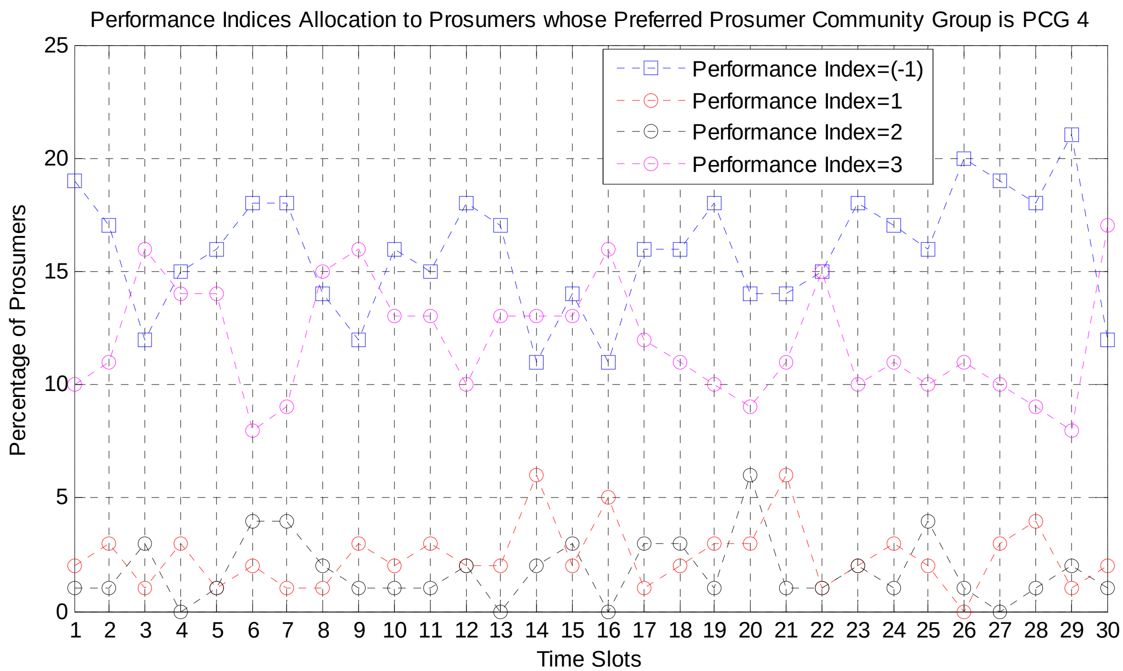


Figure 6. 11: Performance indices allocation to prosumers whose preferred prosumer community group is PCG 4

Accordingly, when the prosumer chooses PCG 1 as its preferred PCG, there is a high chance that such prosumers are retained in performance index 3, which is “total success” (rate of success =100%) throughout the evaluation period (30 time slots). This is because the PCG 1 has the least upper and lower thresholds of energy, which is the easiest pre-qualification criteria to achieve. As a result, if a prosumer chooses PCG 1, the rate of achieving “total success” over the evaluation period is high. However, when prosumer chooses PCG 4 that has harder pre-qualification criteria to achieve (higher energy thresholds), there is a high chance that such prosumers are retained in performance index −1, which is “failure” (rate of success <79.99%) throughout the evaluation period (30 time slots), that means that prosumers are given different PCGs than what they have initially preferred.

Moreover, based on the prosumer’s performance indices in each time slot and the stability indices, the combined index of the prosumer being allocated to the fixed PCG is obtained. Figure 6.12 illustrates the combined index obtained by the prosumers in each PCG. Here, the “X axes” represent the prosumer identifier with respect to the considered PCG. The corresponding PCG, which shows the highest combined index for a specific prosumer when formulated in Equation 6.6, is chosen as that prosumer’s finalized fixed PCG. As shown in Fig. 6.12, all the prosumers who have chosen the PCG 1 as their preferred PCG have recruited to the PCG 1 as their fixed PCG.

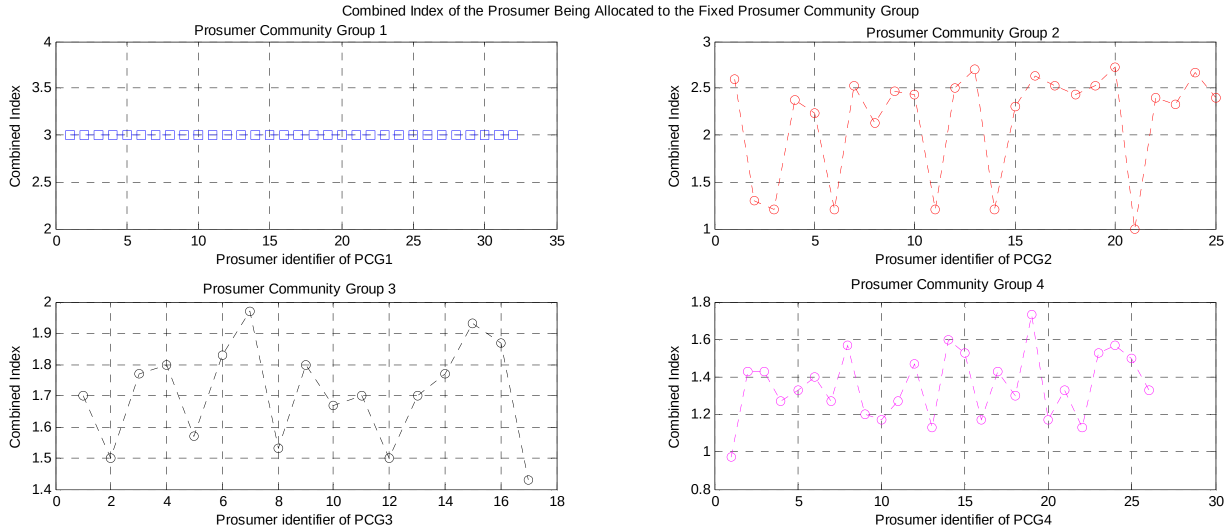


Figure 6. 12: Combined index obtained by the prosumers in each prosumer community group

Fig. 6.13 illustrates the percentage of prosumers recruited to the finalized fixed PCGs.

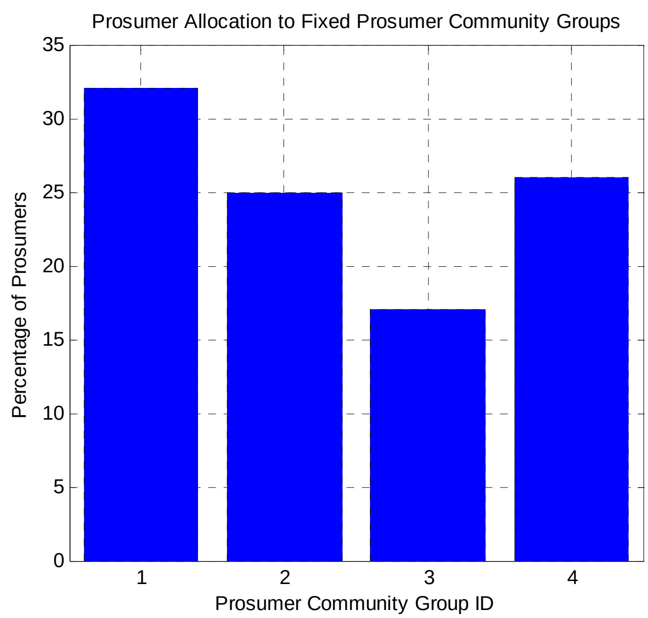


Figure 6. 13: Fixed community group allocation

Overall, all the prosumers who has chosen PCG 1 as the preferred PCG have been recruited to PCG 1 in all the time slots. However, other prosumers who have selected PCG 2, PCG 3 and PCG 4 as their preferred PCGs have been allocated to their preferred PCG if their combined index is higher for the preferred PCG. Otherwise, they are recruited to the most suitable PCG based on the combined index calculated.

6.7 Conclusion

In this chapter, an innovative framework is presented for prosumer recruitment. The proposed framework evaluates the performance of the prosumer throughout the evaluation period, where the prosumer's likelihood of meeting the pre-qualification criteria of his preferred PCG, as well as his stability, is estimated and accordingly decides whether that prosumer is appropriate for the corresponding PCG.

Simulation results have been provided to verify the proposed framework.

This proposed framework has been published in a peer-reviewed international journal (Rathnayaka, Potdar et al. 2014), wherein we have attached a complete list of all the publications arising as a result of the research study carried out in this thesis at the beginning of the thesis.

After recruiting the prosumers to PCGs, another key challenge faced by prosumer community coordinator is managing multiple goals in the community-based energy sharing network and allocating mutual goals to the already-formed PCGs. The following chapter provides the detailed framework for multiple goal management and mutual goal allocation to PCGs.

Chapter 7

Goal Management and Mutual Goal Definition Framework

This chapter provides:

- Introduction to multiple goal management and mutual goal definition for PCGs
- Presentation of a framework to manage the multiple conflicting goals in community-based energy sharing network and define favourable mutual goals to the PCGs
- Verification of the framework for multiple goal management and mutual goal definition for PCGs

7.1 Introduction

In the previous chapters, we proposed frameworks by which the prosumer community coordinator defines and characterizes the PCGs, and recruits new prosumers to the predefined PCGs. The aforementioned two frameworks discussed in the previous two chapters provide the opening building blocks to construct the community-based energy sharing network.

After initiating the community-based energy sharing network, one of the subsequent requirements would be making the defined PCGs goal oriented. In order to make the PCGs goal oriented, the key requisite would be the goal management which comprises the determination of overall objectives of the community-based energy sharing network followed by effective compromise among the conflicting multiple goals and the definition and allocation of favourable mutual goals to the diverse PCGs.

However, goal management in a community-based energy sharing network is challenging due to several reasons which we identify as follows. For instance, the community-based energy sharing network comprises multiple irreconcilable objectives such as demand constraints, cost constraints, incentive maximization, etc. In many cases, one goal is achievable only at the expense of other goals. For example, in order to reduce the overall cost associated with PCGs, the overhead of managing prosumers in community groups is to be reduced by reducing the number of prosumers involved; however, this will reduce the total energy production and sharing, while reducing the total feed-in tariff income received by the PCG. Therefore, it is necessary to reach a favourable compromise among these multiple diverse goals with respect to the given constraints, and to realize what alterations are required in parameters to achieve a satisfactory attainment of all the goals.

Moreover, the aforesaid goals of community-based energy sharing network are to be effectively broken down into customized mutual goals for different PCGs, where the prosumers of each PCGs are inspired to achieve the respective mutual goal. Defining a customized goal for each PCG will make the members much more comfortable in achieving the goals. Such personalized goals can be motivating to a PCG as well as the individual members in each group.

In fact, the aforementioned factors necessitate the development of an effective framework to manage the goals and define mutual goals. In this chapter, we develop an effective goal management and mutual goal definition framework by which the prosumer community coordinator first negotiates among the multiple goals within the community-based energy sharing network and obtains an optimized set of overall goals. In order to negotiate among the multiple goals, we propose a goal programming model based on the MCGP method. The optimized set of goals obtained from the goal programming model is divided into optimal mutual goals which are allocated to the PCGs.

In Section 7.2, we explain the aspects of the framework of goal management and mutual goal definition. In Section 7.3, we discuss the requirements for this framework followed by the design rationale in Section

7.4. In Section 7.5, we discuss the theoretical foundation of this framework, and in Section 7.5 we verify the proposed framework. Section 7.6 concludes the chapter.

7.2 Overview of the Goal Management Framework

In this section, we explain our solution framework for goal management and mutual goal definition in detail. The concise overview of the solution framework is illustrated in Fig. 7.1.

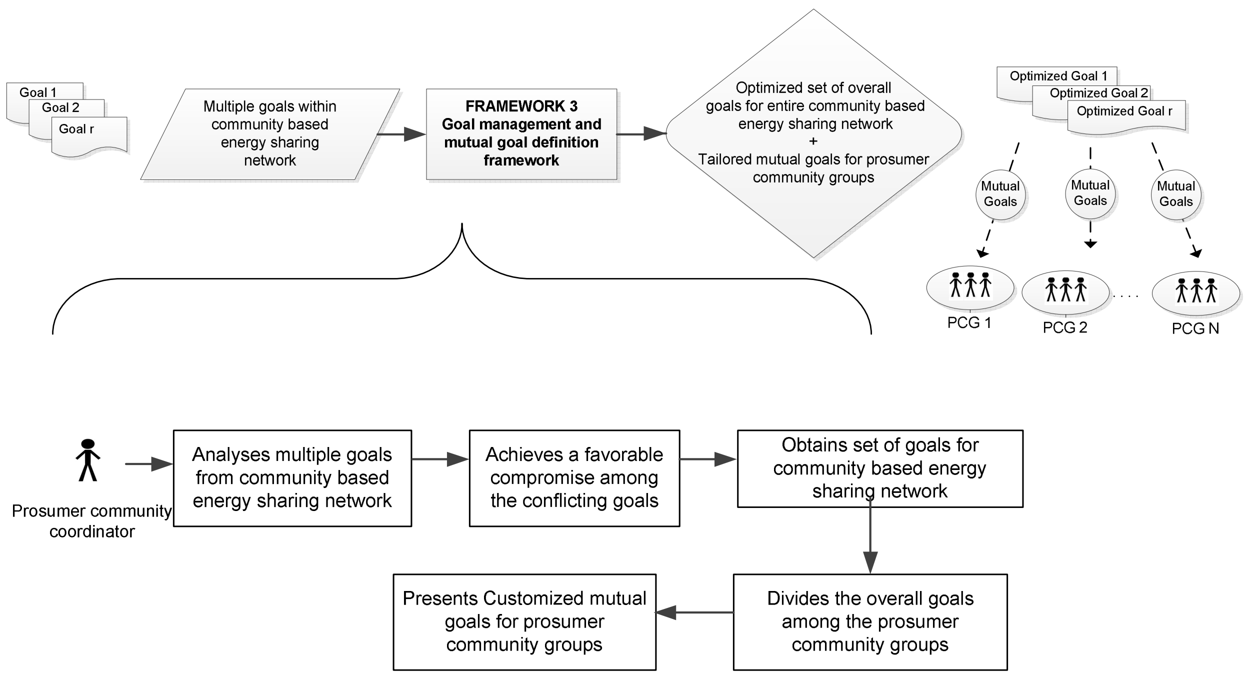


Figure 7. 1: Concise overview of the goal management and mutual goal definition framework

As shown in Fig. 7.1, the input for this framework is the multiple goals in community-based energy sharing network. In the solution framework, we identify five objectives: (i) the resource objective, which represents the objective on maximum usage of the available resources such as energy storage resource and human resource (prosumers), (ii) the local demand objective, which aims to fulfil the local energy demand of prosumers within each PCG, (iii) the external customer demand objective that aims to satisfy the energy requests of external customers as utility companies, (iv) income objective that aims to achieve the predefined income or profits by selling the energy, (v) cost objective, which aims to reduce the cost involved in energy sharing process, and (vi) sustainability objective that aims to promote the number of prosumers who actively share the energy in the community-based energy sharing network.

The solution framework includes two main ongoing phases: (i) goal management phase and (ii) mutual goal definition phase. The output of the goal management phase is the optimized set of overall goals for the community-based energy sharing network, which become the input to the mutual goal definition phase. The outcome of the mutual goal definition phase is the customized set of mutual goals that are designed for the requirements of different PCGs.

As shown in Fig. 7.1, the fundamental processes identified in the goal management and mutual goal definition framework is illustrated as follows: the prosumer community coordinator first identifies the objectives of community-based energy sharing network as a whole and efforts to achieve the most favourable compromise among the goals. After obtaining the optimized set of overall goals, the prosumer community coordinator divides these goals among the PCGs as customized mutual goals. These mutual goals are defined based on the characteristics of PCGs, thus facilitating a tailored mutual goal for each PCG.

In the following section, we discuss the requirements for this research.

7.3 Requirements

The following requirements are laid down for the proposed solution. This represents the *first* stage of the conceptual process where requirements are elicited and prioritized. The requirements of the solution are as follows:

1. **Classify multiple conflicting goals within a community-based energy sharing network:** As the initial step, the goal management phase should clearly classify the multiple goals within the

community-based energy sharing network. Moreover, the rigid restrictions on achieving the goals, as well as the conditions one would like to achieve but are not mandatory, should be correctly defined.

2. **Evaluation and prioritization of the goals based on their importance**: The goal management solution should facilitate the evaluation and prioritization of identified goals based on their relative importance.

3. **Compromise among the diverse goals to ensure the satisfactory level of attainment of all the goals:** The goal management framework should negotiate among the multiple conflicting goals to find the degree of attainment of those goals compared to the predetermined expectations, to identify what alterations are necessary in parameters to fulfil all the goals and finally to provide the best satisfying solution under a varying amount of resources and priorities.

4. **Define and allocate tailored mutual goals for PCGs:** The solution should divide the optimized overall goals obtained from the goal management phase among the different PCGs as mutual goals. It is necessary to define the practically achievable mutual goals for PCGs, rather than the theoretically promising mutual goals.

This concludes stage 1 of the conceptual process. The design rationale is based on the above-mentioned requirements. A design decision for each requirement is made in the design rationale along with a discussion of how the requirement is met.

7.4 Design Rationale

This section provides a design rationale to meet all the requirements listed above. This is the *second* stage of the conceptual process. The following design decisions are proposed in order to address each requirement. The concise overview of the design decisions are shown in Fig. 7.2.

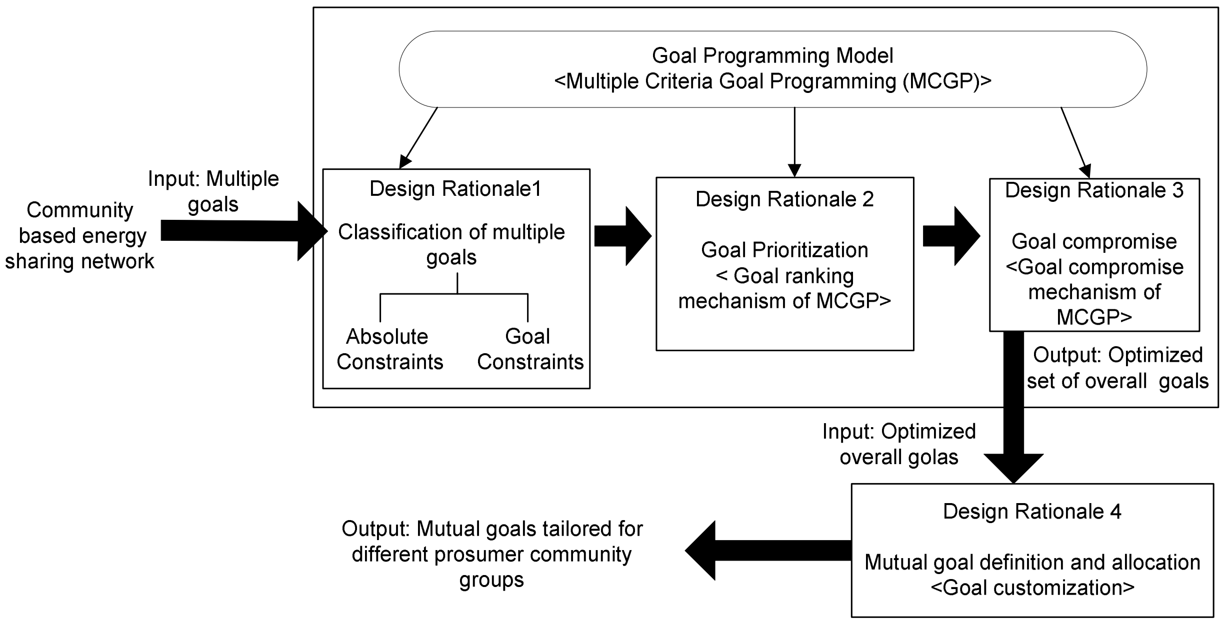


Figure 7. 2: Concise overview of the design decisions

1. **Design rationale 1**: The multiple goals are classified as absolute constraints and goal constraints, where the former represents inflexible restrictions on the goals such as possible energy storage being limited to the available storage resources and the latter represents the conditions one would like to attain but are not mandatory such as the attempt to reduce the cost of energy sharing. This would satisfy the requirement for classification of multiple goals within the community-based energy sharing network (Req. 1).

2. **Design rationale 2:** In order to prioritize the goals based on their relative importance, we propose an approach adapting the goal ranking technique used by the MCGP. This would satisfy the requirement for goal prioritization (Req. 2).

3. **Design rationale 3:** In order to compromise among the conflicting goals, we adapt the concepts of goal negotiation techniques used in MCGP, which provide the optimized goal solution under a varying amount of resources and priorities of the goals, as well as present what alterations are necessary in parameters to attain the goals in reasonable degree. This would satisfy the requirement for goal compromise (Req. 3).

4. **Design rationale 4:** In order to divide the optimized overall goals obtained from the goal management phase among the PCGs as cusomized mutual goals, we use the following approaches. The overall goals are divided among the PCGs based on the general fixed characteristics of the PCGs, as well as based on the varying energy behaviour profiles of the PCGs over previous energy transactions. This would satisfy the requirement for definition and allocation of tailored mutual goals for diverse PCGs (Req. 4).

In the development of the solution for goal management and mutual goal definition, the above design decisions should be considered. This concludes stage 2 of the conceptual process. The next stage is the theoretical foundation for the proposed solution.

7.5 Theoretical Foundation

The theoretical foundation for the goal management framework is discussed in this section which represents the *third* stage of the conceptual process. Entire design decisions are analysed and an algorithm is proposed. The theoretical foundation of this framework has two main parts (Fig. 7.3): (i) *Phase 1: goal management phase* and (ii) *Phase 2: mutual goal definition phase.*

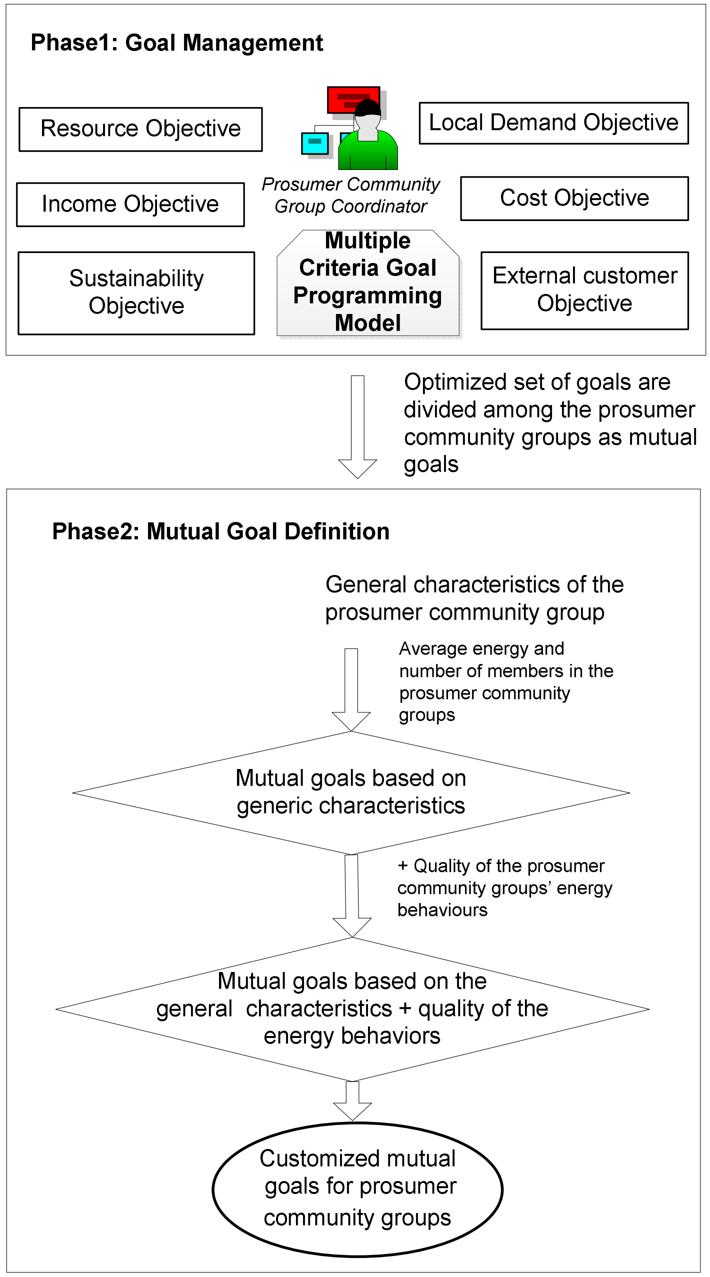


Figure 7. 3: Theoretical foundation of goal management framework

The first part of the framework is the *goal management*. The goal management is initiated with identification of the multiple goals of the community-based energy sharing network. As shown in Fig. 7.3, the key backbone of this part of the system is the goal programming model, which is developed adapting the concepts of MCGP techniques. The input for the goal management phase is the multiple goals of the community-based energy sharing network. The output of this phase is the optimized set of overall goals of the community-based energy sharing network, which assure the satisfactory level of attainment of all the goals.

The second part of the framework is *mutual goal definition.* In this part, the set of optimized overall goals of the community-based energy sharing network that is obtained from the previous phase are divided into mutual goals for different PCGs. In order to attain that, we suggest a model that defines the mutual goals based on the PCGs' generic characteristics, as well as its varying energy behaviours. The ultimate outcome of the mutual goal definition phase would be the customized mutual goals for different PCGs.

Next, we describe the development of algorithms for the solution framework. We first discuss the development of the goal management phase of the solution framework.

7.5.1 Phase 1: goal management

This phase involves the management of multiple conflicting goals in the community-based energy sharing network to obtain an optimal set of goals. In order to formulate an optimal solution to the problem of conflicting goals, we adapt the aspects of MCGP (Masud and Ravindran 2009). Here, the objectives are assigned target levels for achievement and relative priority of achieving these levels. These targets are treated as goals to aspire for, and thus efforts to find an optimal solution that comes as "close as possible" to the targets in the order of specified priorities. Goal programming minimizes the deviations between the goals themselves and the expected achievement. These deviational variables can be both positive and negative deviations from each goal, in which the objective function minimizes these deviations based on the relative importance assigned to them (Masud and Ravindran 2009).

In the past, goal programming models have been successfully implemented in many application areas like academic planning, environment, and health planning (Masud and Ravindran 2009), and are claimed as an efficient and feasible way to handle multiple conflicting goals. Nevertheless, goal programming has rarely been used as a working model in energy networks. In this framework, we adapt and further develop

MCGP techniques for our solution framework. Figure 7.4 gives a concise view of the algorithm of goal programming model. This model has five steps: (i) goals identification, (ii) parameter definition, (iii) formulation of constraints, (iv) determination of priority levels, (v) formulation of goal equations and (vi) development of objective functions. The numerical parameters and equations referred in Fig. 7.4 are explained as appropriate in the following sections.

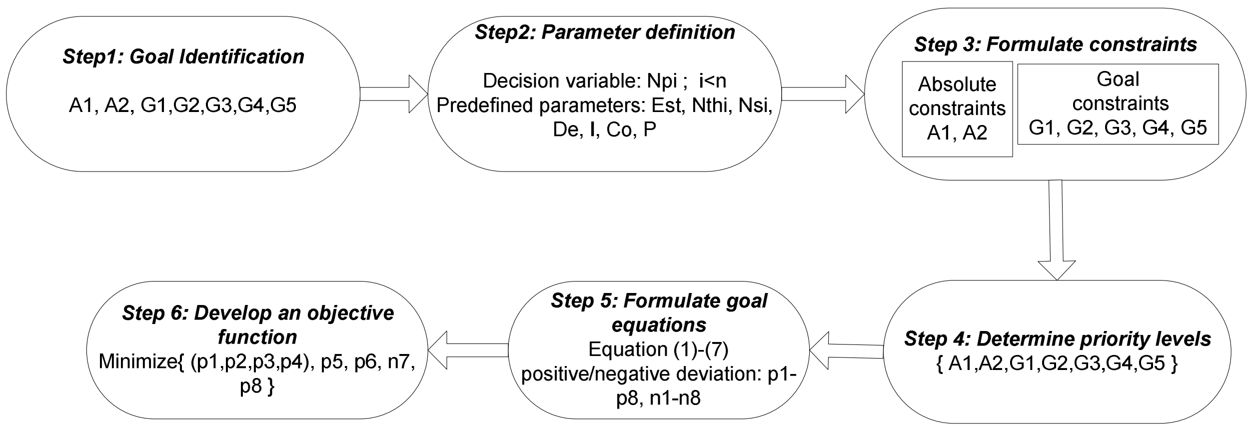


Figure 7. 4: Goal programming model

7.5.1.1 Step 1: Goal Identification

In this step, we identify the multiple objectives of community-based energy sharing network, which is illustrated as follows:

- ***Resource objective (A1, A2)*****:** The "*resource objective*" refers to the maximum usage of limited available resources. The resources within the community-based energy sharing network take two forms: equipment resource and human resource (prosumers). The former describes maintaining sufficient storage and handling resources to manage the power flow data produced by PCGs, which is limited to the available storage and handling equipment. The latter describes the number of prosumers from each PCG who are actively sharing energy, which is limited to the maximum number of registered prosumers of the corresponding PCG.

- ***Local demand objective (G1):*** The "*local demand objective*" refers to fulfilling the energy demand of local prosumers within the PCGs. In practical scenarios, some prosumers within a PCG may fail to produce sufficient quantity of green energy even to cover up their own energy consumption. In such cases, the collective surplus energy produced by the fellow prosumers of the PCG will be used to fulfil the shortfall of its local members.
- ***External customer demand objective:*** The "*external customer demand objective*" refers to fulfilling the energy requests of external customers or energy buyers such as utility grid, and the external energy consumers that are not registered to the community-based energy sharing network. The PCGs can enhance the income by selling the surplus energy to external energy buyers.
- ***Income objective:*** The "*income objective*" refers to the achievement of the expected income level from selling the surplus energy of PCGs to energy buyers.
- ***Cost objective:*** The "*cost objective*" refers to reducing the cost of managing the PCGs in community-based energy sharing network. For example, this term "cost" can represent the combined cost of accumulating the energy information from members, providing privileges to the members and bringing the energy resource to the end-use point. Moreover, the cost associated with each PCG is variable due to the different traits of each PCG. For example, if higher privileges are assigned to a PCG, the cost involved with managing the prosumers in that community group is also higher compared to the other PCGs.
- ***Sustainability objective:*** We define the "*sustainability objective*" as increasing the active members of the PCGs, who dynamically share the energy in community-based energy sharing framework.

7.5.1.2 Step 2: Parameter definition

In this step, we identify all the predefined parameters and variable parameters involved in the MCGP framework. The variable parameters here are the decision variables, i.e. the set of parameters that need to be determined when solving the goal programming problem (Masud and Ravindran 2009). In this study, we denote the quantities of energy to be produced by each community group as the decision variables.

The identify predefined values for following parameters: the maximum resource availability, minimum expected local energy demand of each PCG, minimum expected energy request from external energy buyers, maximum budgeted cost allowance, the minimum expected income level and minimum expected active prosumer participation from PCGs.

7.5.1.3 Step 3: Formulate constraints based on objectives

In this step, absolute constraints and goal constraints based on the aforementioned objectives (Step 1) are precisely identified. Here, the "absolute constraints" are defined as rigid restrictions on the decision variables, whereas the "goal constraints" are defined as the conditions one would like to achieve but are not mandatory (Masud and Ravindran 2009). In this framework, we differentiate the objectives as absolute constraints and goal constraints as follows:

(i) Absolute constraints: resource objective (A1 and A2) (i.e. equipment resource (A1) and human (prosumer) resource (A2)). For example, the total amount of data collected from PCGs to be limited to the available handling and storage resources and the participation from each PCG to be limited to the number of total registered members of the corresponding PCG.

(ii) Goal constraints: local demand objective (G1), external customer objective (G2), income objective (G3), cost objective (G4) and sustainability objective (G5). Adjustments to the goal constraints are possible and the attainment would be beneficial to the community-based energy sharing network. The predefined parameters of the goal constraints: minimum expected local energy demand of each PCG, minimum expected energy request from external energy buyers, maximum budgeted cost allowance, the minimum expected income level and minimum expected active prosumer participation from PCGs, are termed as "expected values" in the goal programming model.

7.5.1.4 Step 4: Determine priority levels

This step gives ranking or pre-emptive priorities to the goal constraints by assigning them different priority levels and weights. As we mentioned in previous sections, in general, the goals are incommensurable; thus, one goal may be realizable by sacrificing the other goal. This necessitates the establishment of a hierarchy of importance among incompatible goals such that the achievement of the lower-order goals are considered only after the higher-order goals have been fulfilled or have reached a point beyond which no further improvements are desirable.

Using the aforesaid five goal constraints, a set of 120 priority structures (5! number of combinations) can be constructed: G1G2G3G4G5, G1G2G3G5G4,…, G5G4G3G2G1. For instance, the position of a goal in the priority structure indicates the priority assigned to it. For example, in G1G2G3G4G5, G1 is the highest prioritized goal and G5 is the lowest prioritized goal. However, in this framework, we keep the local demand objective (G1) as the highest prioritized goal, as the key objective of creating PCGs is inspiring individual prosumers to work together as a community group to more efficiently manage their energy requirements. Assigning the fixed highest priority to G1 reduces the number of priority structures into 24 (4! number of combinations).

7.5.1.5 Step 5: Formulate goal equations

In this step, we develop the mathematical relations involving the absolute and goal constraints:

(i) Resource Objective (A1, A2): The power flow information collected from all the PCGs should not exceed the limited storage and handling constraints. Let E_i be the average energy possessed by i^{th} PCG, N_{pi} be the number of prosumer participation from the i^{th} PCG, m be the number of PCGs and E_{st} be the handling and storage capacity of the community-based energy sharing network. Then, the MCGP formulation for the equipment resource objective is shown in Equation 7.1:

$$\sum_{i=1}^{n} E_i \times N_{pi} \leq E_{st} \qquad \text{Equation 7. 1}$$

Moreover, the number of participations from each PCG (N_{pi}) should be less than the number of subscribed members of the i^{th} PCG (N_{si}) and higher than the minimum number of prosumer requirement (N_{thi}). Then, the MCGP formulation for the resource human (prosumer) objective is shown in Equation 7.2:

$N_{thi} \leq N_{pi} \leq N_{si}$; $\forall\, i < m$ Equation 7. 2

(ii) Local demand objective (G1): The best attempt to be taken by each PCG to fulfil the energy shortage of its local members. In fact, the surplus energy produced by the members of the PCG to be used to fulfil the shortfall of the local members. Thus, the corresponding goal is stated as: minimize the negative deviation from quantity of surplus energy of each PCG.

Let $N_{pi}E_i$ (or N_{pi} x E_i) be the total surplus energy shared by the i^{th} PCG after fulfilling its own energy shortages (if any), n_i and p_i be positive and negative deviational variables, respectively, and m be the number of PCGs, then the formulae for local demand objective (G1) would be:

$N_{pi}E_i \geq 0$; $\forall\, i \leq m$

$N_{pi}E_i + p_i - n_i = 0$; $\forall\, i \leq m$ Equation 7. 3

For example, for the clarity of the MCGP equations, we assume four PCGs ($m=4$), then $n_i = \{ n_1, n_2\ n_3, n_4\}$ and $p_i = \{ p_1, p_2\ p_3, p_4\}$.

This gives the following MCGP equations for each PCG:

$N_{p1}E_1 + p_1 - n_1 = 0$;

$N_{p2}E_2 + p_2 - n_2 = 0$;

$N_{p3}E_3 + p_3 - n_3 = 0$;

$N_{p4}E_4 + p_4 - n_4 = 0$;

(iii) External customer objective (G2): Effort to be made to ensure the collective surplus energy shared by all the PCGs at least meet the minimum energy requirement of energy buyers. The corresponding goal is stated as: minimize the negative deviation from the quantity of aggregated surplus energy of all PCGs. Let the minimum energy requirement from the customers be D_e, and $n5$ and p_5 be positive and negative deviational variables, respectively, then the formulae for external customer objective (G2) would be as follows:

$\sum_{i=1}^{m} E_i \times N_{pi} \geq D_e$

$\sum_{i=1}^{m} E_i \times N_{pi} + p5 - n5 = D_e$ Equation 7. 4

(iv) Income objective (G3): Another requirement of the framework is to achieve higher income. Let the total minimum income expectation from PCGs be *I*, the income rate of the i^{th} PCG be l_i, and positive and negative deviational variables be n_6 and p_6, respectively, then the formulae for the income objective (G3) is shown in Equation 7.5. The corresponding goal is stated as: minimize the negative deviation from the expected incentives (*p6*).

$\sum_{i=1}^{n} l_i \times E_i \times N_{pi} \geq I$

$\sum_{i=1}^{n} l_i \times E_i \times N_{pi} + p6 - n6 = I$ Equation 7. 5

(v) Cost objective (G4): Another goal of the community-based framework is to keep the cost involved less than the budgeted cost allowance. The cost that will incur to manage different PCGs may vary based on the different characteristics of the PCG and the different benefits its members gain, which introduces the coefficient C_i, i.e. the cost rate of the i^{th} PCG. Let the total budgeted cost allowances be *CO*, and positive and negative deviational variables be n_7 and p_7, respectively, then the formulation of the cost objective (G4) is shown in Equation 7.6. The corresponding goal is stated as: minimize the positive deviation from the total cost incurred (*n7*):

$\sum_{i=1}^{n} C_i \times E_i \times N_{pi} \leq CO$

$\sum_{i=1}^{n} C_i \times E_i \times N_{pi} + p7 - n7 = CO$ Equation 7. 6

(vi) Sustainability objective (G5): Another objective is to increase the sustainability by improving the number of active participation. The corresponding goal is stated as: minimize the negative deviation from overall active participation. Let the minimum expected number of prosumer participation from the community-based energy sharing network be P, and positive and negative deviational variables be n_7 and p_7, respectively, then the formulae for the sustainability objective (G5) would be as follows:

$\sum_{i=1}^{n} N_{pi} \geq P$

$\sum_{i=1}^{n} N_{pi} + p8 - n8 = P$ Equation 7. 7

7.5.1.6 Step 6: Develop an objective function

This step formulates an objective function for each goal, and then seeks a solution that minimizes the deviations from their respective goals. The objective functions here is the {(*p1, p2, p3, p4), p5, p6, n7, p8}*. The set of aforementioned equations are discussed in Section 7.5.1.5 to be solved to minimize the deviations of the objective functions.

The aforesaid six steps present the formulation of the goal programming problem for the community-based energy sharing network. This goal programming problem is represented as linear goal programming problems that can be solved efficiently by the partitioning algorithm(Masud and Ravindran 2009). In the next section, we discuss about the partition algorithm that we use to solve the goal programming problem.

7.5.1.7 Solution to the goal programming problem

As shown in Fig. 7.5, the entire goal programming problem can be considered as a linear problem, which can be broken down into a series of prioritized linear programming subproblems (goal equations). As discussed in the previous sections, we identified 24 priority structures, where the goal equations are solved for different priority structures. The mathematical notations and equations shown in Fig. 7.5 have been discussed earlier in this section.

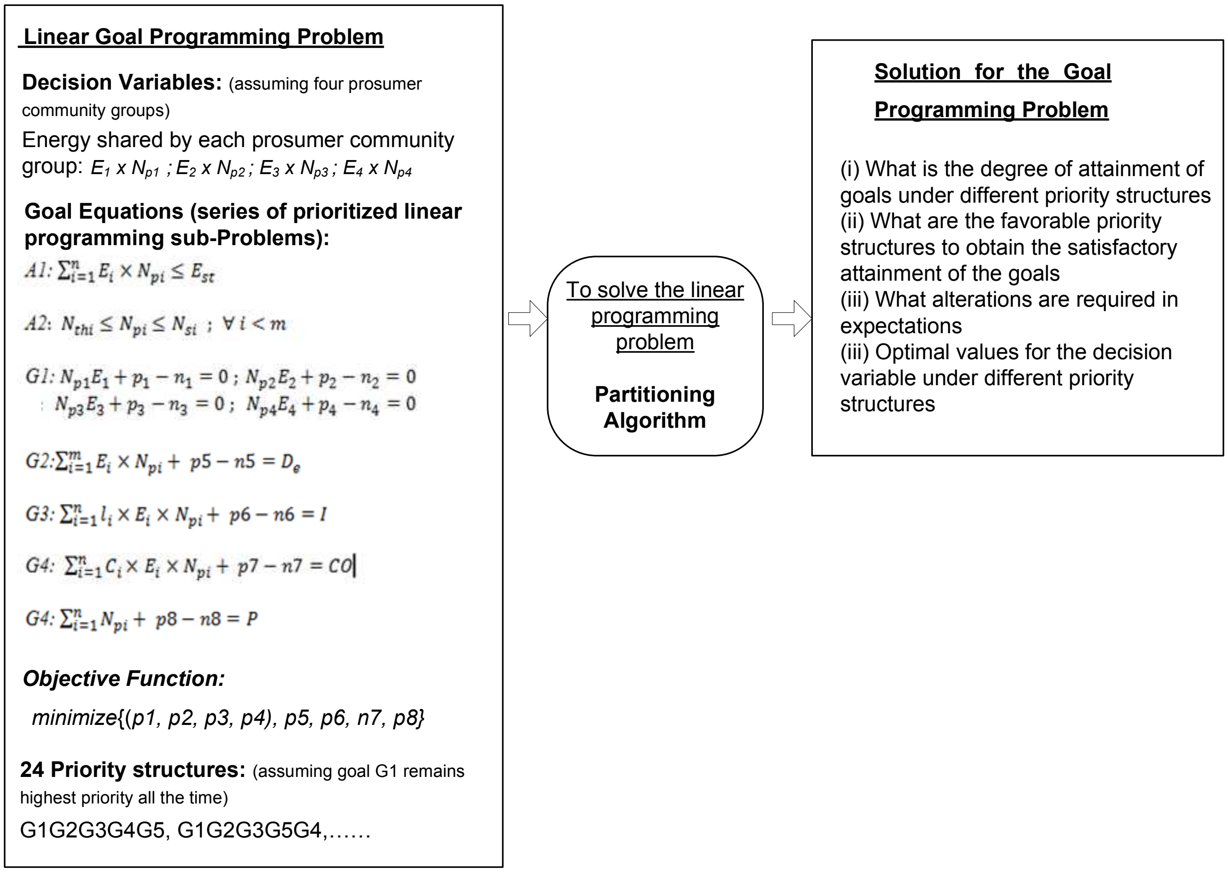


Figure 7. 5: Solution to the goal programming problem

In order to solve the aforesaid linear goal programming problem, we adopt the concepts of partitioning algorithm (Masud and Ravindran 2009). It is based on the fact that the definition of priority structures implies that higher-order goals must be optimized before lower-order goals are even considered. As shown in Fig. 7.6, the solution procedure consists of solving a series of linear programming subproblems by using the solution of the higher-priority problem as the starting solution for the lower-priority problem. The partitioning algorithm begins by solving the subproblem, which is composed of those goal constraints assigned to the highest priority and the corresponding terms in the objective function. The optimal tableau for this subproblem is then examined for alternate optimal solutions. If none exist, then the present solution is optimal for the original problem with respect to all the priorities..

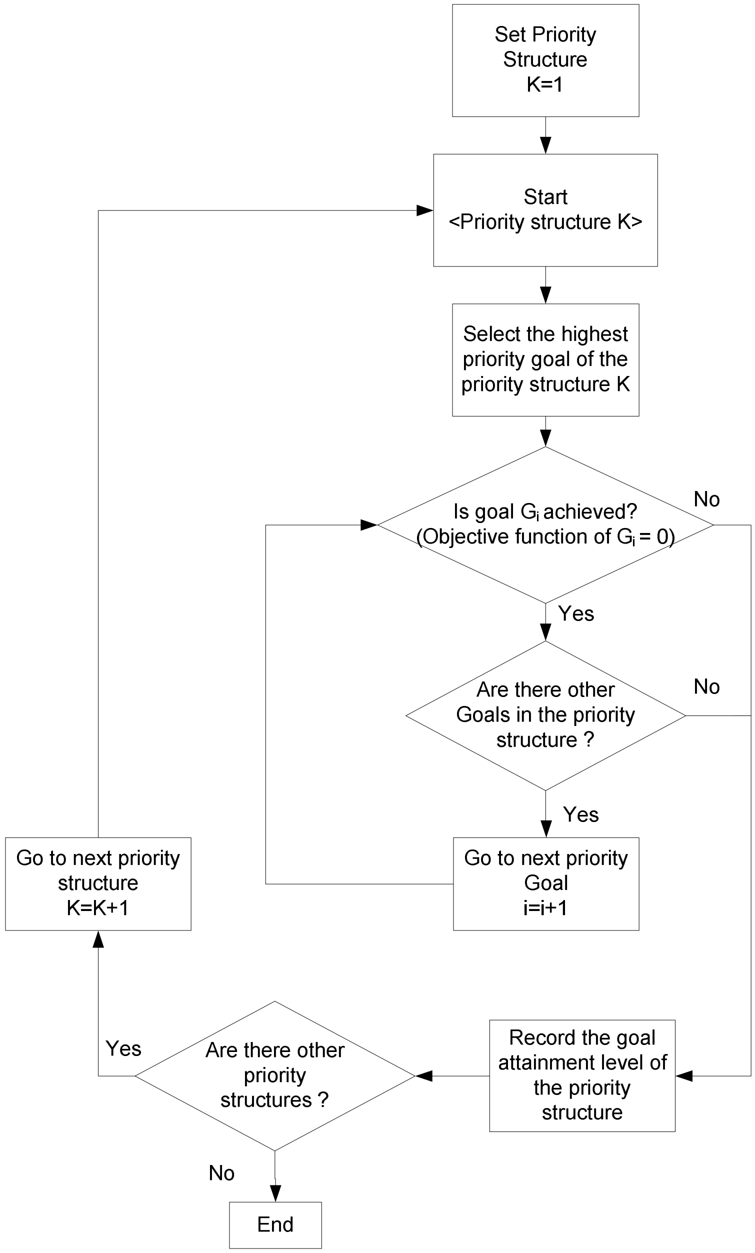


Figure 7. 6: Partitioning algorithm

The algorithm then substitutes the values of the decision variables into the goal constraints of the lower priorities to calculate their attainment levels, and the problem is solved. However, if alternate optimal solutions do exist, the next set of goal constraints (those assigned to the second highest priority) and their objective function terms are added to the problem. This brings the algorithm to the next subproblem in the series, and the optimization resumes. The algorithm continues in this manner until no alternate optimum exists for one of the subproblems or until all priorities have been included in the optimization(Masud and Ravindran 2009)

The ultimate solution for the goal programming problem provides the degree of attainment of the goals compared to the predetermined expectations in different priority structures and the identification of what alterations are necessary in expectations to attain all the goals in different priority structures, and provides the best satisfying priority structure under a varying amount of resources.

7.5.2 Mutual goal definition

This phase involves dividing the optimized goals obtained through the goal management phase among different PCGs in a more sustainable way. The goals allocated to the PCGs represent the mutual goals, in which the members are inspired to achieve collaboratively.

In this section, we discuss the definition of mutual goals in two directions:

- Mutual goal allocation based on the general characteristics of PCGs
- Reshaping the mutual goals based on the quality of behaviours in addition to the general characteristics of PCGs

We first discuss the mutual goal definition based on the general characteristics of PCGs in detail.

7.5.2.1 Mutual goal definition based on the general characteristics of PCGs

One direct way to define and allocate the mutual goals to PCGs is based on the generic characteristics of PCGs (Fig. 7.7), such as the number of prosumers within the PCG and the averaged energy sharing capacity of the PCG. We call this type of mutual goal, which is defined and allocated based on the generic characteristics of PCGs, a “theoretical mutual goal.” The mutual goals defined for each energy transaction will remain fixed (assuming the number of prosumers remains unchanged and the average energy is calculated by using the upper threshold and the lower threshold of the PCGs that are decided when defining the pre-qualification criteria of the PCG).

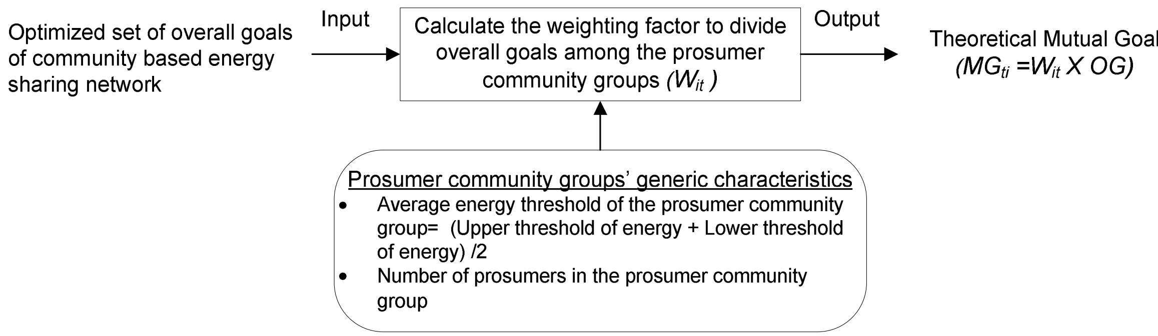


Figure 7. 7: Mutual goal definition based on the general characteristics of prosumer community groups

Let OG be the overall goal to be divided among the PCGs, W_{it} be the weighting factor of i^{th} PCG that is used to divide the overall goal into theoretical mutual goals, N_{pi} be the number of prosumers within the i^{th} PCG, E_i be the averaged energy sharing capacity of the i^{th} PCG, U_i be the upper threshold of the i^{th} PCG and L_i be the lower energy threshold of the i^{th} PCG.

Let the "theoretical mutual goal" allocated to the i^{th} PCG be the MG_{ti}:

$$MG_{ti} = W_{it} \times OG$$

$$W_i = \frac{N_{pi} \times E_i}{\sum_{i=1}^{n} N_{pi} \times E_i}$$

$$E_i = \frac{U_i + L_i}{2}$$

$$MG_{ti} = \left(\frac{N_{pi} \times \frac{U_i + L_i}{2}}{\sum_{i=1}^{n} N_{pi} \times \frac{U_i + L_i}{2}} \right) \times OG \qquad \text{Equation 7. 8}$$

However, the theoretical goals discussed above do not consider the quality of members' behaviours, rather than the mere evaluation of general characteristics. Such mutual goals are suitable at the early age of the PCGs when there are no much historic energy behaviours of prosumers.

In the next section, we propose an approach to define the mutual goals that analyse the fluctuations involved in prosumers' energy behaviours, in addition to the generic characteristics.

7.5.2.2 Reshaping the mutual goals based on the quality of behaviours in addition to the general characteristics of PCGs

In this approach, the mutual goals are reshaped based on the quality of behaviours of PCGs in addition to the general characteristics (Fig. 7.8). We name these goals "realistic mutual goal." In order to analyse the quality of the PCG's behaviours, we analyse how these PCGs have attained the mutual goals in previous energy transactions and the associated deviation of the actual energy commitment in the previous transaction compared from the expectation (mutual goal defined for the previous transaction).

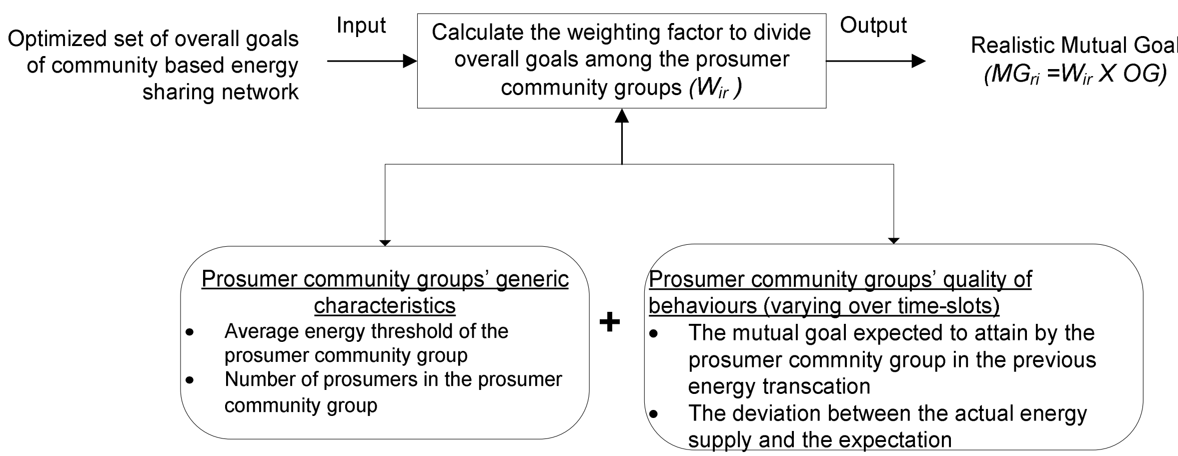


Figure 7. 8: Mutual goal allocation based on the quality of behaviours in addition to the general characteristics of prosumer community groups

Let OG be the overall goal to be divided among the PCGs, W_{ir} be the weighting factor of i^{th} PCG that is used to divide the overall goal into realistic mutual goals, N_{pi} be the number of prosumers within the i^{th} PCG, E_i be the averaged energy sharing capacity of the i^{th} PCG, U_i be the upper threshold of the i^{th} PCG, L_i be the lower energy threshold of the i^{th} PCG, mutual energy goal assigned to the i^{th} PCG in previous transaction is Tp_i, deviation of the actual energy supply from the mutual goal in previous transaction of the i^{th} community group is D_{pi}. This deviation is positive if the PCG has supplied more energy than the expected mutual goal in the previous transaction and will become negative if the PCG has supplied lower-quantity energy than the expected mutual goal in the previous transaction.

Let the "realistic mutual goal" allocated to the i^{th} PCG be the MG_{ri}:

$$MG_{ri} = W_{ir} \times OG$$

$$W_{ir} = \frac{N_{pi} \times E_i}{\sum_{i=1}^{n} N_{pi} \times E_i} \times \frac{(T_{pi} \pm D_{pi})}{T_{pi}}$$

$$MG_{ri} = \left(\frac{N_{pi} \times E_i}{\sum_{i=1}^{n} N_{pi} \times E_i} \times \frac{(T_{pi} \pm D_{pi})}{T_{pi}} \right) \times OG$$

Equation 7. 9

where

$$E_i = \frac{U_i + L_i}{2}$$

Overall, the realistic mutual goals may set higher goals than theoretical mutual goals for the PCG who has shown higher performance in historical energy transactions. Thus, it will be a motivating force for them to show even higher performance. However, corrective measures should be taken to prevent the realistic goals to become lower compared to the theoretical goals for the PCGs who did not attain the expected mutual goals in previous translations.

Therefore, we redefine the realistic mutual goals allocated to the i^{th} PCG (MG_{ri}) as follows:

$$MG_{ri} \begin{cases} \left(\frac{N_{pi} \times E_i}{\sum_{i=1}^{n} N_{pi} \times E_i} \right) \times OG & \text{If } D_{pi} = 0 \text{ OR } D_{pi} < 0 \\ \left(\frac{N_{pi} \times E_i}{\sum_{i=1}^{n} N_{pi} \times E_i} \times \frac{(T_{pi} + D_{pi})}{T_{pi}} \right) \times OG & \text{If } D_{pi} > 0 \end{cases}$$

If D_{pi} =0 OR D_{pi} <0: where the prosumer community group has just met the expected mutual goal OR has not met the expected mutual goal in previous transaction

If D_{pi} >0–: where the prosumer community group has supplied more energy than the expected mutual goal in previous transaction

Equation 7.10

In this section, we have discussed the concepts of managing multiple goals within the community-based energy sharing network. In the subsequent section, we verify the goal management and mutual goal definition framework.

7.6 Verification of the Multiple Goal Management and Mutual Goal Definition Framework

In this section, we verify and validate the solution framework by conducting simulations. In this framework, the multiple goal management is developed as a linear goal programming problem, which is solved using LINDO-32 (version 6.1) software. LINDO (Linear, INteractive, Discrete Optimizer) is an interactive linear, quadratic and integer programming system that can be used to solve interactive linear, quadratic, general integer and zero-one integer programming programs as well as to perform sensitivity analysis and parametric programming.

As mentioned earlier, we modelled the multiple goal management in a community-based energy sharing network as a linear goal programming problem, which will be solved using LINDO in the subsequent section.

We first discuss the experimental settings used for solving the goal programming model.

7.6.1 Experimental setting

In this section, we discuss the parameters required to establish the goal management framework (Table 7.1). As indicated in Table 7.1, some of the parameters for the goal programming problem are obtained based on the actually available data and some parameters are assumed based on the Australian conditions, as access to the real data are not available(Rathnayaka, Potdar et al. 2012). Here, we take the four PCGs defined in PCG definition and characterization framework (Chapter 5).

Table 7-1: Parameters for goal programming model

Parameter	Value
Averaged energy level (daily) • Prosumer community group *1 (PCG 1)* • *PCG 2* • *PCG 3* • *PCG 4*	 3.5 kWh 7.0 kWh 11.0 kWh 16.0 kWh
Available number of prosumers • *PCG 1* • *PCG 2* • *PCG 3* • *PCG 4*	 110 120 120 80
Resource constraints (storage and handling)	10,000 kWh
External energy demand (assumed)	6000 kWh
Income rate (assumed weights) *PCG 1:PCG 2:PCG 3:PCG 4*	1:3:6:9
Total expected income (assumed)	$15,000
Cost rate (assumed weights) *PCG 1:PCG 2:PCG 3:PCG 4*	1:2:3:4
Total budgeted cost constraint (assumed)	$5000
The percentage of overall participations sustainability (N_s)	90%

As mentioned earlier, using the goal constraints and absolute constraints, a set of 120 different priority structures can be constructed. For the purpose of this experiment, we assign the highest priority to the demand objective (G1) and keep it same in all the structures, reducing the number of priority structure to 24. The different priority structures are shown in Table 7.2, where the position of the characters (“G1,” “G2,” “G3,” “G4” and “G5”] in the sequence of the priority structure indicates the priority assigned to different goals, respectively.

Table 7-2: Level of attainment for different priority structures without any variation to the goals

Priority structure				
G1	G2	G3	G4	G5
G1	G2	G3	G5	G4
G1	G2	G4	G3	G5
G1	G2	G4	G5	G3
G1	G2	G5	G4	G3
G1	G2	G5	G3	G4
G1	G3	G2	G4	G5
G1	G3	G2	G5	G4
G1	G3	G4	G2	G5
G1	G3	G4	G5	G2
G1	G3	G5	G4	G2
G1	G3	G5	G2	G4
G1	G4	G3	G2	G5
G1	G4	G3	G5	G2
G1	G4	G2	G3	G5
G1	G4	G2	G5	G3
G1	G4	G5	G2	G3
G1	G4	G5	G3	G2
G1	G5	G3	G4	G2
G1	G5	G3	G2	G4
G1	G5	G4	G3	G2
G1	G5	G4	G2	G3
G1	G5	G2	G4	G3
G1	G5	G2	G3	G4

We determine the level of attainment of different goals in different priority structures using the LINDO-32 (version 6.1) software. In the next section, we illustrate the observations and results we obtained by solving the goal problem in LINDO.

7.6.2 Observation, results and discussion

In this section, we illustrate the solution of the goal programming problem. The solution procedure entails the partitioning of the objective function according to the priority levels and the sequential solution of the resultant mixed integer linear programming models. The solution obtained at each priority level is used as a constraint at the lower level. The generic examples discussed here is intended to serve as an illustration for applicability of the model to a practical-sized problem. The level of goal attainment with the planned expectations for different priority structures are illustrated in Table 7.3.

Table 7-3: Level of attainment for different priority structures without any variation to the goals

Priority structure					Attained goals
G1	G2	G3	G4	G5	G1
G1	G2	G3	G5	G4	G1
G1	G2	G4	G3	G5	G1
G1	G2	G4	G5	G3	G1
G1	G2	G5	G4	G3	G1
G1	G2	G5	G3	G4	G1
G1	G3	G2	G4	G5	G1 G3
G1	G3	G2	G5	G4	G1 G3
G1	G3	G4	G2	G5	G1 G3
G1	G3	G4	G5	G2	G1 G3G5
G1	G3	G5	G4	G2	G1G3G5
G1	G3	G5	G2	G4	G1G3G5
G1	G4	G3	G2	G5	G1
G1	G4	G3	G5	G2	G1
G1	G4	G2	G3	G5	G1
G1	G4	G2	G5	G3	G1
G1	G4	G5	G2	G3	G1
G1	G4	G5	G3	G2	G1
G1	G5	G3	G4	G2	G1G5G3
G1	G5	G3	G2	G4	G1G5G3
G1	G5	G4	G3	G2	G1G5
G1	G5	G4	G2	G3	G1G5
G1	G5	G2	G4	G3	G1G5
G1	G5	G2	G3	G4	G1G5

For example, in the priority structure G1G2G3G4G5, G1 is given the highest priority and thus we minimize *pi* first (where i= {1,2,3,4}) for four community groups. The objective function returns 0; thus, the first goal (G1) is met successfully. When we attempt to fulfil the second goal G2 (external customer objective), we observe that objective function is *1655*, which means *p5= 1655*, or we have a slack of *1655*. That means G2 is not solved with given constraints; as a result, only G1 is solved in the priority structure: G1G2G3G4G5.

Moreover, in the priority structure G1G3G5G4G2, the first three goals G1, G3 and G5 return zeroed objective function; thus, goals are met successfully. However, when we solve the fourth goal (G4), the objective function returns *9695*, which means *n7=9695* and G4 is not met. Therefore, in this priority structure, only G1, G3 and G5 are met with given constraints.

However, the entire set of goals of the aforementioned priority structures can be attained by optimizing the goal constraints. For further optimization analysis, we only consider the following priority structures

(G1G2G3G4G5), (G1G3G4G5G2), (G1G3G5G4G2) and (G1G4G3G2G5), because the optimization of other priority structures also takes the similar results of one of the above four structures. Figures 7.9, 7.10, 7.11 and 7.12 illustrate how different goal constraints are changed to achieve all the goals in the aforesaid priority structures.

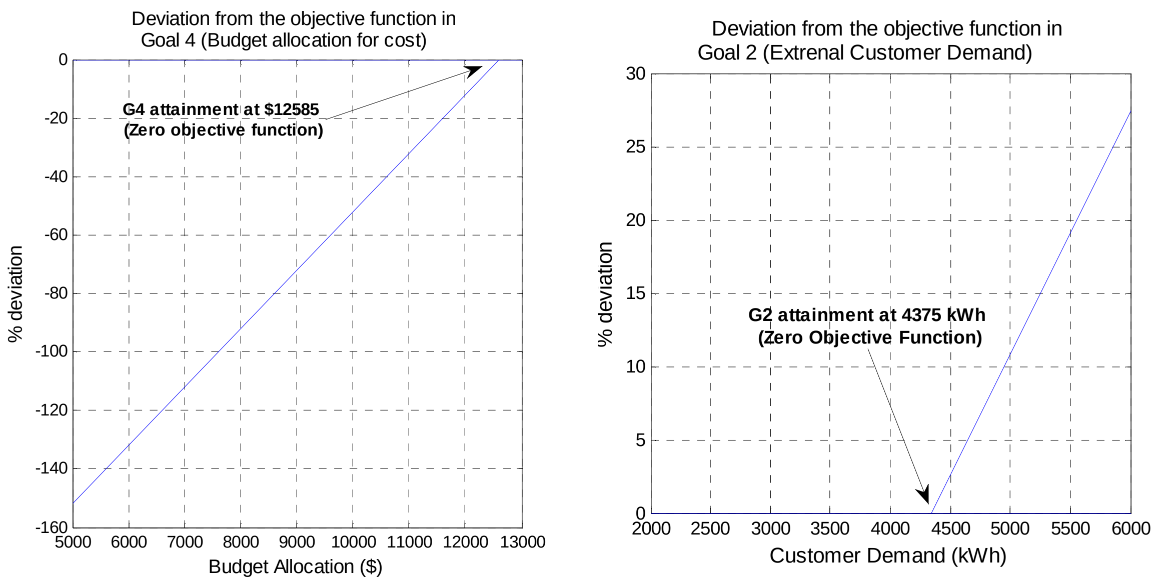


Figure 7. 9: Goal negotiation in the priority structure <G1 G2 G3 G4 G5>

In the priority structure G1 G2 G3 G4 G5 (Fig. 7.9), G1 is solved successfully with given constraints. However, as depicted in Fig. 5, if the external customer demand to be fulfilled by the PCGs is decreased by 27% from 6000 kWh to 4345 kWh, G2 can be achieved with zero objective function in LINDO. Moreover, the allocated cost allowance is to be increased by 151% from $5000 to $12,585 to achieve the G4 (cost objective). With these changes, the subsequent goals G4 and G4 are achieved.

In the priority structure G1 G3 G4 G5 G2, G1 is solved successfully with given constraints. However, as depicted in Fig. 7.10 if the budget allocation for cost is increased by 43% from $5000 to $7180.50, G4 can be achieved with zero objective function in LINDO. With this change, the number of prosumers should be reduced to 222 prosumers (by 50%) to achieve the sustainability objective (G5). Similarly, with the aforesaid changes, the external customer demand that PCGs are expected to fulfil should reduce by 62% from 6000 kWh to 2238 kWh to achieve G2.

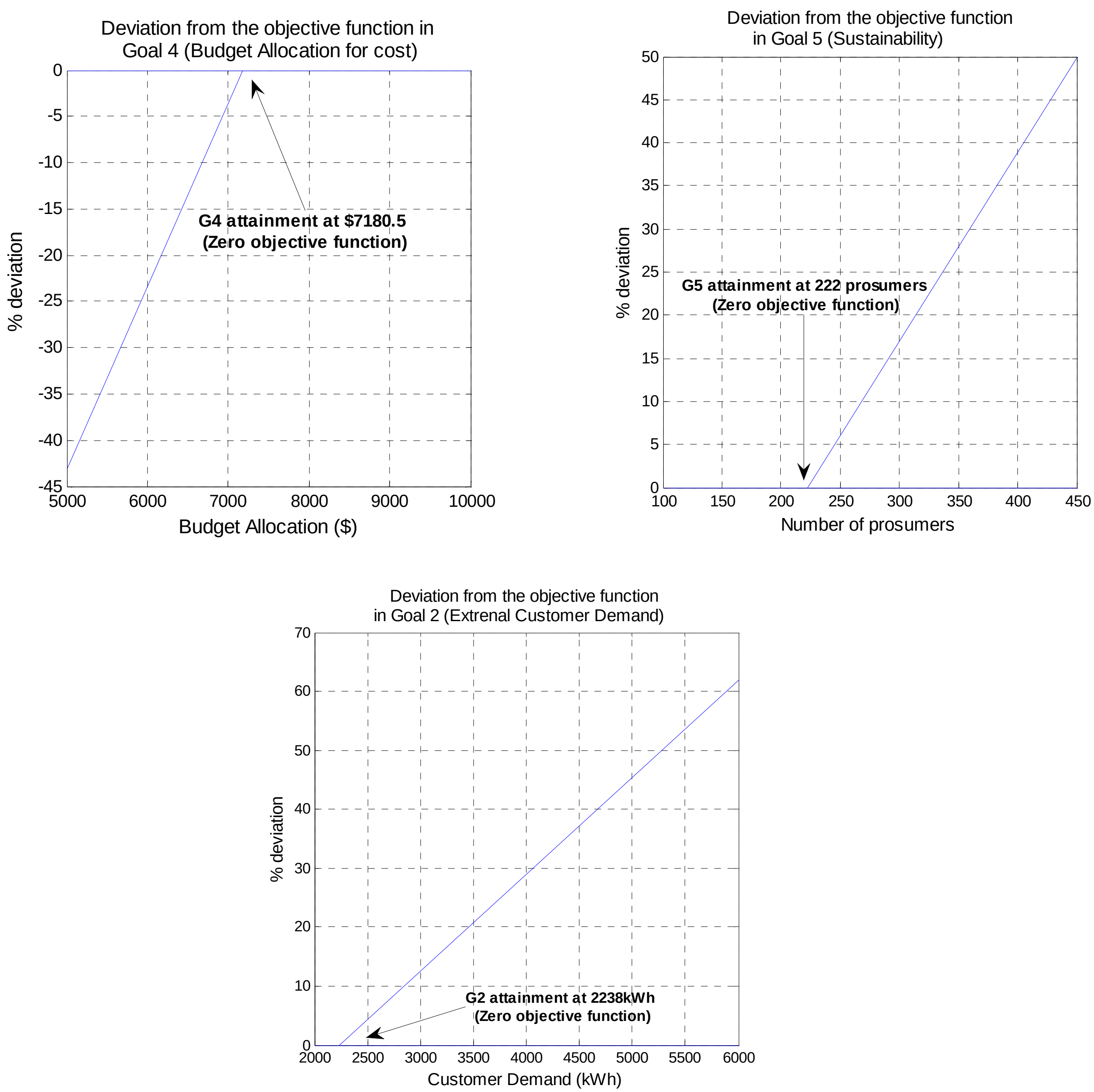


Figure 7. 10: Goal negotiation in the priority structure <G1 G3 G4 G5 G2>

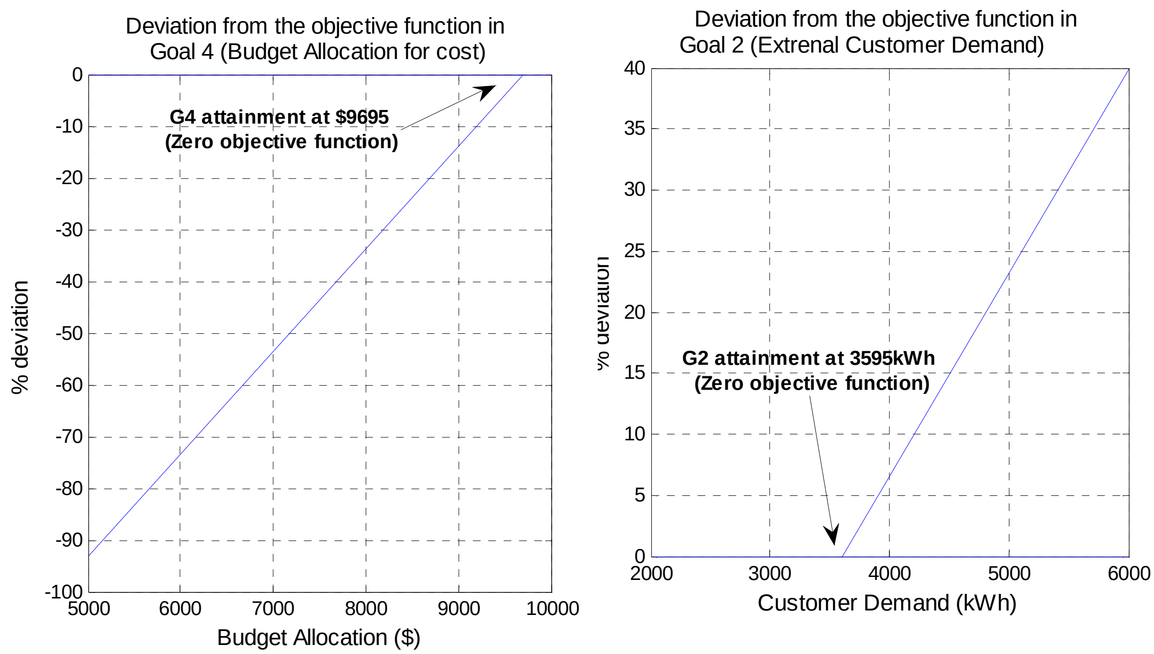


Figure 7. 11: Goal negotiation in the priority structure <G1 G3 G5 G4 G2>

In the priority structure G1 G3 G5 G4 G2, the subsequent goals G1, G3 and G5 are solved successfully with given constraints. However, as depicted in Fig. 7.11, if the budget allocation for cost is increased by 93% from $5000 to $9695, G4 can be achieved with zero objective function in LINDO. With this change, the external customer demand that PCGs are expected to fulfil should reduce by 40% from 6000 kWh to 3595 kWh to achieve G2.

In the priority structure G1 G4 G3 G2 G5, the first goal G1 is solved successfully with given constraints. However, as depicted in Fig. 7.12, if the budget allocation for cost is increased by 14.5% from $5000 to $5725, G4 can be achieved with zero objective function in LINDO. With this change, the income expectations from PCGs should be decreased by 24.8% from $15,000 to $11,725 to achieve G3. The number of actively participating prosumers in PCGs, should be reduced to 200 prosumers to achieve G5. The external customer demand that PCGs are expected to fulfil should reduce by 40% from 6000 kWh to 3595 kWh to achieve G2.

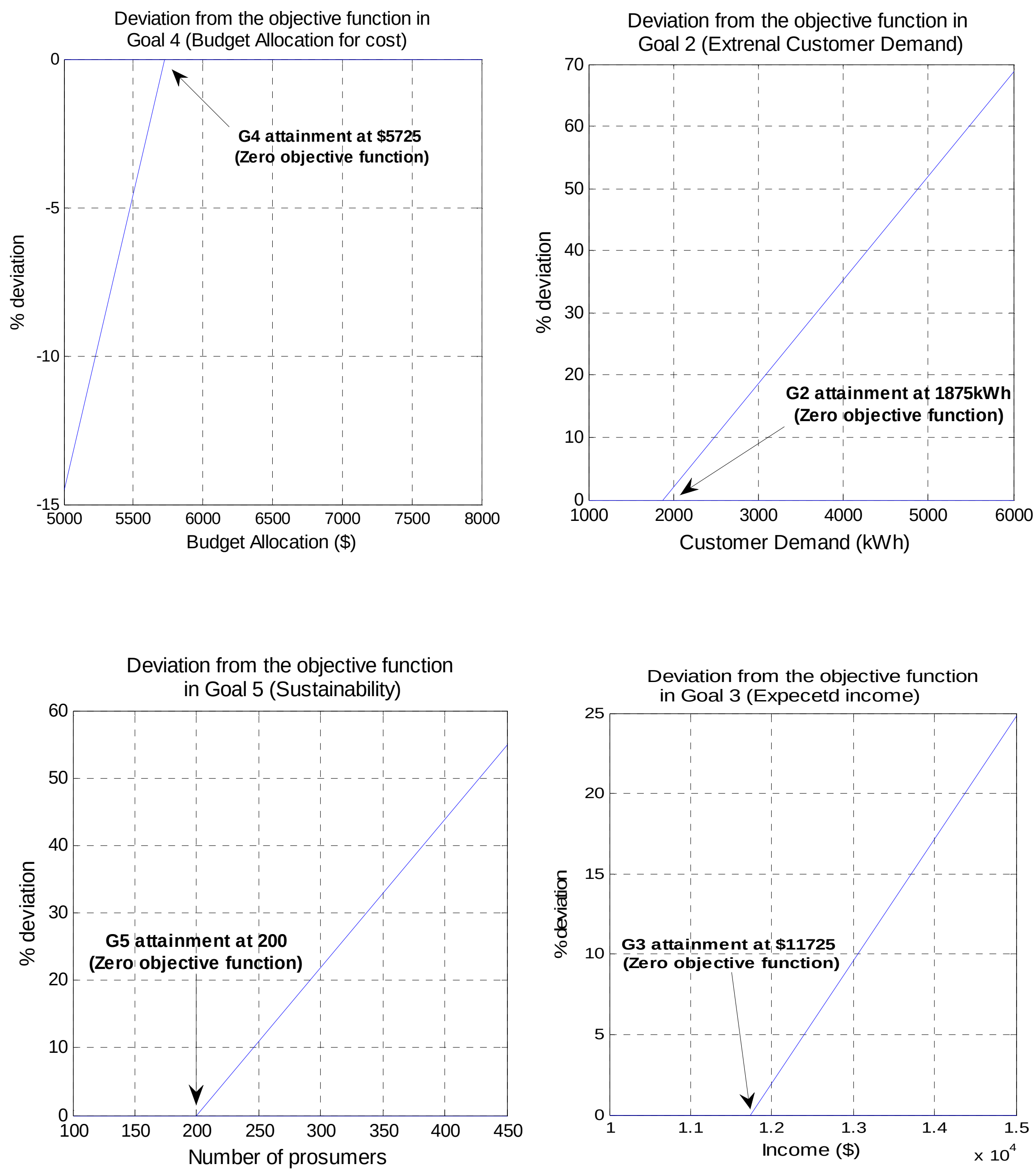


Figure 7. 12: Goal negotiation in the priority structure <G1 G4 G3 G2 G5>

According to the aforementioned analysis, in order to attain all the goals, some adjustments are to be made for the targeted values. We select the priority structure G1 G3 G5 G4 G2 to define the mutual goals for PCGs, as it only needs to adjust two goal constraints (G4 and G2) with less deviation, compared to the priority structure G1 G2 G3 G4 G5, and still achieves other three goals (G1,G3,G5) without any alterations to those goals. Table 7.4 illustrates the negotiated set of goals as follows.

Table 7-4: Negotiated set of goals

Priority structure	G1 G3 G5 G4 G2
G1 (local demand objective)	Achieved (local demand of PCGs)
G2 (external customer objective)	Achieved with the variation (3595 kWh)
G3 (income objective)	Achieved ($15,000)
G4 (cost objective)	Achieved with the variation ($9695)
G5 (sustainability objective)	Achieved (90% prosumer participation)

7.7 Conclusion

In this chapter, an innovative framework is presented for goal management and mutual goal definition. We discussed this framework in two elements: (i) goal management and the (ii) mutual goal definition. The key platform of the proposed framework in this dissertation is the goal management element which is developed using MCGP concepts. The proposed goal management approach determines the multiple conflicting goals within the community-based energy sharing network, prioritizes the goals based on their relative importance and negotiates among the goals to obtain the optimized set of goals for community-based energy sharing network. The proposed approach for goal management assists in deciding the best priority structure to attain the preferred objectives with minimal utilization of available resources, and what adjustments to be made to the expected values of the goal constraints to reach the satisfactory attainment of all the goals. Moreover, the second component of this framework, the mutual goal definition approach, defines an optimal set of mutual goals, by effectively breaking down the overall goals into customized mutual goals for diverse PCGs, where the prosumers of each PCG are inspired to achieve the respective mutual goal. Defining and allocating a customized goal for each PCG will make the individual members much more comfortable in fulfilling their accountabilities in achieving the mutual goals. In this approach, the customized mutual goals are defined based on the general characteristics of the PCG (theoretical mutual goal), as well as the fluctuations in previous energy behaviours (realistic mutual goals). The theoretical mutual goals can be allocated when there are no historic energy behaviours, whereas the realistic mutual goals set higher mutual goals than the theoretical mutual goals when allocated for the PCGs who have supplied more energy than agreed in the previous energy transactions. This acts as a motivational force for them to enhance their energy sharing capability.

This proposed framework has been accepted in a peer-reviewed international journal (Rathnayaka, Potdar et al. 2014)wherein we have attached a complete list of all the publications arising as a result of the research study carried out in this thesis at the beginning of the thesis.

Another key challenge faced by the prosumer community coordinator is assessing and ranking the individual prosumers within a PCG. This is the starting point to determine the more influential prosumers within the PCG that facilitates fair distribution of incentives and privileges. The following chapter provides the detailed framework for prosumer assessment and ranking in PCGs.

Chapter 8

Prosumer Community Group Member Assessment and Ranking Framework

This chapter provides:

- An introduction to prosumer assessment and ranking within a PCG
- A framework to assess and rank the prosumers within a PCG
- Verification of the proposed framework for member assessment and ranking

8.1 Introduction

In the previous chapters, we proposed methodologies to establish PCGs, by which the prosumer community coordinator first defines and characterizes the PCGs followed by prosumer recruitment and defining mutual goals for those PCGs. After creating the PCGs, one key challenge faced by the prosumer community coordinator is the assessment of the contribution made by individual prosumers of a PCG, and thus finding a subset of the most influential prosumers whose behaviour would facilitate the long-term sustainability of the PCGs.

We discuss the significance of addressing this challenge of prosumer assessment and ranking as follows. From the prosumer community coordinator's perspective, this concept can be used to understand the individual members' fluctuating energy behaviours over a period of time. Thus, the more influential members can be differentiated, whose future behaviour will facilitate the long-term sustainability of the PCG; thus, one can take appropriate actions to make the more influential members feel privileged within the PCG, and also to encourage the other members to become relatively influential members. As a result, the proposed prosumer assessment and ranking framework can be adopted as the opening building block to implement incentive management schemes, motivation schemes, etc. On the other hand, from the PCG member's perspective, being an influential member who has committed to the long-term sustenance of the PCGs, they will receive higher privileges or incentives compared to the other members. This will create a competitive environment among the members, which will further encourage the members to invest in additional green energy resources connecting them to the SG, knowing that they will be getting greater profits as their contribution (energy generation capacity) increases.

The aforementioned circumstances necessitate the development of an effective framework to assess and rank the prosumers within the PCG. Therefore, in this chapter, we focus on this challenge and propose an innovative methodology to assess and rank the prosumers, in order to determine the relatively influential membership base. The proposed framework assesses the long-term and short-term energy behaviours of prosumers based on a multiple evaluation criteria and accordingly decides the ranks of the prosumers, whereby the higher-ranked prosumers are deemed to be more influential in enhancing the long-term sustenance of the PCG. The key method we used to assess and rank the members of the PCG is based on MCDM techniques.

In Section 8.2, we provide an overview of member assessment and ranking framework in detail. In Section 8.3, the requirements for this framework are discussed followed by the design rationale in Section 8.4. In Section 8.5, we discuss the theoretical foundation of the framework followed by the verification of it in Section 8.6. Finally, in Section 8.7, we conclude the chapter.

8.2 Overview of PCG Member Assessment and Ranking Framework

The main objective of this framework is to assess and rank the members within the PCG. For a better understanding, we give an overview of the member assessment and ranking in this section. The abstract overview of the member assessment and ranking is illustrated in Fig. 8.1.

As mentioned in the last chapters, each PCG is defined and characterized with pre-qualification criteria that includes "*lower threshold*" that is the least quantity of energy, which an ideal member may share, and the "*upper threshold*" of a PCG, which is the highest quantity of energy that the ideal member may share. When prosumers are recruited to a PCG as members, these members commit to meet the respective PCG's pre-qualification criteria at their level best. Upon the recruitment, that member starts interacting with the other members as well as the external energy buyers such as utility grid through the prosumer community coordinator (centralized controlling point).

Accordingly, we identify different energy interactions of a member within a PCG in long-term operation:

- Some members supply energy to meet the pre-qualification criteria (the supplied amount of energy lies within the upper and lower threshold defined at pre-qualification criteria).
- Some members fail to meet the pre-qualification criteria (i.e. less than the lower threshold).
- Some members supply more energy than expectation (i.e. more than the upper threshold).
- Based on the member's consent, the energy accumulated is used to fulfil the local energy demand as well as to meet the energy requests of external customers such as utility grid and energy retailers.
- Some members share energy directly with the fellow members, contributing towards the member's social responsibility to share the surplus energy with other local members who has energy shortfall to meet the lower threshold of the pre-qualification criteria.

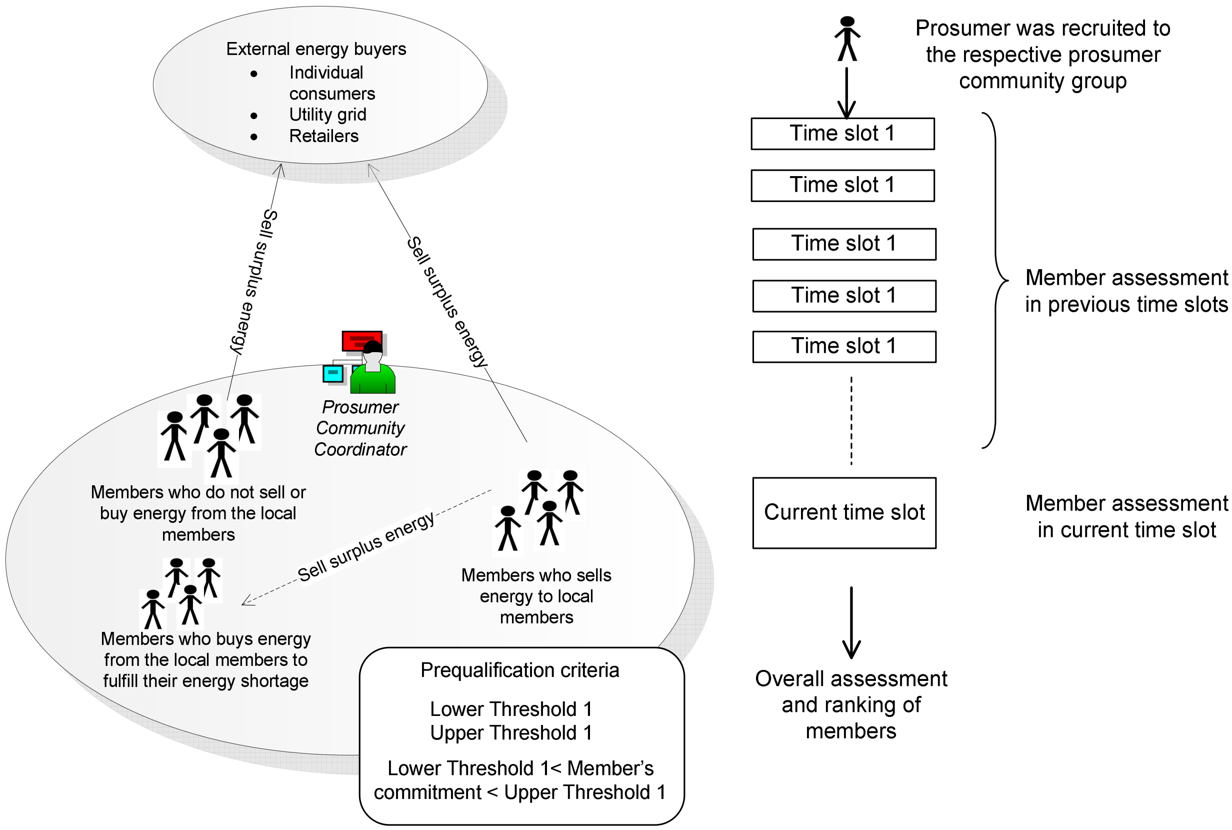


Figure 8. 1: Overview of member assessment and ranking

Due to such varied interactions, treating all the members in a PCG in the same fashion may be discriminatory particularly in certain scenarios like when distributing privileges (or incentives). Moreover, in long-term operation, some members may exhibit fluctuating behaviours than what was expected initially during the recruitment process. Therefore, in order to facilitate the member's fluctuating behaviours over time, the member should be assessed in the current time slot as well as in the previous time slots over that member's membership duration. Here, the term "time slot" is defined as a non-overlapping interval of time, in which the members supply energy to the PCG and the respective energy supply measurements are taken.

The brief flow of processes involved in the member assessment and ranking framework is illustrated in Fig. 8.2.

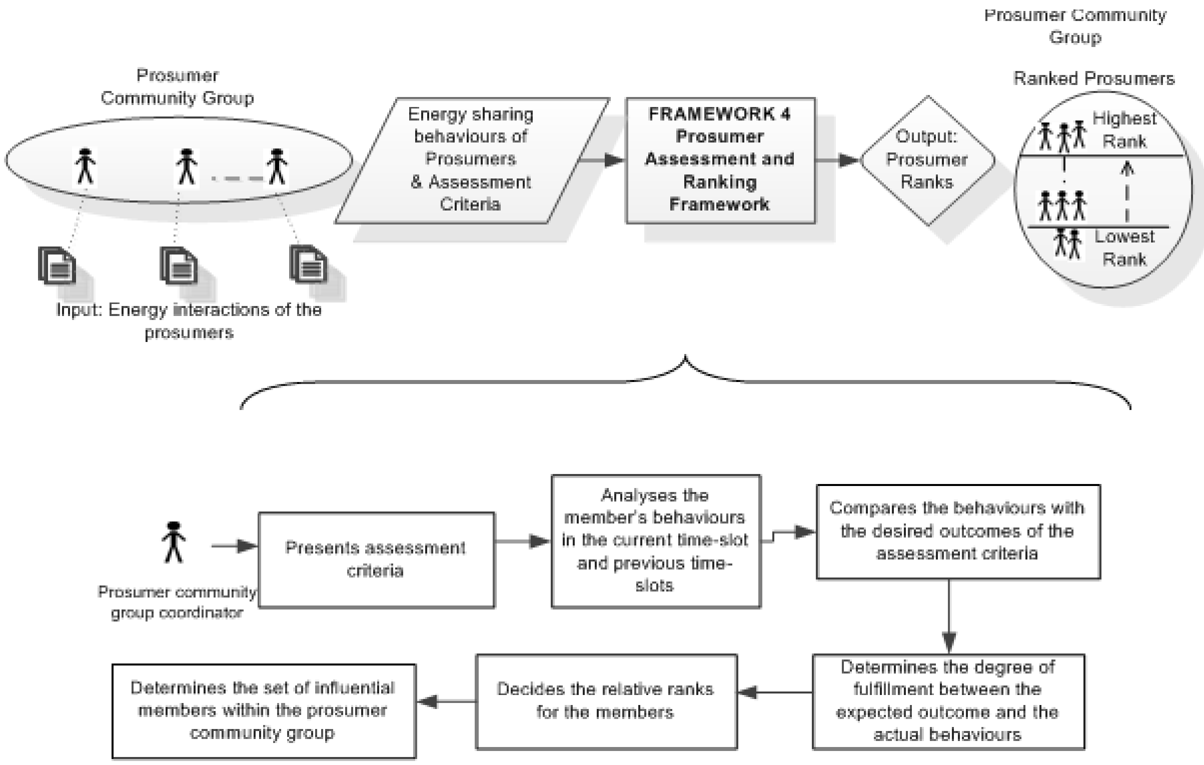


Figure 8. 2: Flow of processes involved in the member assessment and ranking framework

As shown in Fig. 8.2, the input for the member assessment and ranking framework is the member's different energy interactions and the predefined assessment criteria that are in turn used to assess the members' behaviours. In this proposed framework, the prosumer community coordinator first presents the assessment criteria and analyses the energy behaviour of the member in the current time slot, as well as gathers knowledge in the previous time slots throughout their membership duration. The member's actual behaviours are compared with the desired outcomes in assessment criteria. In comparison, the prosumer community coordinator determines whether there are any deviations between the expectations and the actual behaviour of the member in the time-slot, in each assessment criterion. The PCG coordinator determines the degree of fulfilment between the expected outcome of each assessment criteria and actual behaviour in the time-slot, and based on that assigns ranking points to the members. Accordingly, the relative ranks of the members within the PCG are decided. The key output of the framework is the ranks of diverse members within the PCG, which can be further used to find the subset of relatively influential members within the PCG.

In the following section, we discuss the requirements for this research.

8.3 Requirements

The following requirements are specified for the proposed solution. This represents the *first* stage of the conceptual process where requirements are elicited and prioritized. The requirements are as follows:

1. **Define suitable assessment criteria to assess the member's energy interactions within the PCG**: The prosumer assessment and ranking framework should determine the different assessment criteria and prioritize them based on the relative importance. The assessment criteria should represent the functionalities, which the prosumer community coordinator wants to achieve while interacting with the members of the PCG by taking into account the variable nature of members' long-term and short-term energy sharing characteristics.

2. **Assess the members' long-term and short-term energy sharing behaviours:** Even though the PCGs are formed on the basis of homogeneity of the prosumers' energy profiles; in the long term, the members may exhibit divergent energy sharing behaviours compared to the performance they have agreed during the prosumer recruitment process. Therefore, the member assessment and ranking framework should assess the fluctuations in long-term energy behaviours in addition to the short-term energy behaviours with respect to the predefined set of assessment criteria.

3. **Find the most influential subset of prosumers, who enhance the long-term sustenance of the PCG:** The proposed prosumer assessment and ranking framework should rank the members within the PCG, thus determining the subset of members who are deemed to be more influential.

The following section defines the design rationale based on the above-mentioned requirements. A design decision for each requirement is made in the design rationale along with a discussion of how the requirement is met.

8.4 Design Rationale

This section provides a design rationale to meet all the requirements that were listed in the previous section. This is the *second* stage of the conceptual process. The following design decisions are proposed to address each requirement. The concise overview of the design decisions are shown in Fig. 8.3.

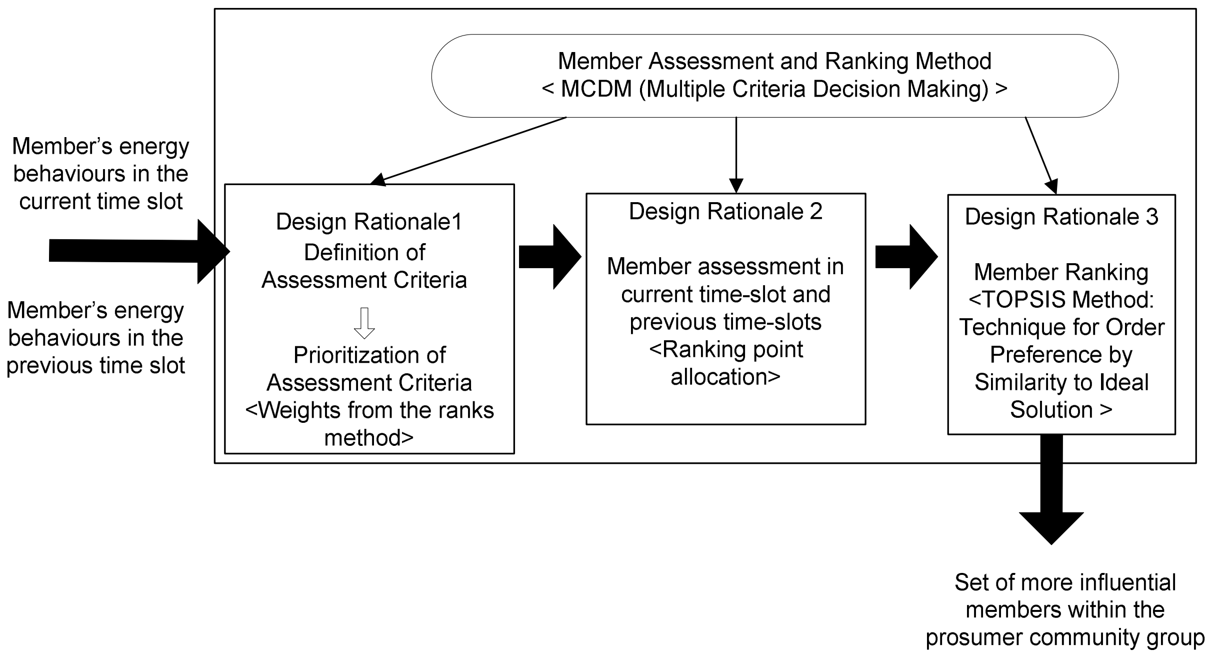


Figure 8. 3: Design rationale

1. **Design rationale 1:** In the proposed member assessment and ranking framework, we identify four assessment criteria to assess the members' short-term and long-term energy behaviours within the PCG by taking the following attributes of a member into account: the member's commitment that meets the respective PCG pre-qualification criteria which has been formalized

between the member and the prosumer community coordinator during the recruitment process, energy contribution to fulfil external customer's energy request, social responsibility to help fellow members to cover up their energy shortage (to help them to meet the pre-qualification criteria) and the member's quality of the energy behaviours throughout the tenure. These criteria are prioritized using the method "weights from ranks" of MCDM techniques. This would satisfy the requirement for the definition of suitable assessment criteria to assess the members within a PCG (Req. 1).

2. **Design rationale 2:** In the proposed member assessment and ranking framework, we allocate points to the members based on their long-term and short-term energy behaviours that are assessed against the multiple criteria. These ranking points determine the degree of deviation between the expected and actual behaviour and provide a relative judgment for each member's behaviours. This would satisfy the requirement for assessment of members' short-term and long-term energy sharing behaviours (Req. 2).

3. **Design rationale 3:** In order to find the subset of influential prosumers within the PCG, we develop a ranking technique by adopting the concepts of the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method of MCDM techniques. In this method, the commitment of each member is compared with the other members to rank the members. The members with higher ranks are considered as the subset of influential members. This would satisfy the requirement for finding influential members within the PCG (Req. 3).

In the development of any solution, the above design decisions should be considered. All these design decisions are included in the proposed method to assess and rank the members within the PCG. This concludes stage 2 of the conceptual process. The next stage is the establishment of the theoretical foundation for the proposed solution.

8.5 Theoretical Foundation

In this section, the theoretical foundation for the member assessment and ranking framework is discussed, the design decisions are analysed and an algorithm is proposed. The theoretical foundation as depicted in Fig. 8.4 consists of four main ongoing phases: (i) assessment criteria definition, (ii) criteria prioritization, (iii) point allocation and (iv) member ranking.

The first phase of the framework is the "*assessment criteria definition*" process involving the definition of four assessment criteria. In the second process of "*criteria prioritization*," we prioritize the aforesaid criteria based on their importance in attaining the community group's enrichment. In the third process of "*point allocation*," we allocate points to the members based on their capacity in satisfying the criteria, and finally in the "*member ranking*" process, we rank the individual members based on the allocated points.

In order to formulate an optimal solution for this methodology, one of the efficient theoretical platforms would be MCDM technique(Masud and Ravindran 2009). MCDM techniques have been successfully implemented in many application areas, like academic planning and health planning, and are claimed to be an efficient and feasible way to handle multiple conflicting criteria(Masud and Ravindran 2009). Nevertheless, this concept has not been used as a working model in energy networks. The techniques presented in MCDM have offered better results for ranking as compared to other well-known methods in which the ranking process is based on the analysis of "Euclidean distance" or "Manhattan distance" among the objects. Particularly for the ranking phase, we used the TOPSIS of MCDM (Masud and Ravindran 2009; ur Rehman, Hussain et al. 2012).

TOPSIS operates on the principle that the preferred solution (alternative) should simultaneously be closest to the ideal solution that is the highest expectation for a considered criterion, and farthest from the negative-ideal solution that is the lowest bound for a considered criterion. TOPSIS does not require the specification of a value (utility) function but it assumes the existence of monotonically increasing value (utility) function for each criterion. The method uses an index that combines the closeness of an alternative to the positive-ideal solution with its remoteness from the negative-ideal solution.

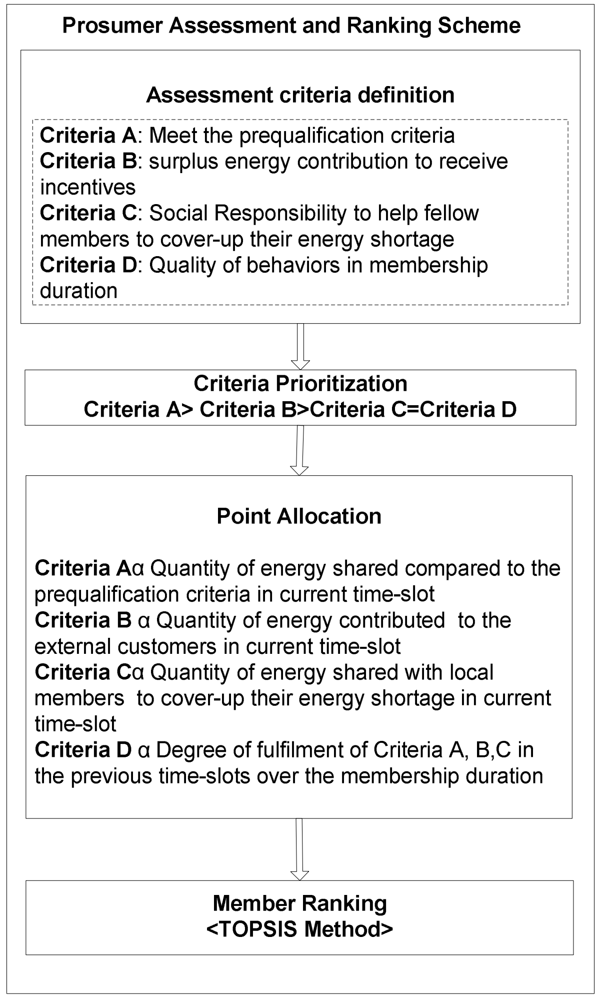


Figure 8. 4: Theoretical foundation

Furthermore, the TOPSIS method of MCDM has shown better performance compared to the other methods in MCDM, such as “max–min method” and “min–max method”. Therefore, we use the TOPSIS method of MCDM models to rank a finite number of prosumers by measuring several conflicting criteria. In the subsequent subsections, we discuss the theoretical formulation of the different processes of the methodology.

In the next section, we describe the aforementioned phases of prosumer assessment and ranking framework in detail. First, we discuss the assessment criteria definition of the solution framework in the next section.

8.5.1 Assessment criteria definition

In this section, we decide the criteria that are used to assess the members. In this model, we select four criteria of assessment, which are broadly categorized into two components: (i) assess the members' short-term energy behaviours in the current time slot and (ii) assess the members' long-term energy behaviours in previous time slots. Assessing the members' short-term energy behaviours in the current time slot covers the first three assessment criteria shown in Fig. 8.4, namely (i) *Criterion A: meet the pre-qualification criteria***,** which measures the member's ability to supply energy more than the lower threshold of the pre-qualification criteria, which was acknowledged to the member when that member was recruited to the respective PCG, (ii) *Criterion B: surplus energy contribution to receive incentives*, which measures the surplus energy production and sharing by the member to meet the external energy buyers' requests such as utility grid and thus receive incentives, and (iii) *Criterion C: social Responsibility to help fellow members to cover up their energy shortage*, which measures the member's energy sharing to the fellow members to meet the lower threshold of the pre-qualification criteria. On the other hand, assessing the long-term behaviours of members covers the fourth criteria shown in Fig. 8.4: (iv) *Criterion D: Quality of behaviours in membership duration* that assesses the members' ability to fulfil the first three criteria in the previous time periods.

Figure 8.5 illustrates the flow of steps we followed when forming the assessment criteria.

As shown in Fig. 8.5, when forming the assessment criteria, the initial step would be the determination of attributes of the members. From the decision-making point of view of MCDM, attributors are the descriptors of the alternatives. Here, we denote the alternatives as the members within the PCG.

For this decision situation of choosing the “best” set of members within the PCG, the attributes that form the assessment criteria could be the member’s ability to meet the pre-qualification criteria, member’s energy contribution to supply surplus energy, member’s social responsibility to help fellow members to cover up their energy shortage and the member’s quality of behaviours in membership duration.

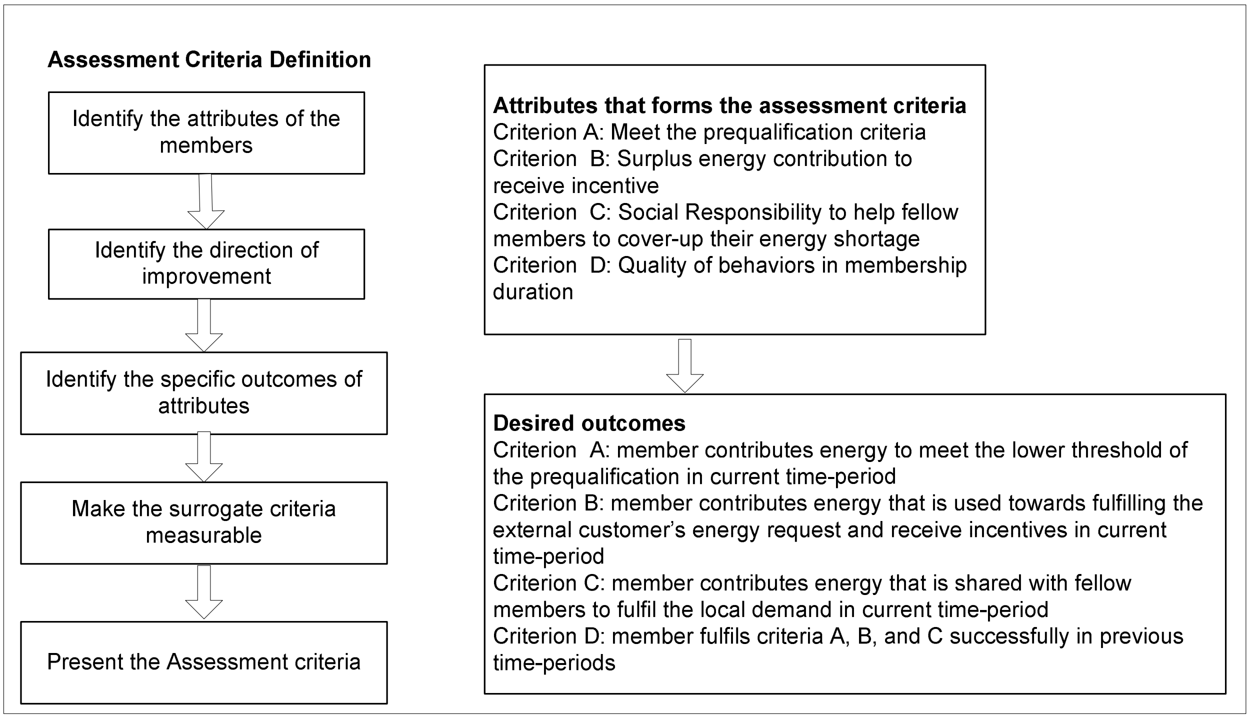


Figure 8. 5: Assessment criteria definition process

The second step of defining the assessment criteria is the identification of the directions of improvement or to do better, as perceived by the decision maker (prosumer community coordinator). Considering the requirement of choosing the “best” set of prosumers, an objective is to increase the values of the attributes (or assessment criteria). For example, the decision maker (prosumer community coordinator) prefers a higher quantity of energy from the members when assessing the first attribute and second (assessment criteria) of meeting the pre-qualification criteria, the higher the better.

The third step would be to identify the specific (or desired) outcomes of attributes. In general, the desired outcomes of attribute are the thresholds of attribute values that are expected to be attained by the bet set of members within the PCG ("best" alternative). For example, in choosing the "best" set of members within the PCG, the key desired outcomes for different assessment criteria (attributes) are as follows: Criterion A: member contributes energy to meet the lower threshold of the pre-qualification in the current time slot, Criterion B: member contributes energy that is used towards fulfilling the external customer's energy request and receive incentives in the current time slot, Criterion C: member contributes energy that is shared with fellow members to fulfil the local demand in the current time slot and Criterion D: member has fulfilled criteria A, B and C successfully in the previous time slots.

The subsequent step would be to identify whether the criterion is true or surrogate. When a criterion is directly measurable, it is called a true criterion. A surrogate criterion is used in place of one or more others that are more expressive of the decision maker's underlying values but are more difficult to measure directly. For example, the attribute of the member's "social responsibility to help fellow members to cover up their energy shortage" and the "quality of behaviours in membership duration" are more expressive as a criteria, and is very difficult to measure. However, "the quantity of energy shared with the fellow members within the same prosumer community group" is, easier to measure and can be used as one of the surrogate criteria for representing "social responsibility to help fellow members to cover up their energy shortage." In addition, "the member's ability to fulfil the criteria A, B and C in previous time periods" is used for representing "quality of behaviours in membership duration."

Accordingly, we present the following assessment criteria and the justification of selecting them for the proposed member assessment and ranking framework.

- ***Criterion A: meet the pre-qualification criteria***

This criterion assesses the member's ability to supply more energy than the lower threshold associated with the PCG pre-qualification criteria. This is selected as an assessment criterion because, if a member fails to meet the lowest energy boundary of the PCG, that member is said to be unfavourable to the rules of the contract. The members who lie within the boundaries of the community group are to be treated evenly with respect to this criterion.

- ***Criterion B: surplus energy contribution to receive incentives***

This criterion assesses the member's surplus energy sharing capacity over the upper threshold of the pre-qualification criteria. This is selected as an assessment criterion because the members who offer a higher amount of energy than the maximum expectation can lead the PCG to sell more energy in the energy market to the external customers, thus receiving higher level of incentives from them and thus should be ranked higher than the usual members should. Here, we assume that the energy accumulated is generally used to fulfil the local energy demand if required and the rest is sold in the energy market to the external customers (such as utility grid, other PCGs and other customers). If all the members generate and share up to the upper threshold, that members receive the usual feed-in income, but if any member generates more than the upper threshold that results in incentives.

- ***Criterion C: social Responsibility to help fellow members to cover up their energy shortage*** (Converted surrogate criterion: the quantity of energy shared with the fellow members within the same PCG)

This criterion assesses the member's local energy sharing to the fellow members, who are in need of energy to meet the lower threshold of the pre-qualification criteria of the respective PCG. For clarity, the following assumptions are made when assessing the members in this criterion:

- If a member meets the lower threshold of the PCG, but does not own surplus than the upper threshold, that member cannot buy or sell energy from fellow members.

- If the member cannot meet the lower threshold, that member can request energy from the fellow members who have surplus energy than upper threshold.

- If the member has surplus amount of energy than the upper threshold, that member is unable to buy the energy from other local members, but that member can either sell the surplus energy to other members or stay stand-alone without selling.

In this criterion, although the selling or buying energy to/from the local members does not increase the collective energy of the PCG, it creates social sustenance within the PCG by minimizing the number of members who may receive penalties due to the breach of contract (not meeting the lower threshold). Therefore, the prosumers who share their energy to the fellow members, who are in need of energy, should be treated favourably than others.

- ***Criterion D: Quality of behaviours in membership duration*** (Converted surrogate criterion: the member’s ability to fulfil the criteria A, B and C in previous time slots)

This criterion represents the quality of the long-term energy behaviours of a member throughout the membership duration. As discussed earlier, the above criteria (criterion A, criterion B and criterion C) are measured as per the current time slot, whereas criterion D is measured as per the previous time slots. This is selected as an assessment criterion because the member who supplies a lower amount of energy during the current time slot may have offered a higher amount of energy throughout all its previous time slots. Therefore, it is unjust to decide the member’s ranks based only on their behaviours in the current time slot.

8.5.2 Assessment criteria prioritization

In this process, we prioritize the different assessment criteria adopting the “weights from ranks” methodology. We prefer this weighting method (“weights from ranks”) over the other existing methods “rating method” and “pair-wise comparison” method due to the following reasons. The rating method provides a rating to each criterion, based on an agreed appropriate rating scale, and thus may fail to assure a ratio scale (Masud and Ravindran 2009). On the other hand, the “pair-wise comparison” method (also called the ratio weighing method) compares two criteria at a time, using pair-wise evaluation. This method is not adaptable when the number of criteria is large because such methods require a large number of pair-wise comparisons, causing inconsistency inherent in a large number of such comparisons (Masud and Ravindran 2009).

In the chosen "weights from ranks" method, the priorities of ranks are calculated using Equation 8.1.

Let r_j represent the position of the j^{th} criterion. The criterion weight, λ_j, for k number of criteria given in Equation 8.1:

$$\lambda_j = \frac{k-r_j+1}{\sum_{i=1}^{i=k}(k-r_i+1)} \quad \text{Equation 8. 1}$$

Accordingly, at first, the criteria are to be arranged in the order of increasing relative importance; the most important criterion takes the first priority. The final weights obtained through Equation 8.1 are dependent on the priorities assigned to different criteria.

At this point, we assign relative importance of criteria based on the controlling point's (prosumer community coordinator) point of view as follows:

Criterion A: This is the most important criterion, which highlights the member's ability to meet the basic guidelines (pre-qualification criteria) of the PCG. This determines whether the member is in breach of contract or not. Therefore, this receives the highest position in the criteria list, thus receiving the highest criterion weight.

Criterion B: Having surplus energy than the upper threshold increases the overall collective energy of the PCG, resulting in receiving more incentives. Therefore, we assign this criterion the second highest position, hence receiving the second highest criterion weight.

Criterion C and Criterion D: We assign both these criteria the third position. Although criteria C and D do not make a direct impact on increasing the amount of overall energy of the PCG for the considered time period, these reveal the member's aptitude to improve the longevity and sustainability of the PCG.

8.5.3 Point allocation

This process involves allocating points to the members according to their capability in satisfying the aforementioned assessment criteria. We assign positive points to the member if the behaviours affect positively towards the overall performance of the PCG and negative points if the member's behaviours affect adversely towards the overall performance of the PCG.

We allocate the ranking points for different criteria as follows:

***Criterion A*:** The ranking points for criterion A is the amount of energy shortage shown by a member, who fails to meet the lower threshold of the PCG, whereas it is zero for the others, who meet the pre-qualification criteria of the PCG. Since showing an energy shortage adversely affects the performance of the PCG, the ranking points are in negative form for that member, who fails to meet the lower threshold.

Let E_i be the amount of energy shared by the member, $E_{sh,i}$ be the energy shortage if any and L be the lower energy threshold of the PCG. The i^{th} member's ranking points for criterion A ($rp_{A,i}$) are as follows:

$$rp_{A,i} = \begin{cases} -E_{sh,i} & ; \quad E_i < L \\ 0 & ; \quad E_i \geq L \end{cases}$$ Equation 8. 2

Criterion B: Similar to the above, ranking points for criterion B is the amount of surplus energy compared to the upper threshold, which takes a positive point form. This is zero for the members, whose energy lies within the pre-qualification criteria of the PCG or who demonstrate energy shortage. Let E_i be the amount of energy presented by the prosumer, $E_{ex,i}$ be the energy surplus if any and U be the upper threshold of the PCG. The i^{th} prosumer's ranking points for criterion B ($rp_{B,i}$) are as follows:

$$rp_{B,i} = \begin{cases} +E_{ex,i} & ; \quad E_i > U \\ 0 & ; \quad E_i < U \end{cases}$$ Equation 8. 3

Criterion C: The ranking points for criteria C is obtained by analysing the member's interactions with other local members within the PCG. In allocating the ranking points, we consider several factors related to the local energy sharing: the amount of energy that the member (energy seller) is willing to sell, the energy requirement of the member (energy buyer) to meet the lower threshold and the number of energy buyers and sellers in network.

We develop a method to find ranking points for criterion C by further developing some concepts of rank prestige and unidirectional graph edges (Hon Wai and Chen 2009). In our method, the nodes are considered to be individual members within the PCG. The edge is local energy trading that one prosumer would have with other prosumers. Let N_b be the number of energy-buying members; N_s is the number of energy-selling members; N is the total number of prosumers in the community group. The main measurements of assessing criterion C are, $E_{i,\rightarrow q}$, which denotes the amount of energy sold by the ith energy-selling member to the qth member, and $E_{i\leftarrow p}$, which denotes the amount of energy bought by the ith energy-buying member from the pth member. The ranking points of criterion C for different types of members are as follows:

$$rp_{C,i} = \begin{cases} \sum_{q=1}^{Nb} E_{i\rightarrow q} \times \frac{N_b}{N} \text{ ; } for\ all\ i\ (energy\ selling\ member) \\ \sum_{p=1}^{Ns} E_{i\leftarrow p} \times \frac{N_s}{N}\text{ ; } for\ all\ i\ (\ energy\ buying\ member) \\ \quad 0 \quad ;\ for\ standalone\ member \end{cases} \qquad \text{Equation 8. 4}$$

Criterion D: The ranking points for criterion D depends on how the member behaves in previous time slots and is illustrated as the combined ranking points in all the previous time slots throughout the membership record. Let *n* be the present time slot and $RP_{i,h}$ be the accumulated ranking points a member obtained in the h^{th} time slot. The ranking points a member obtained for criterion D ($rp_{D,i}$) is given by:

$$rp_{D,i} = RP_{i,1} \times RP_{i,2} \times \ldots \times RP_{i,n-1} \qquad \text{Equation 8. 5}$$

Relying on the priorities assigned to the assessment criteria and ranking points allocated to the members for each assessment criteria, in the next section, we propose a ranking method that ranks the members.

8.5.4 Member ranking

This process involves the ranking of the members of the PCGs. In order to achieve that we used the TOPSIS method of MCDM (Masud and Ravindran 2009) , which is explained as follows: Let *x* be any member of the PCG and *C1(x)*, *C2(x)*, *C3(x)* and *C4(x)* be the expected values for four assessment criteria. The objective of this model is to rank the participating members of the PCG based on their ability to meet the expected level of achievement of criteria values or *maximize [C1(x), C2(x), C3(x), C4(x)]*. The selected attribute of the highest-ranked member should be closest to the "*ideal solution,*" H^*_j, which is the highest expectation for a considered criteria *j*, and farthest from the "*negative-ideal solution,*" L^*_j, which is the lower bound of the criteria *j*. This method produces an index combining these factors and the prosumer that maximizes this index value is ranked first. A concise flow chart of the TOPSIS method, which is applied to this decision situation of choosing the "best" set of members within the PCG, is illustrated in Fig. 8.6, and can be explained as follows;

We first define the normalized pay-off matrix (r_{ij}) for four criteria as:

$$r_{ij} = \frac{rp_{ji}}{\left[\sum_i (rp_{ji})^2\right]^{1/2}}\ ; 1 \le i \le N\ ;\ \ j = 1,2,3,4$$ Equation 8. 6

$$q_{ij} = \lambda_j \times r_{ij}$$ Equation 8. 7

where λ_j is the relative importance weight of the *j*th criterion (Equation 1).

Here, rp_{ji} is the ranking points for the *i*th prosumer for the j^{th} evaluation criterion. *N* is the number of members within the PCG. The weighted pay-off matrix, q_{ij}, is computed using the importance weights obtained in Equation 8.1.

Using the weighted pay-off matrix, ideal solution, H^*_j, is defined as the maximum of q_{jj}, for all *i* and *j=1,2,3,4* and the anti-ideal solution, L^*_j, as the minimum of q_{jj}, for all *i* and *j=1,2,3,4*. Accordingly, the separation measures with ideal solution and anti-ideal solution for each prosumer are calculated. The separation measure of the *i*th member's performance for the j^{th} criterion with ideal solution (D_{Hi}) is given in Equation 8.8:

$$D_{Hi} = \left[\sum_j \left(q_{ij} - H_j^*\right)^2\right]^{1/2} \quad \text{Equation 8. 8}$$

The separation measure of the i^{th} member's performance with anti-ideal solution (D_{Li}) is given in Equation 8.9:

$$D_{Li} = \left[\sum_j \left(q_{ij} - L_j^*\right)^2\right]^{1/2} \quad \text{Equation 8. 9}$$

where

$H_j^* = maximum\ of\ (q_{ij})$; for all *i* and *j=1,2,3,4*

$L_j^* = maximum\ of\ (q_{ij})$; for all *i* and *j=1,2,3,4*

These two measures are combined to develop a ranking index, "*S*," where the TOPSIS method identifies the preferred solution by maximizing the ranking index, S, defined in Equation 8.10:

$$S = \frac{D_{Li}}{D_{Li}+D_{Hi}}\ ; i = 1,2,3, \dots, N \quad \text{Equation 8. 10}$$

Here, $0 \leq S \leq 1$; $S = 0$ when the performance of the i^{th} member is same as the anti-ideal solution and $S=1$ when the performance of i^{th} member is the ideal solution.

Note that all the members can be ranked by their index values; the member with a higher ranking index value is preferred over those with index values smaller than its value.

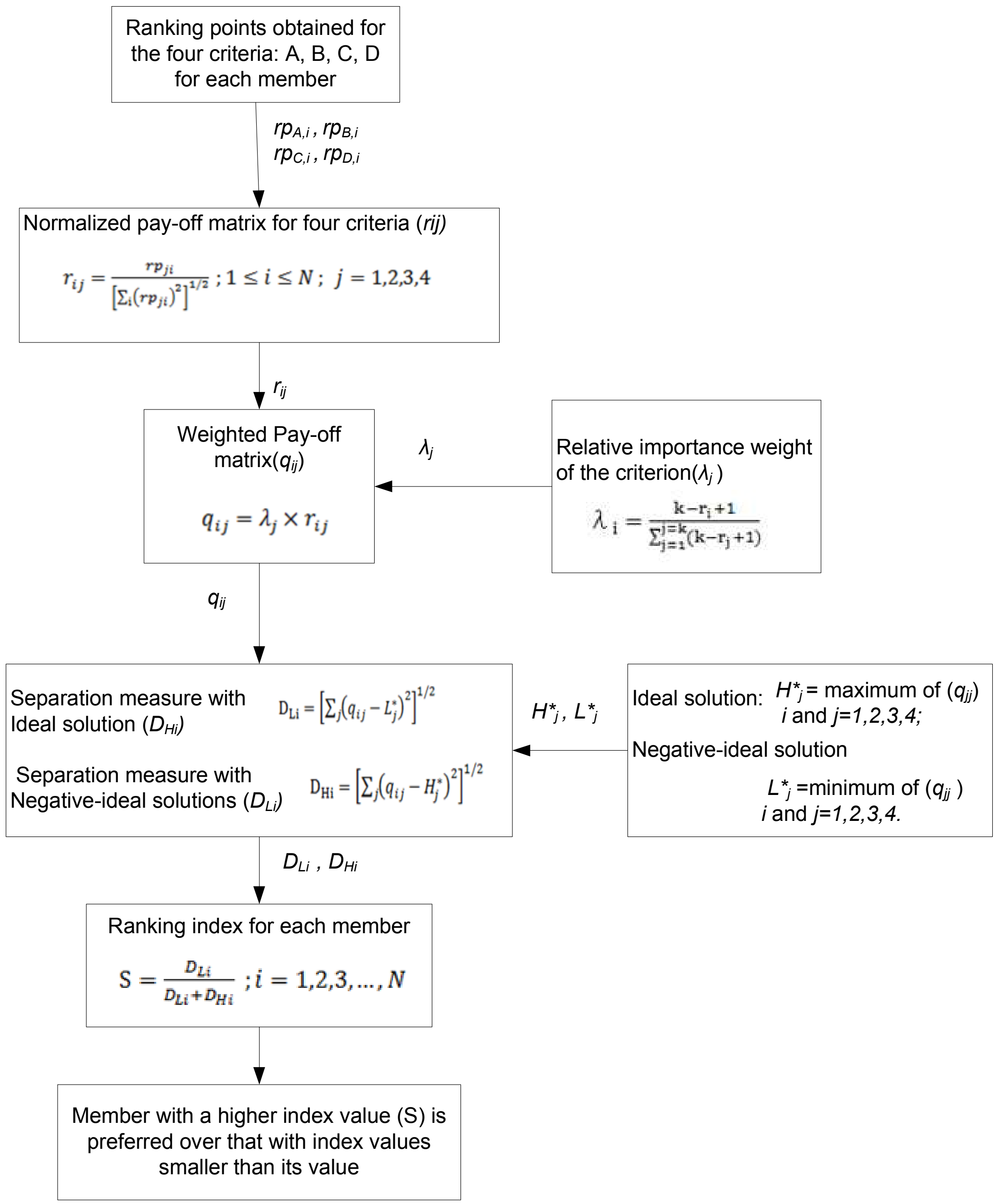


Figure 8. 6: The member ranking method using TOPSIS method

The member assessment and ranking framework discussed above can be utilized to determine the relative performance of the members and can be used to achieve different objectives of the PCG. Some of such objectives are as follows: develop differential incentive/privilege distribution schemes, motivation schemes, measure of sustainability, and performance forecasting schemes.

In this section, we have gained understanding of the theoretical concepts used to assess and rank the prosumers. In the subsequent section, we verify that framework.

8.6 Verification of Member Assessment and Ranking Framework

In this section, we verify the concepts of the prosumer assessment and ranking framework. We first discuss the experimental settings used for testing.

8.6.1 Experimental setting

In this experiment, first we verify the theoretical concepts of the methodology assuming there are only 10 members within the PCG and only two time slots are involved (the very first time slot after the formation of the PCG and the subsequent timeslot). Less number of members and time slots are taken into account in order to give better understanding to the readers on how this member assessment and ranking framework works.

Second, we apply this methodology to 200 prosumers to determine the members who deemed to be relatively influential in enhancing the long-term sustenance of the PCG (members with relatively higher performance or higher ranks).

In this experiment, we assume that the assessment and ranking is done on a monthly basis and the lower and the upper energy thresholds of the selected PCG is 50 kWh and 150 kWh per month, respectively. We illustrate the guidelines for the member assessment and ranking scheme in four phases identified in the theoretical foundation as follows.

8.6.1.1 Assessment criteria definition

- **Criterion A** (*meet the pre-qualification criteria)*: This criterion assesses the member's ability to supply more energy than 50 kWh, which is the lower threshold, associated with the PCG pre-qualification criteria of the chosen PCG.
- **Criterion B** (*surplus energy contribution to receive incentives)*: This criterion assesses the member's surplus energy sharing capacity over 150 kWh, which is the upper threshold of the pre-qualification criteria of the chosen PCG.
- **Criterion C** (*social responsibility to help fellow members to cover up their energy shortage)***:** This criterion assesses the member's local energy sharing to the fellow members, who are in need of energy to meet the 50 kWh, which is the lower threshold of the pre-qualification criteria of the chosen PCG. For clarity, the following assumptions are made when assessing the members in this criterion:
    - If a member meets 50 kWh (lower threshold), but does not own surplus than the 150 kWh (upper threshold), that member cannot buy or sell energy from/to fellow members.
    - If the member cannot meet 50 kWh (lower threshold), that member can request energy from the fellow members who have surplus energy than 150 kWh (upper threshold).
    - If the member has surplus amount of energy than the 150 kWh (upper threshold), that member is unable to buy the energy from other local members, but that member can either sell the surplus energy than 150 kWh to other members or stay stand-alone without selling.
- **Criterion D** (*quality of behaviours in membership duration)*: This criterion assesses the quality of the long-term energy behaviours of a member throughout the membership duration (the member's ability to fulfil criteria A, B and C in previous time slots). In this simulation, we first consider two time slots to show the effect of criterion D. For the first time slot, the prosumer ranks do not depend on criterion D, because, as being the very first time slot after the community group formation, previous time slots

do not exist. For the second time slot, the ranks are influenced by the energy behaviours of the first time slot (the member's ability to fulfil criteria A, B and C in the first time slot).

8.6.1.2 Assessment criteria prioritization

- **Criterion A** (*meet the pre-qualification criteria)*: The most important criterion from all four, it receives the highest importance weight calculated via Equation 8.1 in Section 8.5, which is 0.364.
- **Criterion B** (*surplus energy contribution to receive incentives)*: The second highest important criterion from all four, it receives the second highest importance weight calculated via Equation 8.1 in Section 8.5, which is of 0.272
- **Criterion C** (*social responsibility to help fellow members to cover up their energy shortage)* and **Criterion D** (*Quality of behaviours in membership duration)*: Receives third highest important criteria, thus receives the importance weights of 0.182.

8.6.1.3 Point Allocation

- **Criterion A** (*meet the pre-qualification criteria)*: The ranking points are proportional to the energy shortage calculated from 50 kWh.
- **Criterion B** (*surplus energy contribution to receive incentives)*: The ranking points are proportional to the surplus energy calculated from 150 kWh.
- **Criterion C** (*social responsibility to help fellow members to cover up their energy shortage)***:** Ranking points are proportional to the positive value of energy given to the other members and negative value of the energy bought from other members.
- **Criterion D** (*quality of behaviours in membership duration)*: Evaluation of Criterion D adds iterative nature to the final ranking points of a member. In this simulation, we consider two time slots to show the effect of criterion D. For the first timeslot, the prosumer ranks do not depend on criterion D, because, as being the very first time slot after the community group formation, previous time slots do

not exist. For the second time slot, the ranks are influenced by the energy behaviours of the first time slot.

The process of ranking follows Equations (8.2)–(8.10) in Section 8.5, and the final ranks of the prosumers are decided based on the ranking index ("*S*" value of Equation 8.10). In the next section, we present the observations, results and discussions we obtained in this simulation.

8.6.2 Observations, results, validation and discussion

In this section, we first verify the theoretical aspects of the prosumer ranking and assessment framework using the aforementioned experimental settings. Tables 8.1 and 8.2 illustrate the final ranks of prosumers obtained using the proposed methodology that assesses the members through multiple assessment criteria.

Figures 8.7 and 8.8 demonstrate the prosumers' final ranks obtained for each time slot. Here, we compare the ranks obtained via the proposed ranking scheme with the conventional ranking that ranks the prosumers based on the distance measures (Manhattan distance) in a single dimension (quantity of energy).

Table 8-1: Energy sharing patterns of 10 prosumer-community-group prosumers in the first time slot

Prosumer ID	Energy owned (kWh)	Criterion A (kWh)	Criterion B (kWh)	Criterion C (kWh)	Criterion D	Final rank
1	50	1	0	0	NA	5
2	46	−6	0	−14	NA	8
3	190	1	40	20	NA	1
4	176	1	26	10	NA	2
5	176	1	26	5	NA	3
6	36	−14	0	−14	NA	8
7	143	1	0	0	NA	5
8	100	1	0	16	NA	4
9	70	1	0	0	NA	5
10	28	−22	0	−22	NA	10

Table 8-2: Energy sharing patterns of same 10 prosumer-community-group prosumers in the second time slot

Prosumer ID	Energy owned (kWh)	Criterion A (kWh)	Criterion B (kWh)	Criterion C (kWh)	Criterion D	Final rank
1	38	−12	0	−12	5	10
2	184	0	34	34	8	1
3	45	−5	0	−5	1	8
4	40	−10	0	−10	2	9
5	188	0	38	10	3	2
6	100	0	0	0	8	7
7	100	0	0	0	5	6
8	100	0	0	0	4	5
9	164	0	14	12	5	3
10	158	0	8	8	10	4

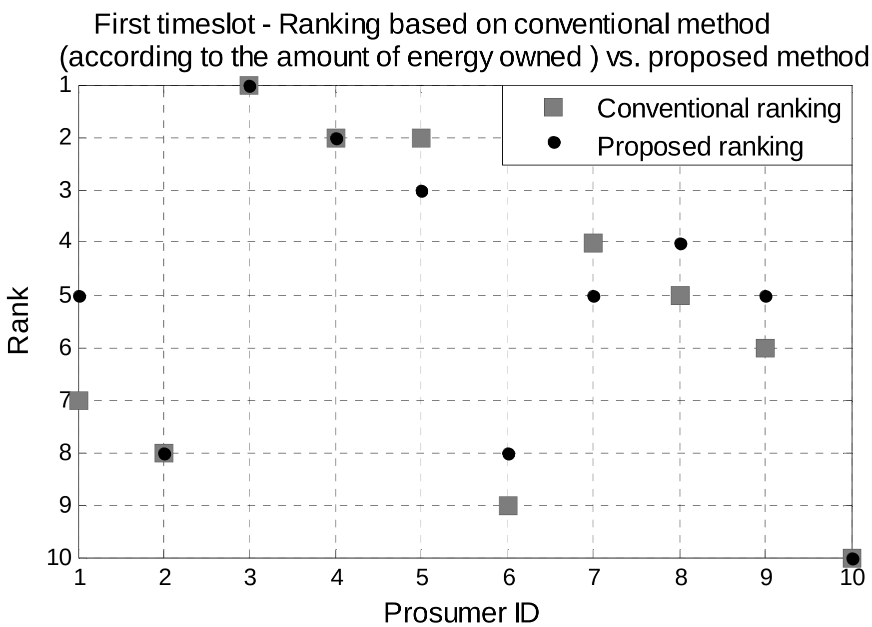


Figure 8. 7: Ranks of prosumers in 1st time-slot

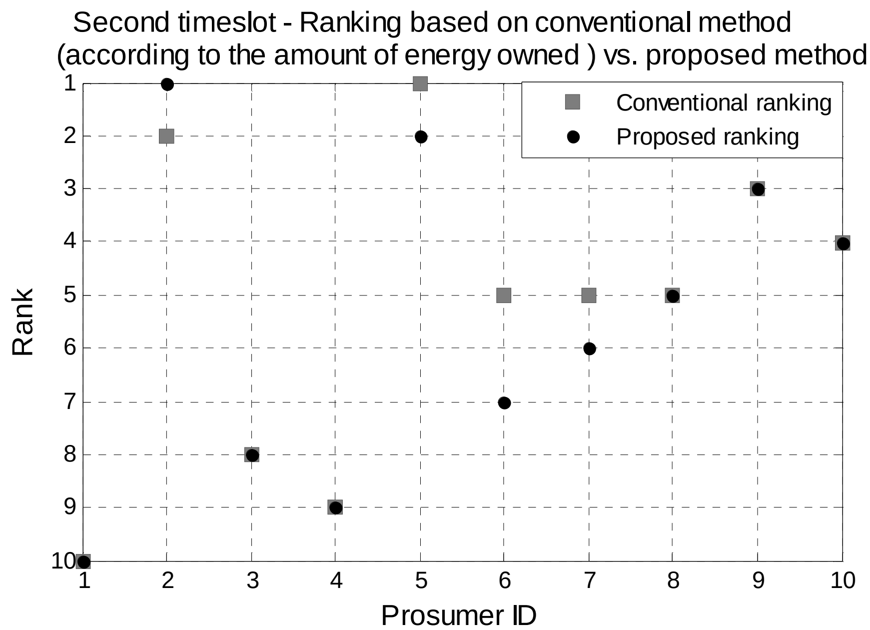


Figure 8. 8: Ranks of prosumers in the second time period

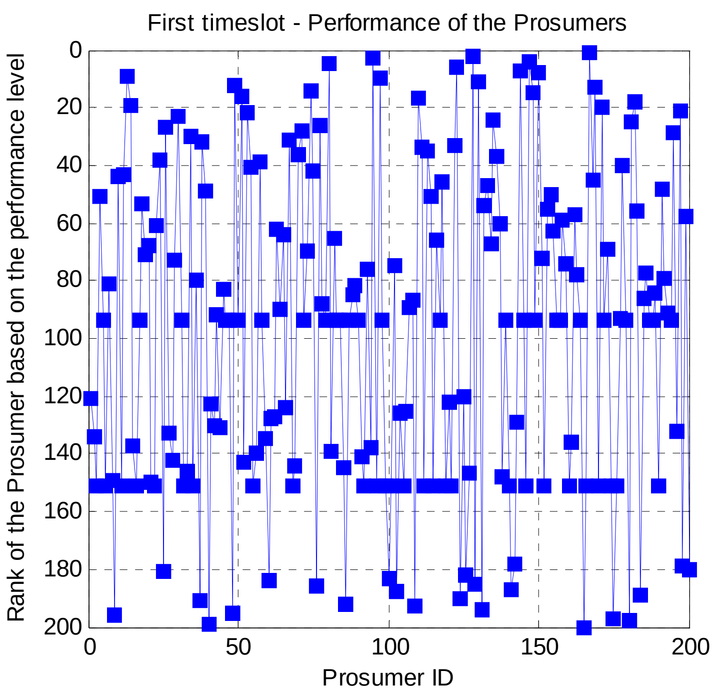
According to Fig. 8.7, with the conventional ranking method, the fourth and fifth prosumers have received the same rank based on the same amount of energy they own, but with the proposed ranking method, the fourth prosumer receives a better rank as that prosumer shares higher percentage of excess energy of 10 kWh with the other prosumers who are in need, compared to the fifth prosumer, who only shares 5 kWh with other prosumers. The effect of criterion D is clearly visible in Fig. 8.8, in which the sixth and seventh prosumers, who own similar amounts of energy, are ranked the same in the conventional ranking method. However, in the proposed ranking method, the seventh prosumer receives a better rank than the sixth, as the seventh prosumer shows comparatively better performances in the previous time slot. Overall, the proposed method that coordinates different criteria shows a fairer ranking than the conventional ranking methods that consider a single dimension.

Now we illustrate the application of the proposed prosumer assessment and ranking methodology to 200 members and thus find out the members with relatively higher ranks, who deemed to be relatively influential within the PCG.

8.6.2.1 Application of the prosumer ranking and assessment framework

In this section, we experiment the methodology using an energy behaviour data set of 200 prosumers. For the purposes of clarity, we consider four time slots: time slot 1, time slot 2, time slot 3 and time slot 4 (the very first time slot after the formation of the PCG, and the subsequent three time slots). Here, each member is identified using a unique ID, starting from "1" to "200." However, this methodology can be extended for any number of time slots, and even any number of members. Moreover, in order to evaluate Criterion C, 60 energy-buying members and 65 energy-selling members are introduced to the data set.

Figures 8.9, 8.10, 8.11 and 8.12, respectively, identify the relatively influential members (members with relatively higher ranks, assuming ranks above the 50th rank) for time slot 1, time slot 2, time slot 3 and time slot 4. On the figures, we have indicated the prosumer IDs of the influential members.



Influential prosumer IDs:

[6,7,15,22,25,26,45,51,60,62,63,76,77,85,93,97,113,134,141,142,148,150,159,163,167,170,186,191,192,]

Figure 8. 9: Time slot1-prosumers' status

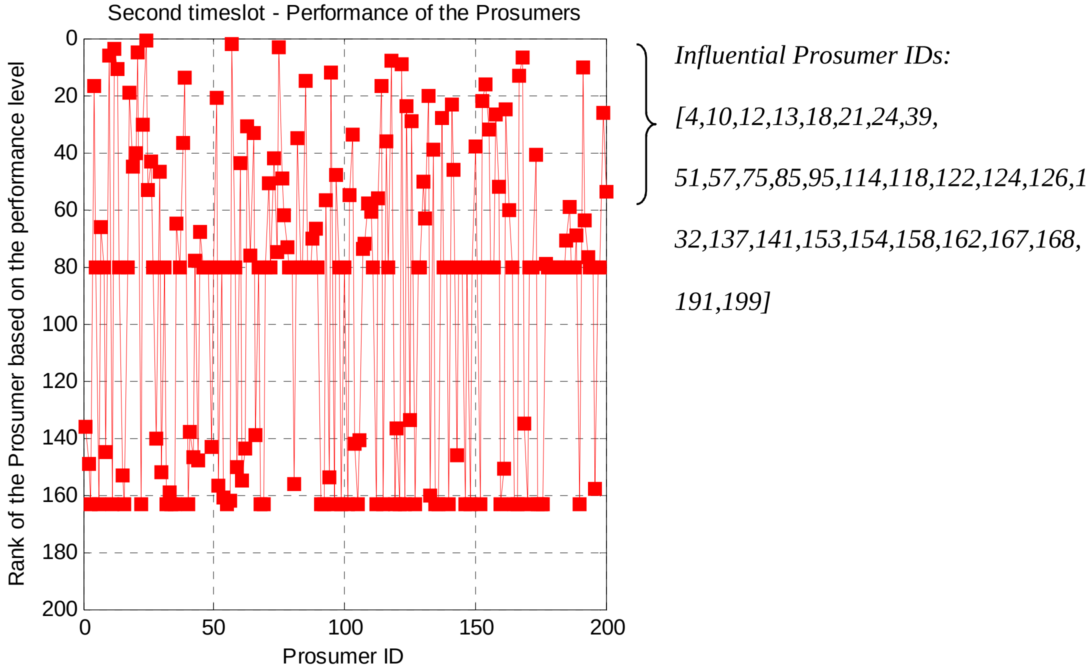


Figure 8. 10 : Time slot2-prosumers' status

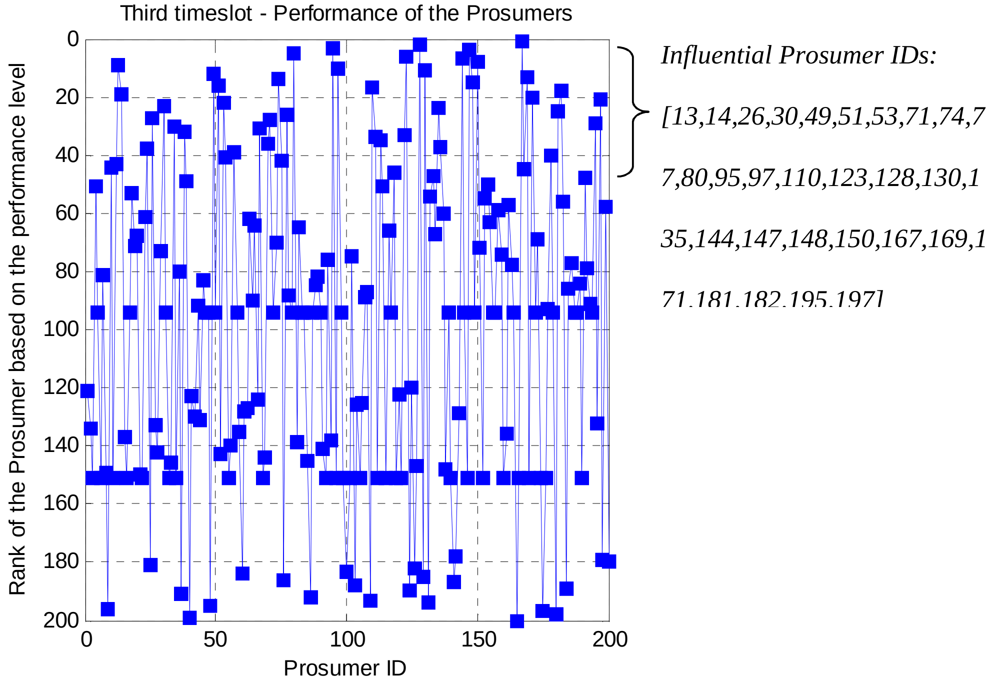
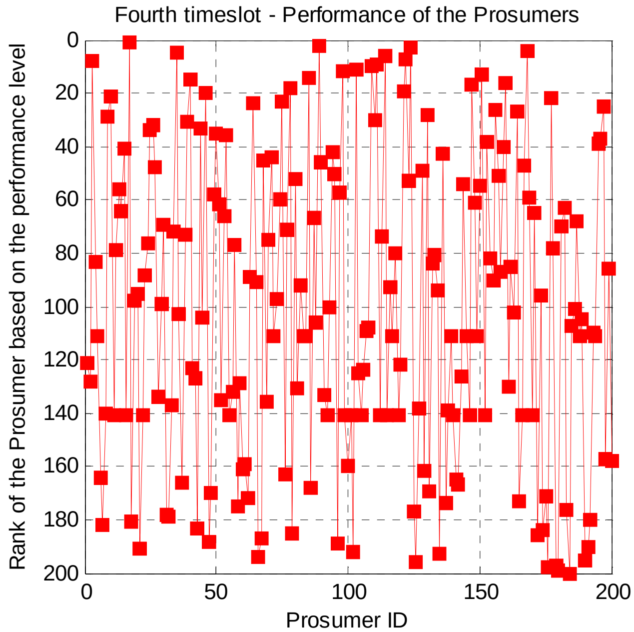


Figure 8. 11: Time slot3-prosumers' status



Influential Prosumer IDs:

[4,10,12,13,18,21,24,39,

51,57,75,85,95,114,118,122,124,126,1

32,137,141,153,154,158,162,167,168,

191,199]

Figure 8. 12: Time slot 4 prosumers' status

As shown in the above figures, this methodology can be applied to any number of time slots throughout the PCG operation. Following the above results over the time slots, the members' overall performance can be evaluated. For example, the member with ID 167 remains as an "*influential*" prosumer in all four time slots, whereas the member with ID 85 and 168 has kept the "*influential*" status for three time slots, however having failed to do so in one time slot. Using such evaluation, the prosumer community coordinator can classify the prosumers' performance and eventually used for achieving many objectives; some of those are as follows:

- *Develop differential incentive/privilege distribution schemes*: The community management can utilize these benchmarks to offer different levels of incentives/privileges to the members based on the relative performance (ranks) of the members.

- *Motivation schemes:* This enables community management to develop customized motivation schemes for different members.

- *Performance forecasting schemes:* This enables the community coordinator to analyse the trend of the prosumers' performance and make forecasts. For instance, if member's relative performance variation over the time slots follows a positive trend, that member can be considered to follow a positive trend.

8.7 Conclusion

This chapter presents a member assessment and ranking framework, which is capable of assessing the members' energy behaviours and rank them based on their relative performance. The proposed framework defines the suitable criteria to assess the members within the PCG, prioritizes the criteria based on their relative importance, allocates ranking points to the different members based on the degree of attainment of the desired outcomes of assessment criteria and finally ranks the members. The key theoretical platform of the proposed member assessment and ranking framework in this dissertation is developed using the TOPSIS method in MCDM techniques. The proposed method coordinates multiple criteria when ranking the members when compared to the conventional ranking methods that consider a single criterion.

Moreover, in this chapter, we verify the theoretical concepts of the framework and application of the framework to the PCG in order to find the more influential members. Determination of influential members can be adapted and further developed to achieve different objectives of the PCGs such as fair incentive distribution, development of motivational schemes, etc.

This proposed framework has been published in a peer-reviewed international journal (Rathnayaka, Potdar et al. 2014), wherein we have attached a complete list of all the publications arising as a result of the research study carried out in this thesis at the beginning of the thesis.

Chapter 9

Implementation of Community-based Energy Sharing Network in JADE Platform

This chapter provides:

- The development of the realistic model of community-based energy sharing network

9.1 Introduction

In the previous four chapters, we explained in detail the methodologies we used for four key frameworks that we addressed in developing the sustainable goal-oriented PCGs, namely PCG definition and characterization framework, prosumer recruitment framework, goal management and mutual goal definition framework and member assessment and ranking framework.

In order to demonstrate the effectiveness of the overall community-based energy sharing network, we created a multi-agent community-based energy sharing network prototype system, while combining the above-mentioned frameworks into a single platform. This platform assists the prosumer community coordinator agent to interact with prosumer agents in recruiting prosumers to the PCGs and allocating them optimal goals, and to initiate energy sharing among the prosumers within the PCG as well as the energy sharing between PCGs and the external energy buyers.

This prototype is designed as multi-agent systems using JADE (Bellifemine, Poggi et al. 2001)that is implemented in Java language and simplifies the implementation of multi-agent systems through a middleware that complies with the FIPA specifications and through a set of graphical tools that supports the debugging and deployment phases.

In Section 9.2, we provide a generic overview of the agent-based systems and JADE deployment. Section 9.3 illustrates the phases in the multi-agent community-based energy sharing network, and Section 9.4 concludes the chapter.

9.2 Generic Overview of an Agent-based System with JADE

Agent-oriented programming is an extensively used comparatively new software paradigm that models an application as a collection of components called agents that are characterized by autonomy, proactivity and an ability to communicate. Being autonomous enables agents to independently carry out complex, and often long-term, tasks. Being proactive enables the agents to take the initiative to carry out a given task even without an explicit motivation from a user. Being communicative facilitates interaction among the entities (agents) to assist with achieving the goals. Generally, the architectural model of an agent-oriented application is peer to peer, in which an agent can commence communication with any other agent or be the subject of an incoming communication at any time.

Agent technology has shown a significant degree of exploitation in multi-agent systems, which are employed in a wide variety of applications, ranging from comparatively small systems for personal assistance to open, complex, mission-critical systems for industrial applications. For instance, multi-agent systems have been productively utilized in the industrial domain for system diagnostics, manufacturing, transportation logistics, network management, etc.(Jun, Junfeng et al. 2011).

When an agent-oriented approach is adopted, there are several issues to be solved such as how to allow agents to communicate. It is convenient for the developers to build multi-agent systems on top of an agent-oriented middleware that provides the domain-independent infrastructure, rather than developing the core infrastructure themselves; in this thesis, we use JADE as the agent-oriented middleware.

JADE is probably the most well-known agent-oriented middleware, which is a completely distributed middleware system with a flexible infrastructure that facilitates the development of complete agent-based applications. JADE facilitates the core logic of agents themselves, the run-time environment implementing the support features required by agents and graphical tools.

At present, JADE is a community project and distributed as open source under the LGPL licence(Bellifemine, Poggi et al. 2001).

JADE is written completely in Java, which benefits from the huge set of language features and third-party libraries on offer, and facilitates a rich set of programming abstractions.

In this thesis, we implement the community-based energy sharing network by using a multi-agent system on top of JADE. In the subsequent section, we describe different phases of a multi-agent community-based energy sharing network that we develop in this thesis.

9.3 Phases in the Multi-agent Community-based Energy Sharing Network

The developed multi-agent community-based energy sharing network consists of four phases as shown below. They are as follows:

- ***Initialization phase:*** In this phase, the user specifies the fundamental parameters needed for the prototype system to initialize the multi-agent community-based energy sharing network. The key parameters include the number of PCGs (here, we take four PCGs as obtained in Chapter 5) and pre-qualification criteria of different PCGs (as obtained in Chapter 5), i.e. the upper threshold and the lower threshold of different PCGs. Moreover, the prototype system chooses an agent to act as the prosumer community coordinator agent and prosumer agents. Furthermore, the terms “user” and “prosumer community coordinator agent” are used interchangeably to represent the agent that controls the community-based energy sharing network.
- ***Forming PCGs phase:*** The broad purpose of this phase is to recruit the prosumers to the suitable PCGs and allocate optimized goals to the PCGs.
- ***Energy sharing phase:*** During this phase, the commencement of energy sharing among the prosumers within the PCG and the energy sharing between the PCGs and external energy buyer (we name this agent “requester”) is discussed.

9.3.1 Initialization phase

The initialization phase of the multi-agent community-based energy sharing network prototype system includes the following highlights:

1. The user initiates the agents that it desires to be in the prototype system, according to their behaviour types. The agents employed in this framework and their communication boundaries in different aforementioned phases are shown in Fig. 9.1 and are described as follows:
    - **Directory Facilitator:** The Directory Facilitator (DF) in the JADE framework, which provides yellow pages services to other agents. In this thesis, we adapt the DF as an intermediary between the prosumer agents and the prosumer community

coordinator. When an agent attempts to communicates with another agent, that agent obtains the address of the other agent from the DF.

- **Prosumer community coordinator agent**: The prosumer community coordinator agent is the centralized controlling point that forms and maintains the PCGs.

- **Prosumer agents:** In the PCG formation phase, the prosumer agents refer to the prosumers who show interest in joining the PCGs. After forming the PCGs, the prosumer agents refer to the members of the PCG. In the energy sharing phase, the energy-selling prosumer agents refer to the members who have excess energy than the agreed quantity of energy and are interested to sell energy to other local members, and the energy-buying prosumer agents refer to the members who have energy shortage and interested to buy energy from other local members.

- **PCG leader agent**: The PCG leader agent refers to the key contact point for a PCG.

- **Requester agen**t: The requester (also called external energy buyer) refers to the external contact point of external energy market that requests energy from the PCGs, which can be utility grid, energy retailer, etc.

2. The number of PCGs is defined with suitable pre-qualification criteria: i.e. upper energy threshold and lower energy threshold.

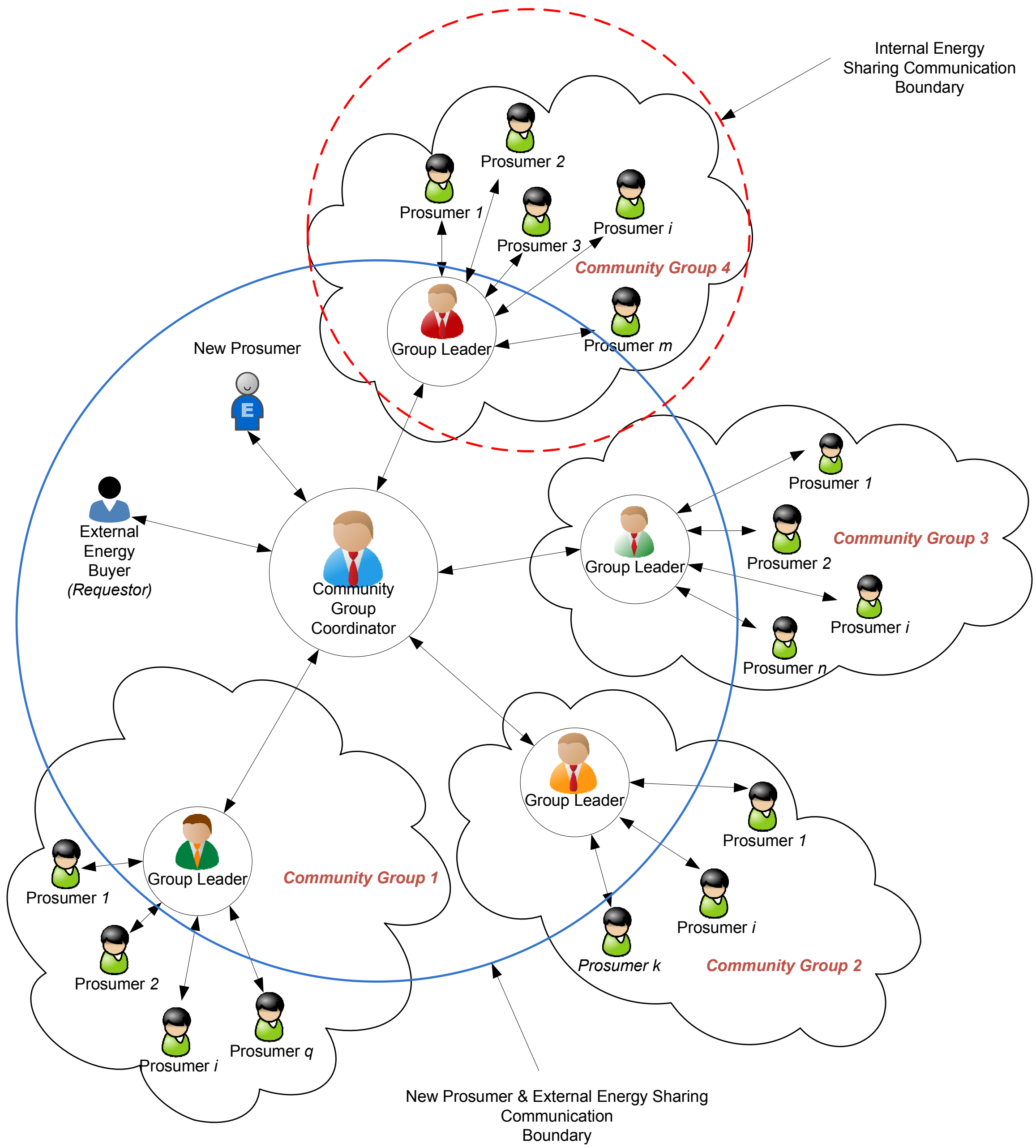


Figure 9. 1: Communication boundaries for different phases within the community-based energy sharing network

Accordingly, based on these factors, the initialization phase of the community-based energy sharing network includes an interface for the prosumer community coordinator's side, which are illustrated in Fig. 9.2.

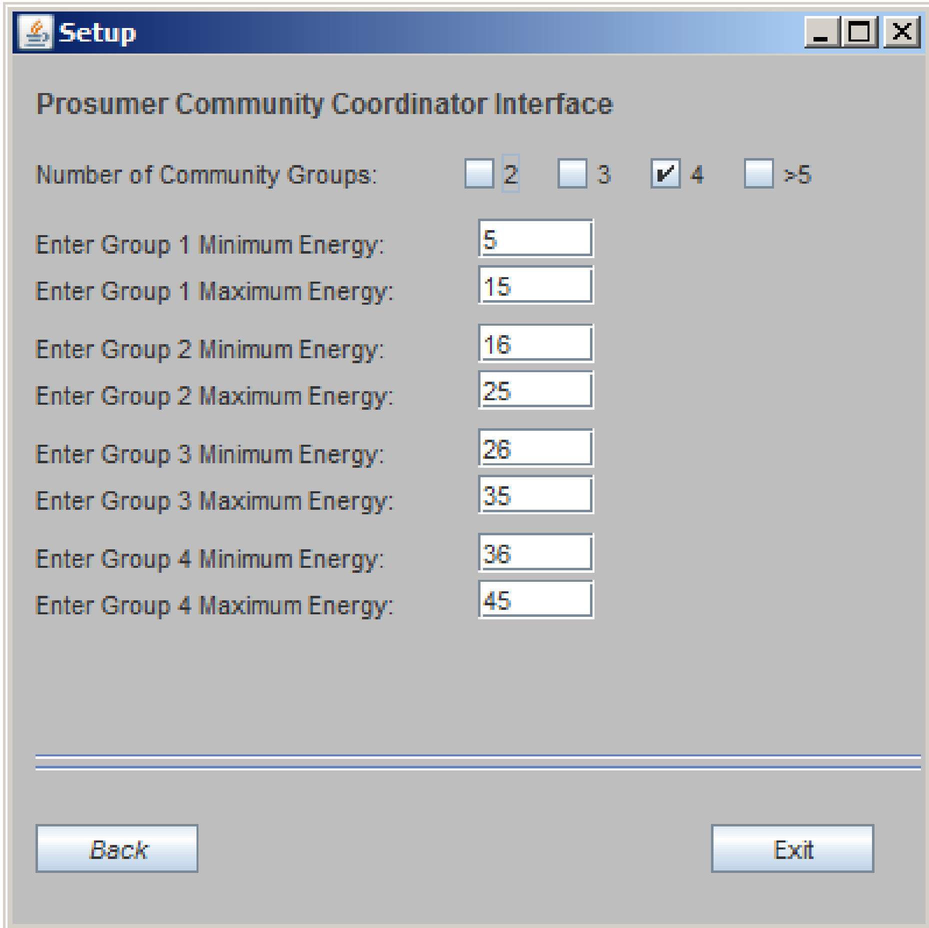


Figure 9. 2: Initialization of the multi-agent community-based energy sharing system interface in the prosumer community coordinator agent

In the next section, we illustrate the PCG formation phase.

9.3.2 PCG formation phase

In the PCG formation phase, a prosumer agent specifies its energy sharing capacity and the preferred PCG, whereas the prosumer community coordinator specifies the number of time slots in the evaluation period, and different performance semantics. Moreover, the prosumer community coordinator specifies the overall mutual goals of the community-based energy sharing network, which the system divides those overall goals into sub-goals, which are allocated to different PCGs as mutual goals. Accordingly, the PCG formation phase of the multi-agent community-based energy sharing network is discussed in two components: (i) recruiting prosumers and (ii) allocation of mutual goals.

First, we discuss the prosumer recruitment component of the PCG formation phase. Figure 9.3 illustrates the prosumer interface, in which the new prosumer enters its details together with energy sharing capacity and the preferred PCG (PCG that new prosumer is interested to join), whereas Figure 9.4 illustrates the prosumer community coordinator interface, where the prosumer community coordinator enters the number of time slots in the evaluation period and the success/failure ratios for different performance indices to initiate the new prosumer recruitment phase. The theoretical aspects of evaluation period and performance indices are discussed in Chapter 6.

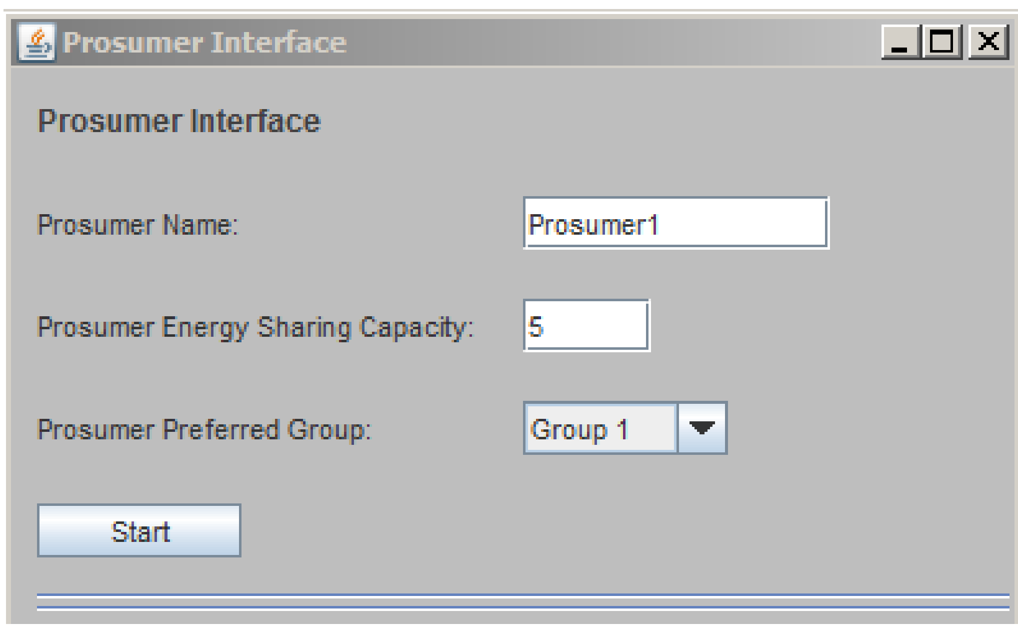


Figure 9. 3: The prosumer interface of the prosumer recruitment of the multi-agent community-based energy sharing system

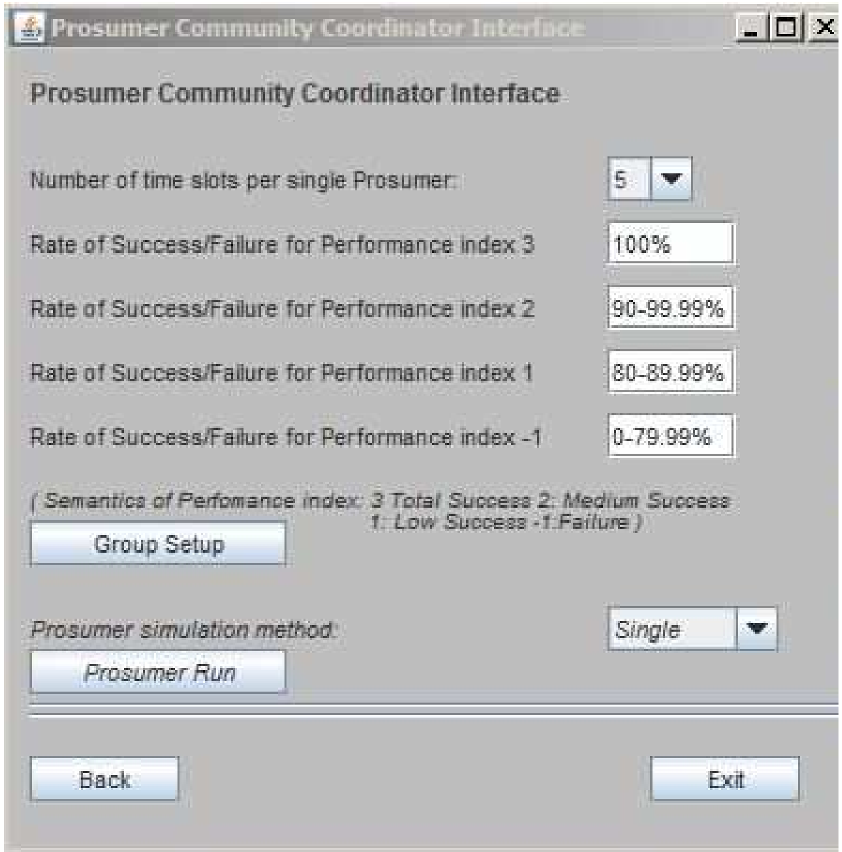


Figure 9. 4: The prosumer community coordinator interface of the prosumer recruitment of the multi-agent community-based energy sharing system

The interactions among the agents of the community-based energy sharing network during the prosumer recruitment of PCG formation phase are discussed in two scenarios: Scenario 1: the new prosumer is recruited to its preferred PCG (PCG 2) (Fig. 9.5); Scenario 2: The prosumer is not recruited to its preferred PCG (PCG 4) due to the failure in meeting the pre-qualification criteria as expected, but recruited to the different more suitable PCG (PCG 1) (Fig. 9.6). The underlying theory of the prosumer recruitment is discussed in Chapter 6.

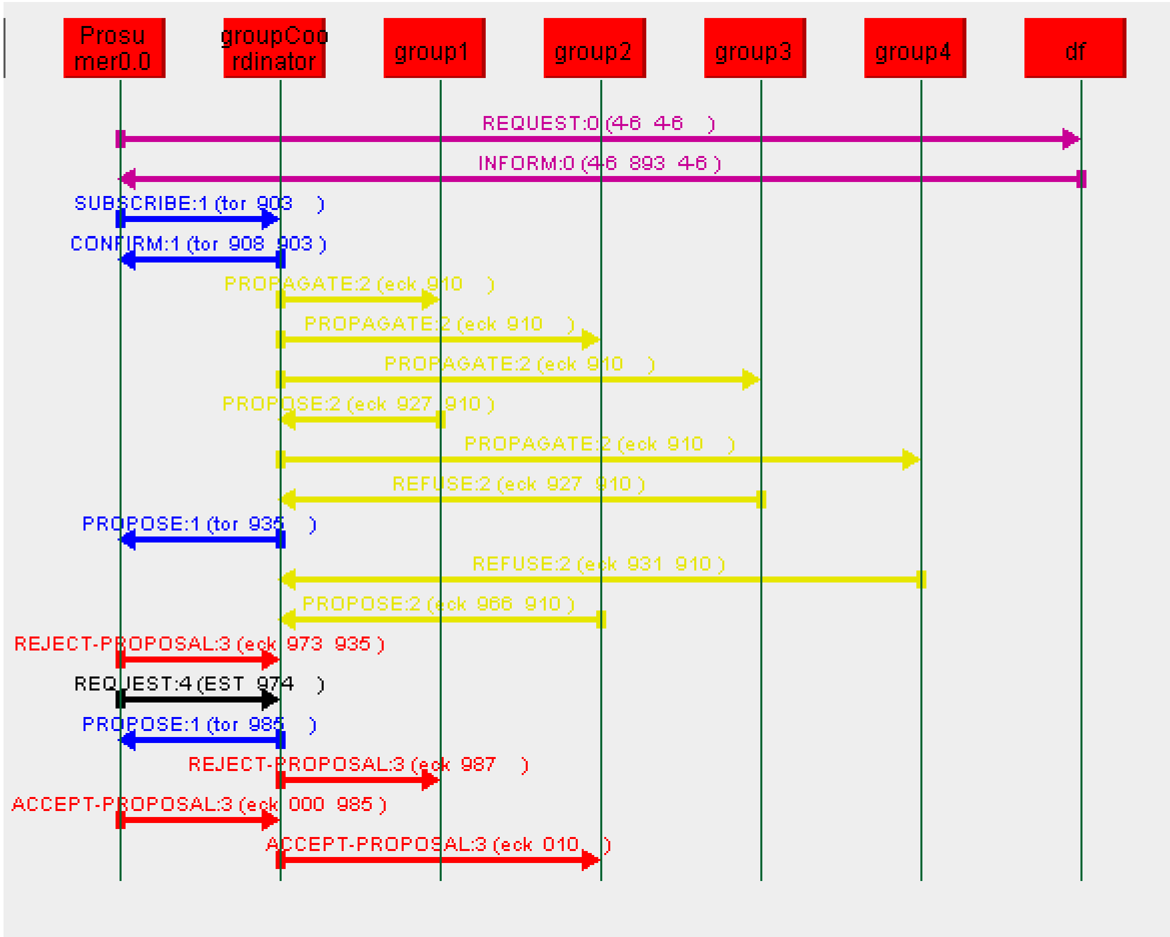


Figure 9. 5: Interactions among the agents in prosumer recruitment – Scenario 1

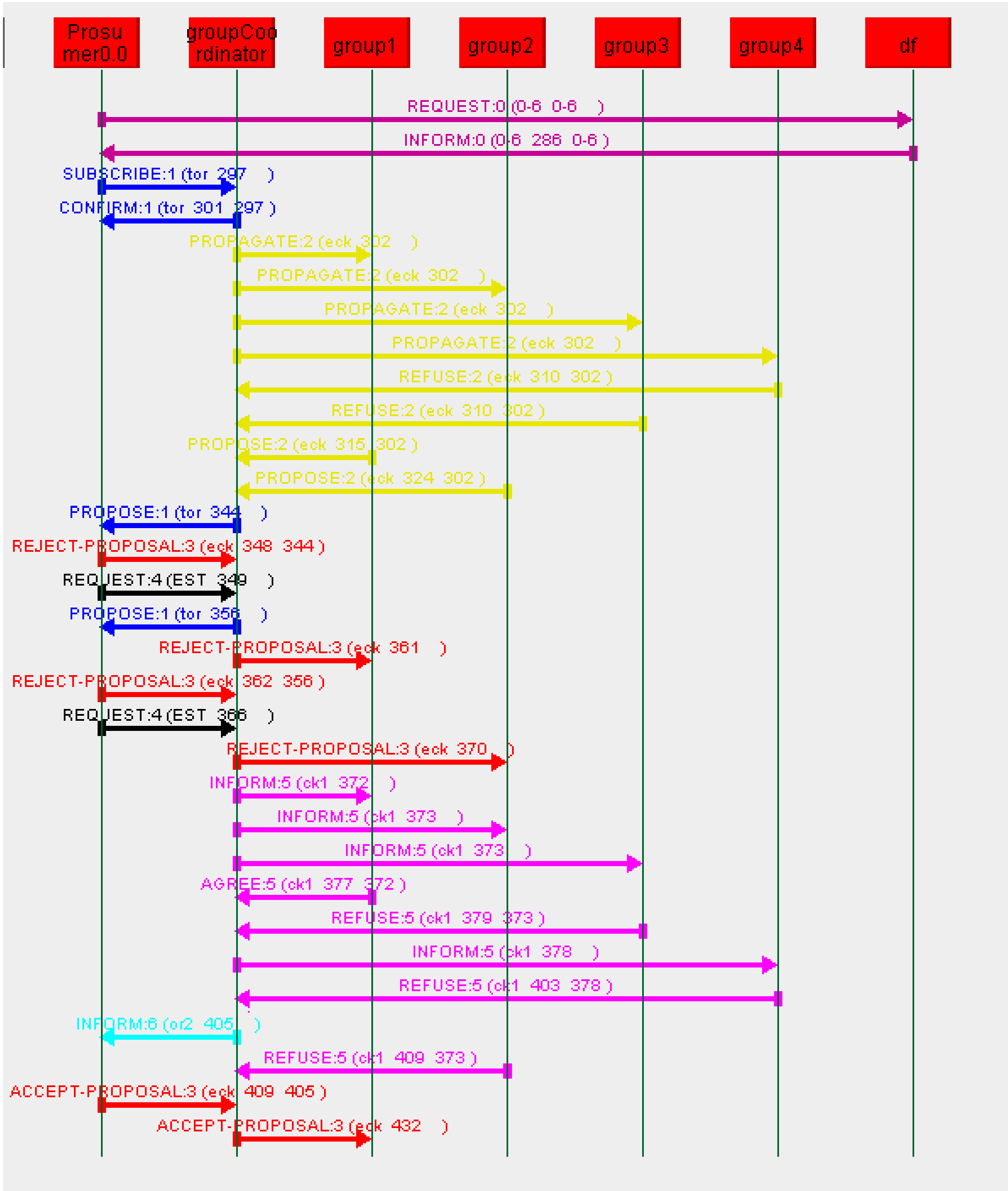


Figure 9. 6: Interactions among the agents in prosumer recruitment – Scenario 2

The key interactions among the different agents in prosumer recruitment are illustrated below:

1. The new prosumer agent sends a proposal to the prosumer community coordinator agent indicating its request to join a PCG and the energy level that prosumer is intended to supply [JADE ACL message: SUBSCRIBE]. Prosumer community coordinator confirms the subscription [JADE ACL message: CONFIRM].

2. The prosumer community coordinator agent sends the information about the new prosumer agent to the PCG leader agents of available PCGs [JADE ACL message: PROPAGATE]. The individual PCG leader checks the new prosumer's suitability to the PCG based on the performance index demonstrated in Section 6.5 (performance index greater than or equal to 1). If the new prosumer meets the requirements of the PCG as expected, the corresponding group leader sends propose notification to the prosumer community coordinator [JADE ACL message: PROPOSE]. If the new prosumer does not meet the requirements of the PCG as expected, the corresponding group leader sends refuse notification to the prosumer community coordinator [JADE ACL message: REFUSE].

3. The prosumer community coordinator transfers the propose notifications obtained from PCG leaders to the new prosumer in sequence [JADE ACL message: PROPOSE]. The new prosumer checks whether that allocated PCG is the same as its preferred PCG.

    i. If the proposed PCG (PCG 2) is matching with the preferred PCG (PCG 2), the new prosumer accepts the corresponding proposal initiated from the preferred PCG and informs to the prosumer community coordinator [JADE ACL message: ACCEPT-PROPOSAL]. Other proposals are rejected [JADE ACL message: REJECT-PROPOSAL]. The new prosumer's acceptance is informed to the relevant PCG by the prosumer community coordinator by transferring the acceptance message to the PCG leader (PCG 2) [JADE ACL message: ACCEPT-PROPOSAL]. (Scenario 1).

ii. If the new prosumer does not receive acceptance from the preferred PCG (i.e. if the allocated PCG is different from the preferred PCG), the new prosumer sends the reject message to the community coordinator [JADE ACL message: REJECT-PROPOSAL]. Meanwhile, the new prosumer requests the prosumer community coordinator that he wants to join the most suitable PCG by sending a request message [JADE ACL message: REQUEST]. The prosumer community coordinator informs that to the PCG leaders to check whether that prosumer's energy sharing capacity lies within the upper and lower thresholds of the pre-qualification criteria of the PCGs [JADE ACL message: INFORM]. As mentioned in Chapter 5, each PCG has unique pre-qualification criteria, i.e. unique upper and lower energy threshold. The leader from the most suitable PCG replies to the prosumer community coordinator [JADE ACL message: AGREE] and the other PCGs refuse [JADE ACL message: REFUSE]. The Prosumer community coordinator informs the new prosumer about the most suitable PCG [JADE ACL message: INFORM]. The new prosumer accepts the proposal [JADE ACL message: ACCEPT-PROPOSAL] and this acceptance is informed to the relevant PCG by the prosumer community coordinator by transferring the acceptance message to the corresponding PCG leader (PCG 1) [JADE ACL message: ACCEPT-PROPOSAL] (Scenario 2).

This concludes the recruitment of prosumers to the PCGs. After recruiting all the prosumers, each PCG is allocated with a mutual goal. The theoretical platform behind managing multiple goals within the community-based energy sharing network and defining optimized mutual goals is discussed and verified in Chapter 7. The user (prosumer community coordinator) initiates the interactions among the agents by inputting the number of community groups (here, we assume 4) and the target values of different goals as shown in Fig. 9.7.

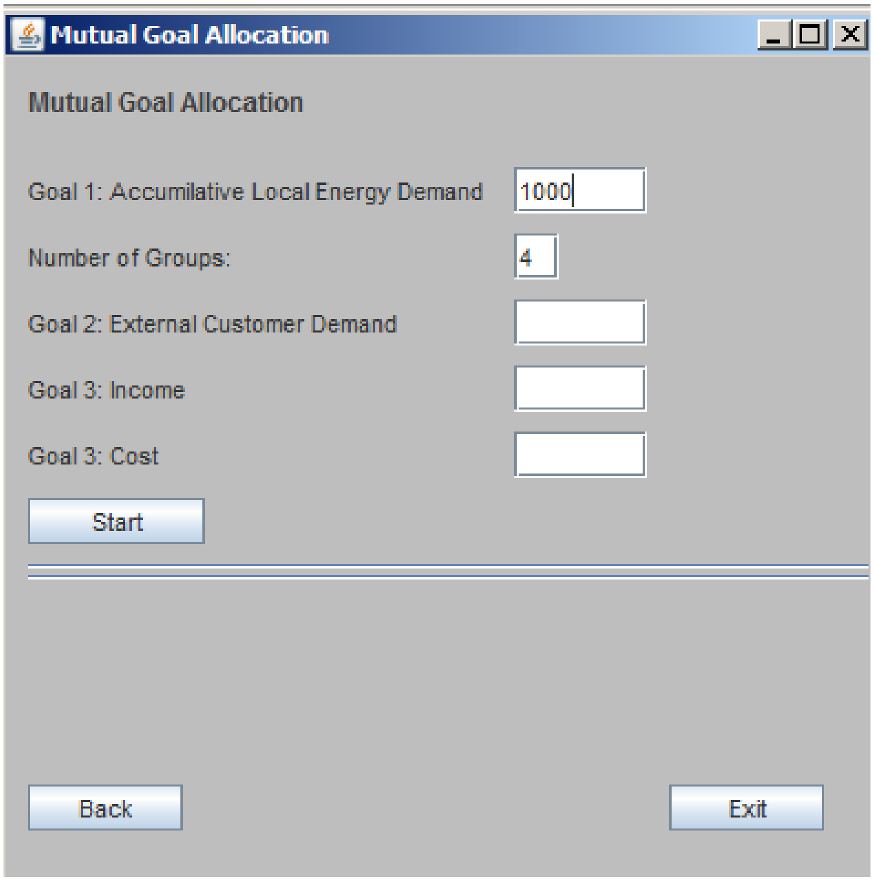


Figure 9. 7: The prosumer community coordinator interface of the mutual goal allocation of the multi-agent community-based energy sharing system

Here, we discuss the interactions among the agents of the community-based energy sharing network during the mutual goal allocation in two scenarios: Scenario 1: The PCG can attain the allocated mutual goal (Fig. 9.8); Scenario 2: The PCG cannot meet the originally allocated goal, thus requesting for reshaping the goals (Fig. 9.9). The key interactions during this component are illustrated as follows:

1. The prosumer community coordinator requests characteristic information from all PCGs [JADE ACL message: REQUEST]. PCG leaders respond with their average energy level and number of active members [JADE ACL message: INFORM].

2. The prosumer community coordinator finalizes the mutual goals for each PCG based on the characteristics of the PCGs and proposes that to each group [JADE ACL message: PROPOSE].

3. Each PCG leader checks whether the mutual goal is achievable or not based on their previous performance in attaining mutual goals:

    i. If the allocated mutual goal is achievable, the PCG leader confirms it to the prosumer community coordinator, also mentioning whether that PCG can achieve over the allocated goal and to what extent [JADE ACL message: ACCEPT-PROPOSAL]. If the acceptance is received from all the PCGs, the prosumer community coordinator confirms goal allocation to the PCG [JADE ACL message: CONFIRM]. Each PCG leader agrees with the mutual goal allocation [JADE ACL message: AGREE] (Scenario 1).

    ii. If the allocated mutual goal is not achievable, the PCG leader informs it to the prosumer community coordinator, also mentioning to what extent that community group can achieve the allocated goal based on the goal attainment performance in the previous energy transaction [JADE ACL message: REJECT-PROPOSAL]. If at least one rejection is received from a PCG, the prosumer community coordinator reshapes the mutual goals and resends to the PCG leaders considering how much maximum the individual PCGs can achieve [JADE ACL message: PROPOSE]. Each PCG agrees with the reshaped goal [JADE ACL message: AGREE] (Scenario 2).

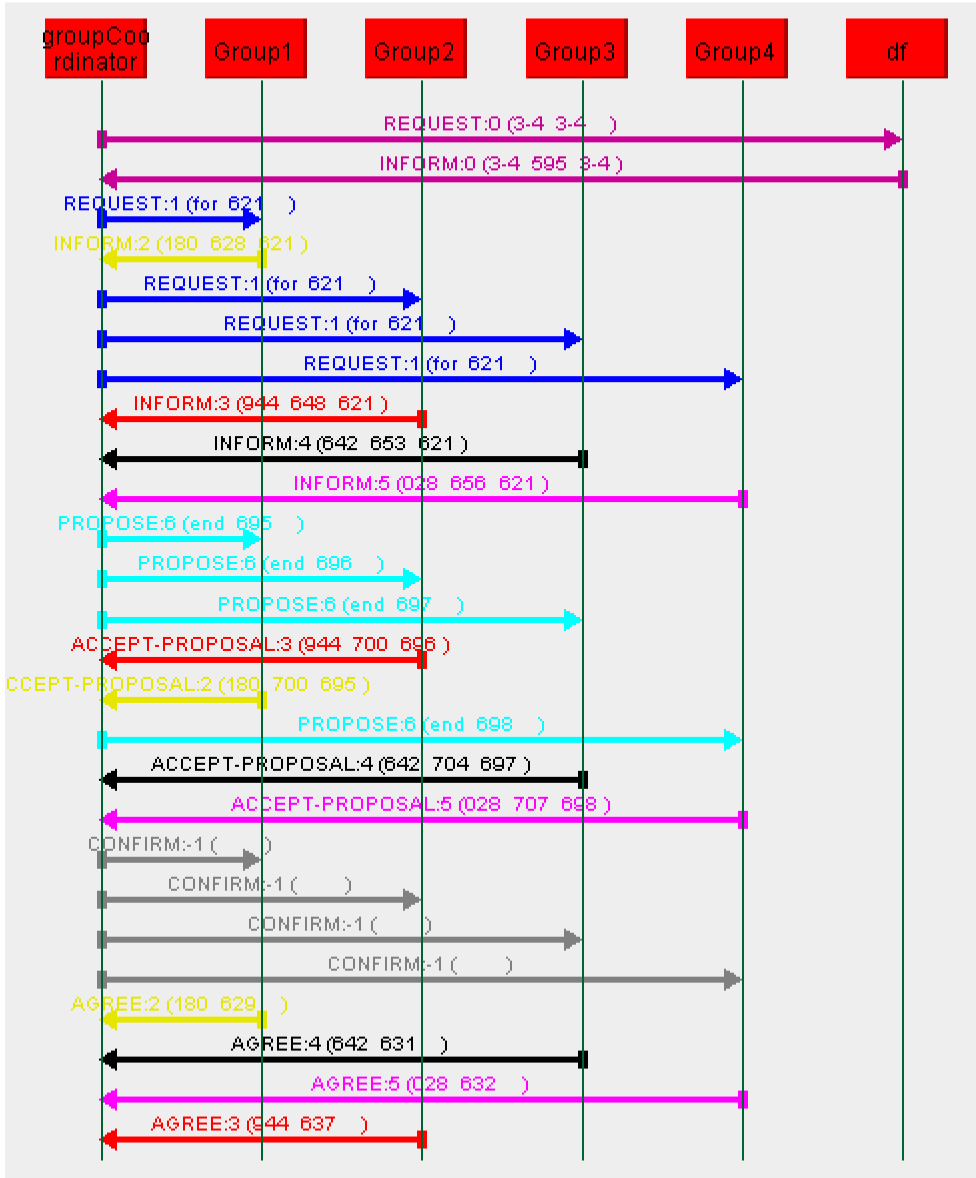


Figure 9. 8: Interactions among the agents' mutual goal allocation of the multi-agent community-based energy sharing system: Scenario 1

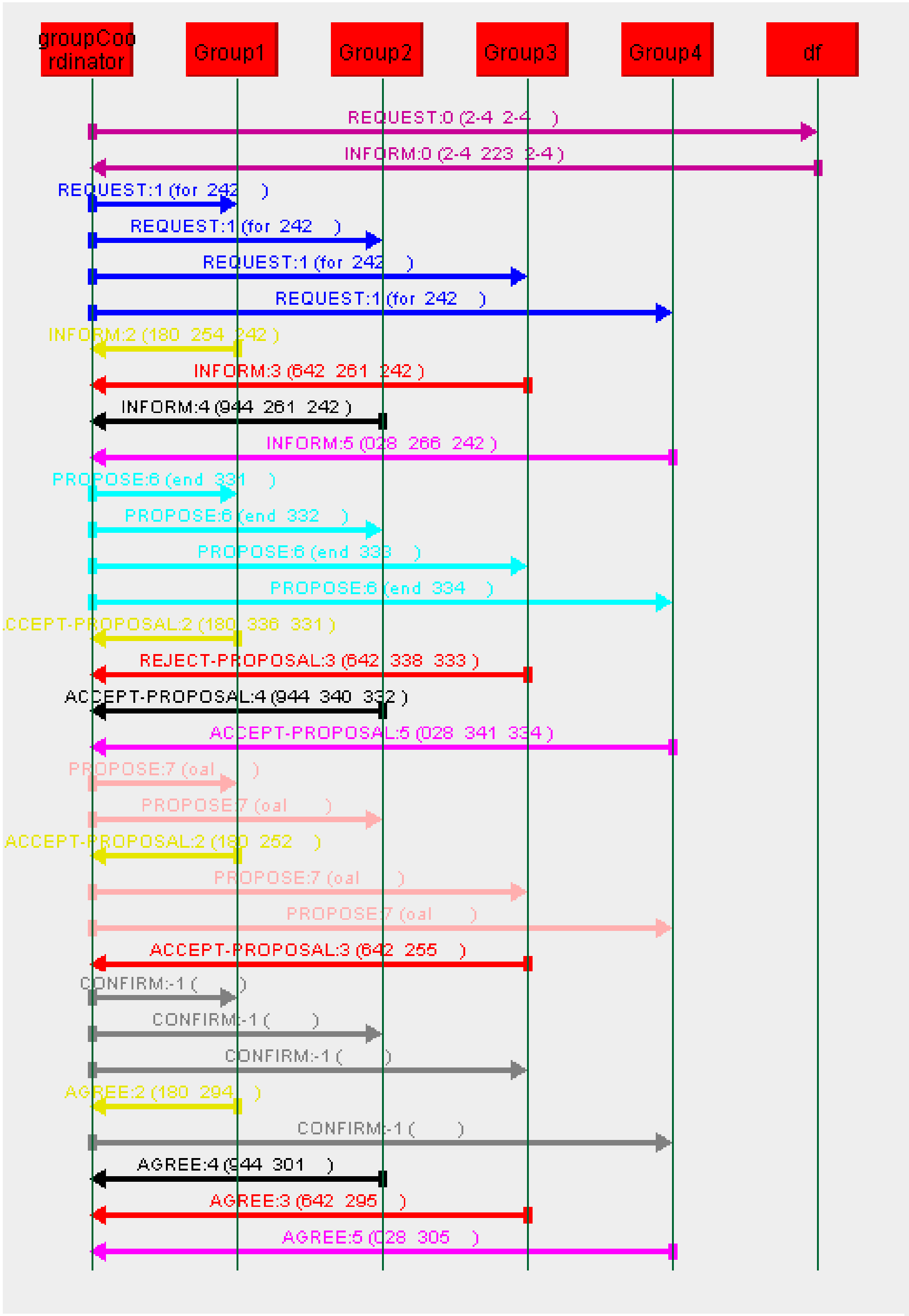


Figure 9. 9 Interactions among the agents mutual goal allocation of the multi agent community based energy sharing system: Scenario 2

9.3.3 Energy sharing Phase

In this section, we discuss the interactions among the different agents in two key elements: (i) energy sharing among the members within the PCG and (ii) energy sharing between the requester (external energy buyers such as utility grid, energy retailer, etc.) and the PCG.

First, we explain the interactions among the agents in energy sharing among the members within the PCG.

9.3.3.1 Energy sharing among the members within the PCG

In this element, the energy sharing among the members within the PCG component is initiated by inputting the prosumer type ("selling," "buying" or "neutral"), which, respectively, represents whether that prosumer intends to sell energy to energy buyers, buy energy from energy sellers or remains neutral without selling and buying energy. Moreover, the quantity of surplus energy that he intends to sell or the energy shortage a prosumer intends to buy from other local members is also to be specified as shown in Fig. 9.10.

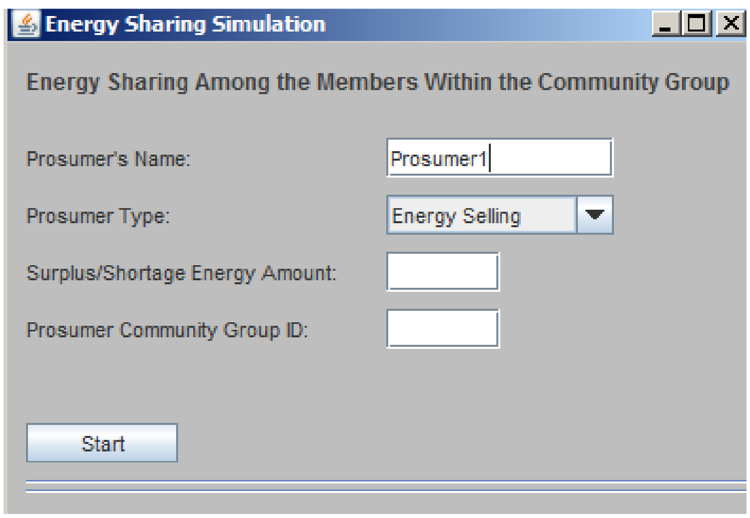


Figure 9. 10: The energy sharing phase of the multi-agent community-based energy sharing system

Here, we made the same assumptions we made in Section 8.5; if the prosumer agent (member) has low energy sharing capacity and unable to attain the lower threshold of the PCG, that prosumer agent can buy energy from the local members who have higher energy capacity than the upper threshold of the PCG. The prosumer agent who shows energy shortfall and interested to buy energy is named as energy-buying prosumer agent, and the prosumer agent who shows excess energy and interested to sell energy is termed as the energy-selling prosumer agent.

Figures 9.11, 9.12, 9.13 and 9.14, respectively, illustrate the interactions among the agents in energy sharing among the members within the PCG for four chosen scenarios: Scenario 1: the energy seller (Prosumer 3) is willing to sell energy to the energy buyer (Prosumer 1) as well as he can meet the complete energy requirement of the buyer (Prosumer 1) (Fig. 9.11); Scenario 2: three energy sellers (Prosumer 2, Prosumer 3, Prosumer 5), are willing to sell, but only two sellers (Prosumer 2, prosumer 5) can meet the complete energy requirement of the buyer (Prosumer 1) (Fig. 9.12); Scenario 3: all the sellers are willing to sell energy, but none can meet the complete energy requirement of the energy buyer (Prosumer 1) (Fig. 9.13); and Scenario 4: no energy sellers are in the system (Fig. 9.14).

Here, we assume the "Prosumer 1" represents the energy buyer who is currently requesting energy from other local members (Prosumer 2, Prosumer 3 and Prosumer 4).

The key interactions among the agents for all the scenarios are as follows:

1. All the local prosumers register with the prosumer community coordinator by indicating their prosumer type ("selling," "buying" or "neutral") and their energy surplus or shortage [JADE ACL message: SUBSCRIBE]. The prosumer community coordinator confirms the subscription [JADE ACL message: CONFIRM].

2. The energy buyer (Prosumer 1) informs the prosumer community coordinator his energy requirement [JADE ACL message: INFORM]. The prosumer community coordinator acknowledges [JADE ACL message: CONFIRM].

3. The prosumer community coordinator chooses the available energy sellers from the local members and informs them the energy requirement of the energy buyer (Prosumer 1) [JADE ACL message: REQUEST].

4. The energy-selling prosumers individually check whether they able to fulfil the energy request of energy buyer (Prosumer 1). If they are ready to fulfil, that is informed to the prosumer community coordinator [JADE ACL message: PROPOSE]; if they are not ready to fulfil, that is also informed to the prosumer community coordinator [JADE ACL message: REFUSE].

5. After receiving the energy proposals from the energy-selling members who are ready to sell, the prosumer community coordinator selects the suitable energy seller (here we use first comes first served method) and accepts the energy proposal of that selected energy seller [JADE ACL message: ACCEPT-PROPOSAL]. The remaining local energy-selling members who have been ready to sell are rejected [JADE ACL message: REJECT-PROPOSAL].

6. The prosumer community coordinator informs the energy buyer (Prosumer 1) about the availability of a suitable energy seller and that seller’s information [JADE ACL message: AGREE]. If there are no single energy sellers available, who are ready to sell energy, that is also informed to the energy buyer [JADE ACL message: REFUSE].

7. The energy buyer (Prosumer 1) sends acknowledgement to the prosumer community coordinator [JADE ACL message: CONFIRM], and at the same time requests energy from the designated energy seller [JADE ACL message: PROPOSE].

8. The designated energy seller confirms his ability to sell energy to the energy buyer (Prosumer 1) [JADE ACL message: CONFIRM].

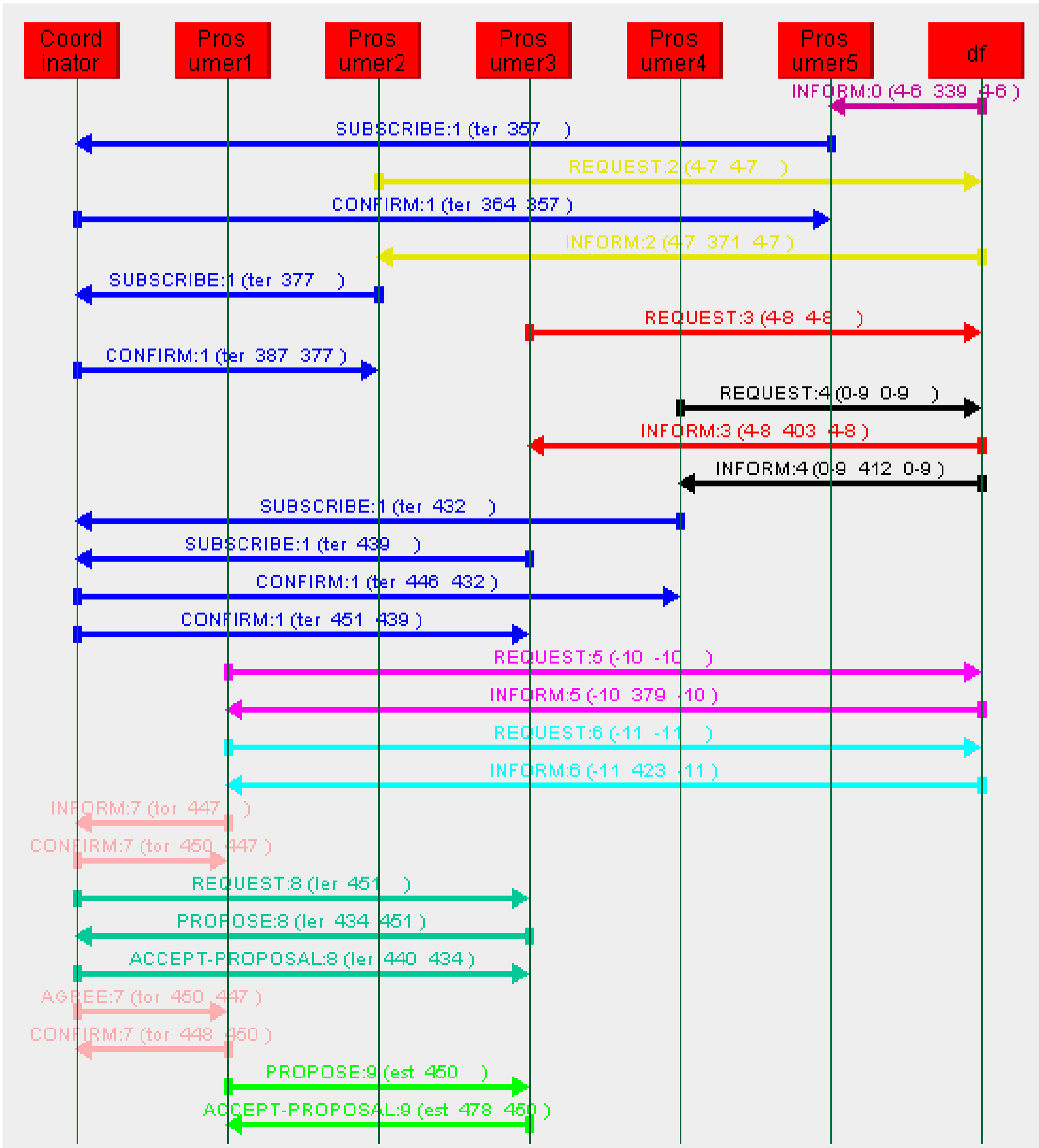


Figure 9. 11: Interactions among the agents in energy sharing among the members within the prosumer community group – Scenario 1

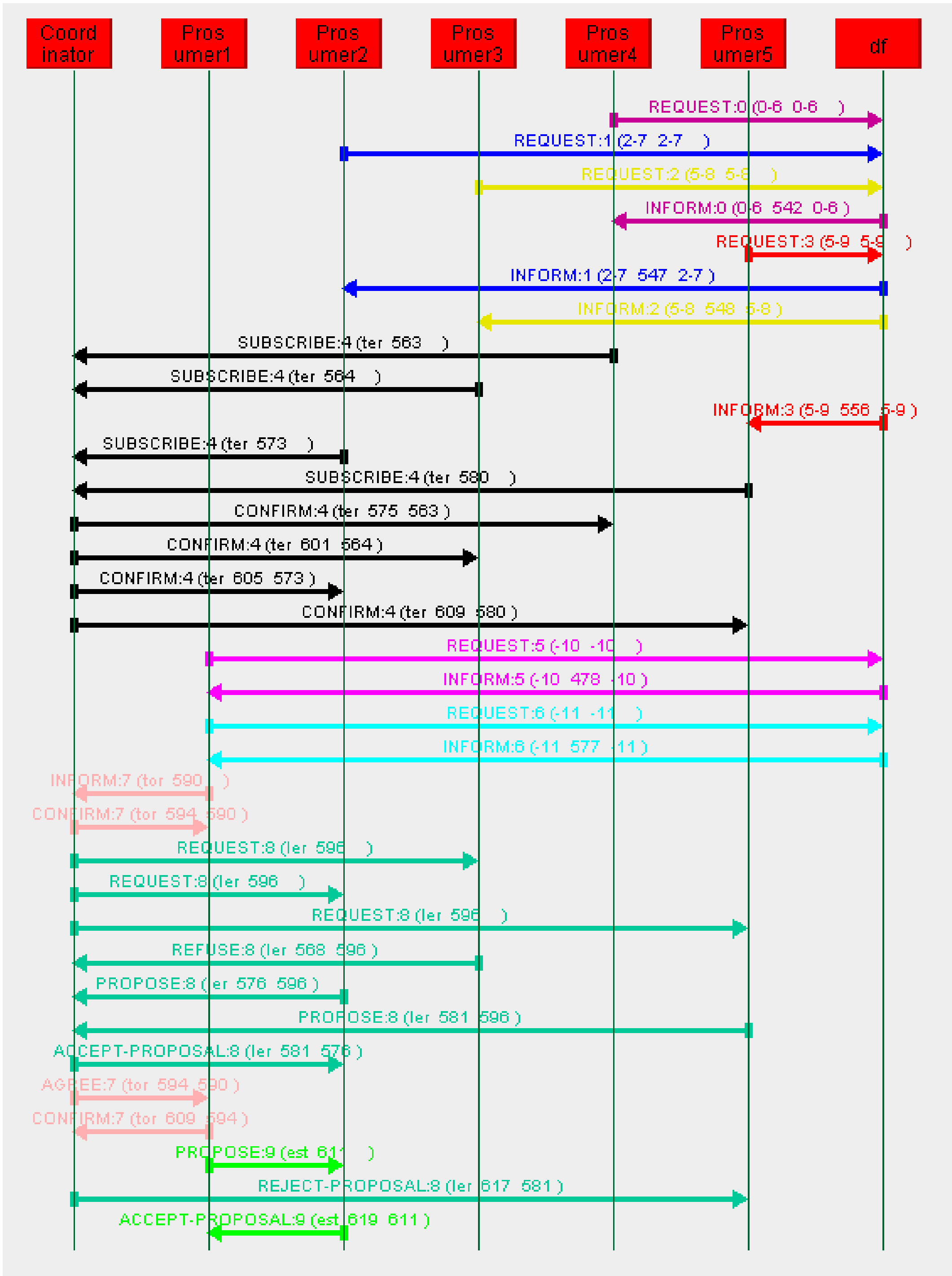


Figure 9. 12 Interactions among the agents in energy sharing among the members within the prosumer community group –Scenario 2

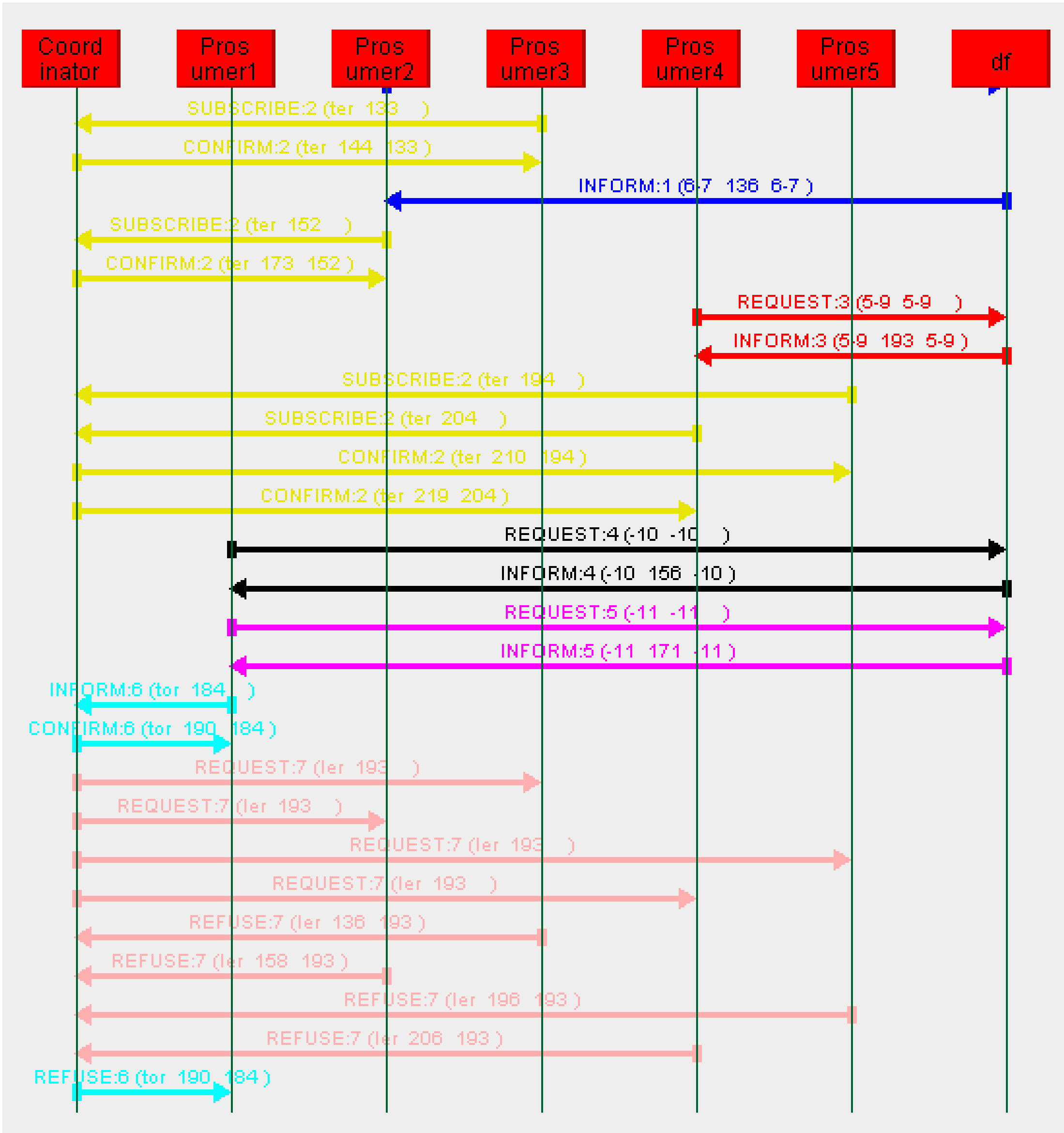


Figure 9. 13: Interactions among the agents in energy sharing among the members within the prosumer community group – Scenario 3

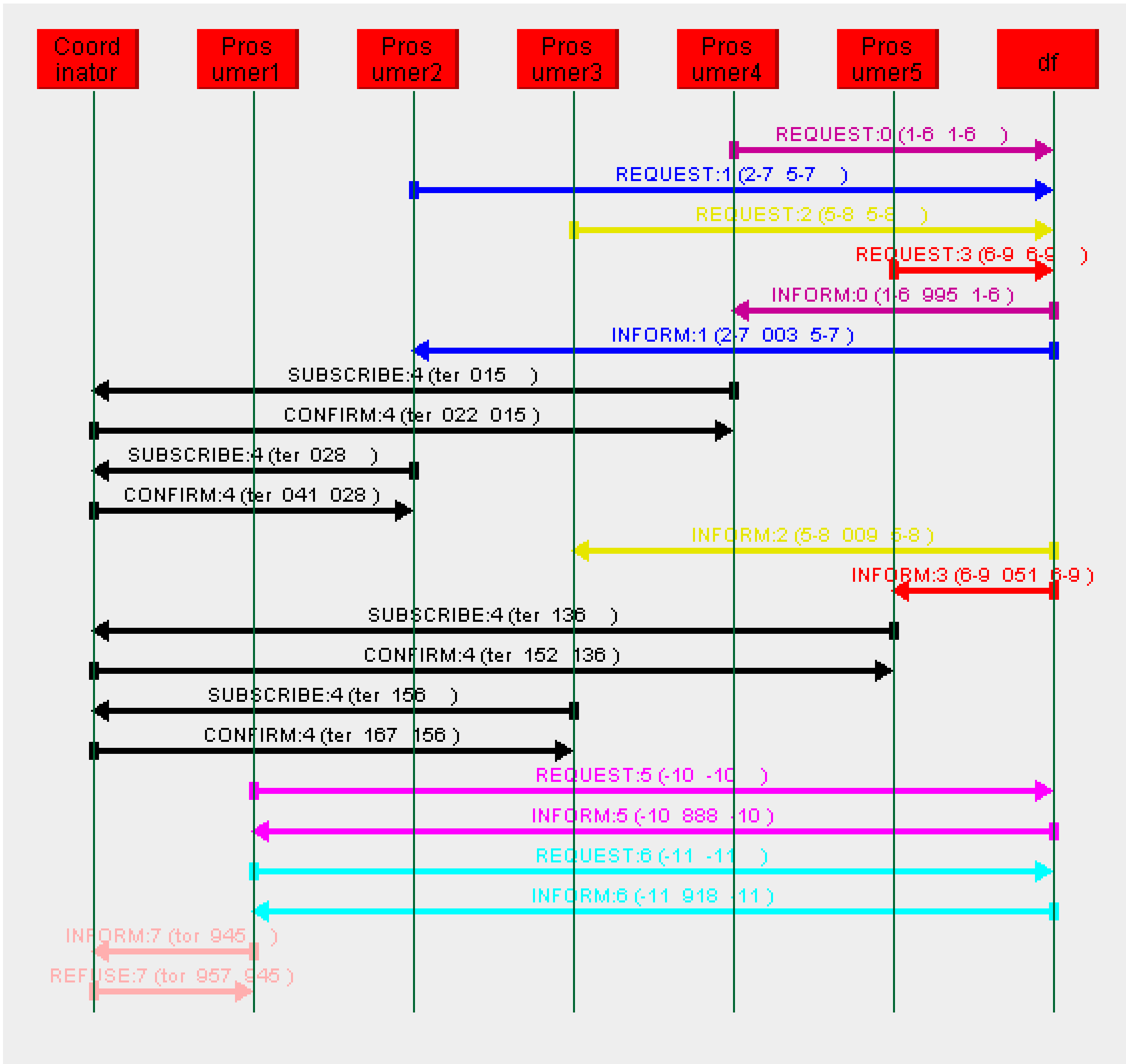


Figure 9. 14: Interactions among the agents in energy sharing among the members within the prosumer community group – Scenario 4

9.3.3.2 Energy sharing between the PCGs and the external energy buyers

In this component, the prosumer community coordinator inputs the external energy buyer's energy requirement to initiate the energy sharing process between the PCGs and the external energy buyers as shown in Fig. 9.15. Accordingly, the initiation of the energy sharing between the PCGs and the external energy buyers is discussed in two selected scenarios: Scenario 1: PCG 1 and 3 collectively meet the energy requirement of the Requestor (here, PCG 2 is willing to give but was refused as the energy requirement is already fulfilled by the first comers (PCG 1 and PCG 3)) (Fig. 9.16); Scenario 2: PCG 2 is willing to give energy to the energy buyer, but the amount that PCG has is insufficient (Fig. 9.17).

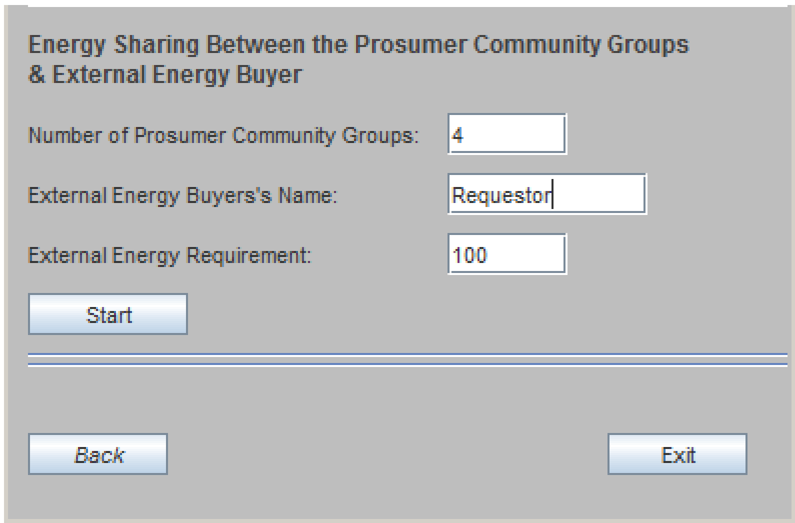


Figure 9. 15: The commencement of the interactions among the agents in energy sharing between the PCGs and the external energy buyers – Scenario 1

The key interactions among the agents in energy sharing between the PCGs and the external energy buyers are illustrated as follows:

1. The requester (the external energy buyer) informs the prosumer community coordinator agent its energy requirement [JADE ACL message: REQUEST]. The prosumer community coordinator acknowledges to message receipt [JADE ACL message: CONFIRM].

2. The prosumer community coordinator sends request to the PCGs to advertise their energy sharing capacities (both excess energy and shortage) [JADE ACL message: REQUEST]. The PCGs notify their energy sharing capacities to the prosumer community coordinator [JADE ACL message: INFORM].

3. The prosumer community coordinator agent chooses the available PCGs who have surplus energy and confirms the receipt of the message and select them as possible energy sellers [JADE ACL message: CONFIRM]. If the PCGs do not have surplus energy, the prosumer community coordinator sends a failure message [JADE ACL message: FAILURE].

4. The prosumer community coordinator checks the energy sharing capacities of the selected PCGs:

    i. If the PCGs can fulfil the energy requirement either individually or collectively, the prosumer community coordinator sends a proposal to supply energy to the requester (external energy buyer) [JADE ACL message: PROPOSE]. Requestor confirms to the prosumer community coordinator [JADE ACL message: ACCEPT-PROPOSAL]. The prosumer community coordinator selects the PCGs that will be used to fulfil the energy requirement of the requestor and notification is sent to them [JADE ACL message: PROPOSE]. The rest of the PCGs, which are not selected, are informed about the decision [JADE ACL message: REFUSE]. The selected PCGs acknowledged the prosumer community coordinator by accepting the notification [JADE ACL message: ACCEPT] (Scenario 1).

    ii. If the PCGs are unable to fulfil the energy requirement either individually or collectively, the prosumer community coordinator informs that to the requester (external energy buyer) [JADE ACL message: REFUSE-PROPOSAL]. The prosumer community coordinator informs the PCGs that their individual energy or collective energy are insufficient to meet the requestor's energy requirement [JADE ACL message: CANCEL] (Scenario 2).

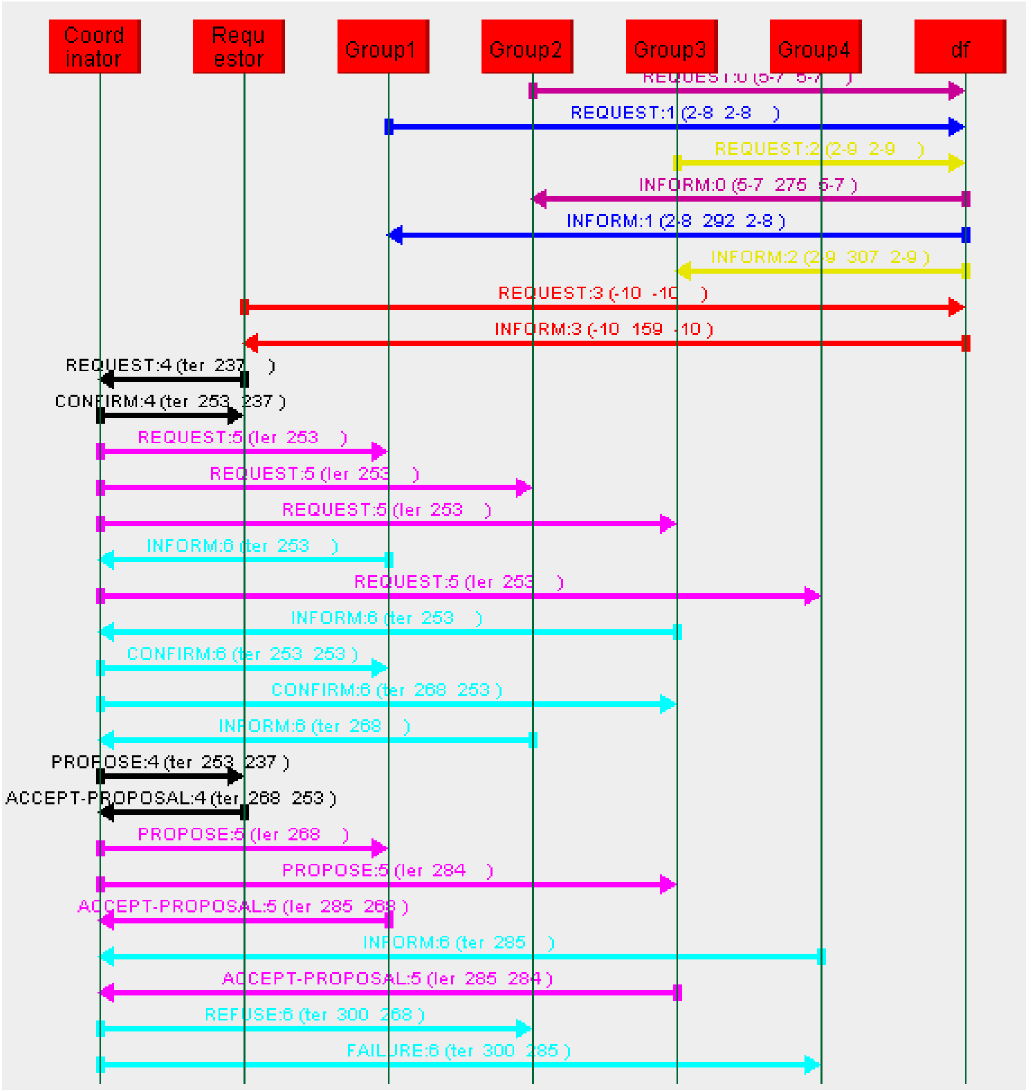


Figure 9. 16: Interactions among the agents in energy sharing between the PCGs and the external energy buyers – Scenario 1

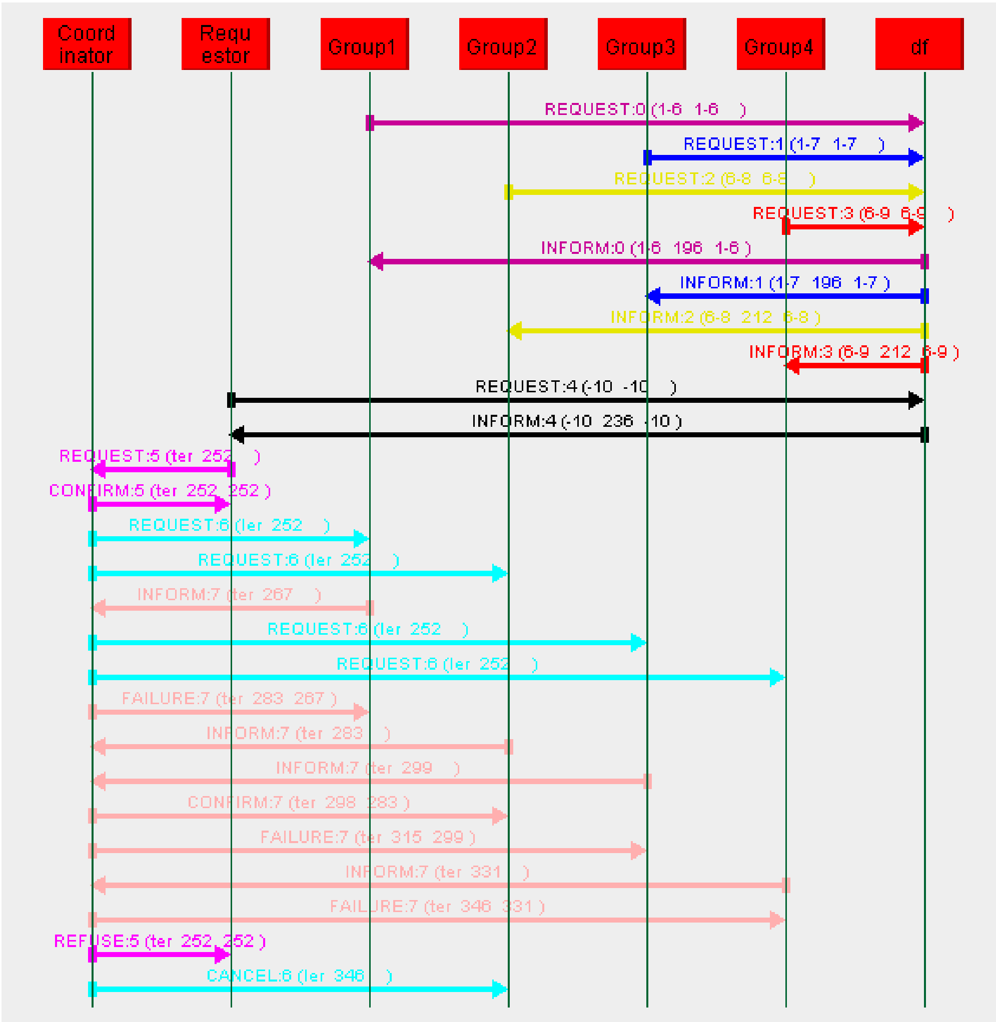


Figure 9. 17 Interactions among the agents in energy sharing between the PCGs and the external energy buyers – Scenario 2

9.4 Conclusion

In this chapter, we developed a prototype system for a community-based energy sharing network. We explained with illustrative examples of how agents interact with each other in community-based energy sharing network, when the new prosumers are recruited to the PCGs, when the mutual goals are allocated to the PCGs and when the energy sharing is commenced among the members within the community group and between the community group and the external energy buyer.

Chapter 10

Conclusion and Future Work

This chapter provides:

- The current issues and problems with managing prosumers in the form of prosumer community groups
- Solutions proposed by this dissertation to address problems
- Conclusion and future works

10.1 Introduction

In the literature, the notion of SG and energy sharing has been widely discussed and various approaches have been proposed to address different challenges associated it. At the same time, the notion of managing prosumers have not been comprehensively investigated; moreover, only a scant amount of research studies are available on developing PCGs to manage prosumers in the SG. Although managing prosumers in the form of PCGs has been acknowledged as an important factor to consider in recent literature, comprehensive approaches to address the issues associated with it have not been proposed and developed.

In order to overcome this disadvantage, and to improve the sustainability of SG energy sharing, in this thesis we identified four key issues in developing PCGs to manage prosumers and address them.

In the next section, we will recapitulate the different issues that we have identified and addressed in this thesis. In Section 10.3, we highlight the contributions, which have been made by the thesis to the literature as a result of addressing the different issues. In Section 10.4, we identify some areas for future work and in Section 10.5 we conclude the chapter.

10.2 Problems Addressed by This Thesis

Although there are approaches proposed in the literature by different researchers to investigate the concepts of PCGs, we noted that none of them develops comprehensive frameworks to address the research problems that we address in this thesis. In this dissertation, the four main problems associated with developing PCGs to manage prosumers have been addressed. As mentioned in Chapter 3, these issues are as follows:

- Problems with defining and characterizing PCGs
- Problems with recruiting new prosumers to PCGs
- Problems with managing multiple goals within the community-based energy sharing network and defining mutual goals to PCGs
- Problems with assessing and ranking members within a PCG

As discussed in Chapter 2, it is clear that current research studies on PCGs are still susceptible to the aforementioned issues, thus, these issues are the drivers of this research and the subsequent development of an innovative frameworks.

10.3 Dissertation Contributions

The major contribution of this thesis to the existing literature is that it addresses four key issues of developing a community-based approach to manage the prosumers in SG energy sharing (developing PCGs). In order to solve the four research problems outlined in Chapter 3, we developed four different frameworks, which form the core contribution of this thesis to the existing literature. In addition to the development of the aforementioned frameworks, we also modelled the community-based energy sharing network as a multi-agent system.

Thus, the key contributions of this thesis are as follows:

- PCG definition and characterization framework
- Prosumer recruitment framework
- Goal management and mutual goal definition framework
- Prosumer assessment and ranking framework
- Agent-oriented architecture to build a realistic model of community-based energy sharing network

10.3.1 PCG definition and characterization framework

This dissertation has investigated the current efforts in the area of PCGs as well as the approaches that exist in the area of SG and the approaches used by literature in the area of generic communities such as online virtual communities. However, the current efforts on PCGs have not proposed approaches in defining and characterizing PCGs. Moreover, the comparable approaches implemented in existing SG projects has attempted to define and characterize prosumer groups in the form of VPP and micro-grid; however, those approaches mostly address the implementation of electrical and ICT interconnection among the DERs or prosumers, and do not offer much attention on the aspects of managing prosumers in

VPPs or micro-grids. Although this research brings in new aspects of PCG definition and characterization, which has not been covered before, attempts have been utilized in relation to the other types of community groups (such as online communities). In this thesis, such research studies are also investigated to gain additional understanding; however, the community group definition and characterization approaches presented by the literature on generic communities such as online virtual communities require major revision if applied to develop PCGs.

In order to address the problem of PCG definition and characterization, in this thesis, we developed a framework for PCG definition and characterization, which analyses the energy sharing behaviours of prosumers (hourly energy sharing load profiles) and clusters the prosumers having similar energy sharing behaviours and ultimately defines and characterizes operational PCGs. The key highlights of this framework include the following:

1. Considered prosumers' data set includes time-series data, which show hourly energy variation profiles for average winter day and average summer day.

2. The outliers within the prosumer data set, i.e. the energy profiles further away from the mean behaviour than what is deemed reasonable, are identified using CCT, which adapts the concepts of the BIRCH algorithm developed by Guojun et al. (Guojun, Chaoqun et al. 2007).

3. The time-series clustering is performed to group the energy profiles based on the homogeneity of the energy profiles.

4. The resulted clusters are optimized to obtain PCGs by either merging the neighbouring small clusters or splitting the large clusters, thus ensuring that each PCG supplies a sufficient amount of energy, and has a sufficient number of prosumer profiles.

5. The pre-qualification criteria of each PCG are defined by analysing the traits of the PCGs obtained. The defined pre-qualification criteria can be used as the guidelines to recruit new prosumers in the future.

6. The proposed framework was evaluated using an energy sharing data set of 550 prosumers in a MATLAB simulation environment, in which total number of eight prosumer clusters were optimized into 4 PCGs in order to guarantee each PCG supplied minimum of daily energy 500 kWh, and each PCG includes at least 80 prosumers in each.

To the best of our knowledge, there is no approach proposed in the literature to define and characterize PCGs, making our work novel within the research field.

10.3.2 Prosumer recruitment framework

As discussed in Chapter 2, the current literature on PCGs lacks comprehensive approaches for recruiting new prosumers to the PCGs. Moreover, the approaches used to connect prosumers (in the form of DERs) to the VPPs and micro-grid prosumer groups in existing SG projects have only focused on investigating the aspects of the electrical backbone when connecting new DERs to the VPPs and micro-grids, but the aspects of managing prosumers in the context of prosumer recruitment such as evaluating prosumers before recruiting them and finding complying and non-complying prosumers are heavily ignored. Moreover, the previous approaches exist in other contexts such as recruiting new members to the online communities require major alteration if adapted to PCGs.

Chapter 6 addresses these problems by providing a framework for new prosumer recruitment in which the prosumer community coordinator evaluates the new prosumers' real-time commitment over a period and assigns them to appropriate PCGs. The key highlights of this framework include the following:

1. The concept of "evaluation period," which is denoted as the defined period of time which involves the evaluation of prosumers before assigning them to the final PCG, is discussed. In this

framework, an ongoing evaluation of prosumers is suggested, where the evaluation period includes several predefined consecutive time slots and the prosumer is evaluated in each time slot as well as the end of the evaluation period.

2. The energy contribution of the new prosumer is evaluated against the pre-qualification criteria of the preferred PCG. An approach is presented to calculate the prosumers' success in meeting the pre-qualification criteria of the preferred PCG, and the prosumer's likelihood of recruiting to a PCG is calculated.

3. The proposed prosumer recruitment framework is verified using 100 new prosumer data in MATLAB simulation environment.

To the best of our knowledge, there is no framework proposed in the literature to recruit new prosumers to the PCGs, making our work novel within the research field.

10.3.3 Goal management and mutual goal definition framework

As mentioned in Chapter 2, the existing literature on PCGs as well as the literature in the area of SG do not provide any approach to manage the multiple goals in community-based energy sharing network and define mutual goals to different PCGs.

Chapter 6 addresses these problems by providing a framework for goal management and mutual goal definition which provides a framework that effectively compromises among the conflicting multiple goals and defines and allocates favourable personalized mutual goals to the diverse PCGs. The key highlights of this framework are as follows:

1. The multiple goals of the community-based energy sharing network are determined and classified as absolute constraints and goal constraints, and prioritized based on their relative importance by adapting the goal ranking technique used by the MCGP.

2. A compromise among the conflicting goals and an optimized goal solution under a varying amount of resources and priorities of the goals are presented, while highlighting what alterations are necessary in parameters to attain all the goals.

3. The optimized overall goals of community-based energy sharing network are divided among the PCGs as mutual goals, while considering the generic characteristics of the PCGs such as average energy level and the number of members, as well as the varying energy behaviour profiles of the PCGs over previous energy transactions.

4. The proposed goal programming problem is verified by implementing it as a linear goal programming problem, which is solved using LINDO-32 (version 6.1) software.

Given that there is no comprehensive work in the literature on the goal management and mutual goal definition for PCGs, this proposed framework becomes novel within the research field.

10.3.4 Prosumer assessment and ranking framework

As discussed in Chapter 3, the member assessment and ranking of prosumers have not been discussed in literature associated to PCGs to date. In addition, the literature on other contexts such as social network communities has several research works on ranking the users and evaluating their contribution; however, due to the extreme differences between the PCGs and the communities in other contexts such as social network communities, such available approaches in other contexts cannot be effectively adapted for PCGs.

In order to address the issues identified in literature, this thesis develops a framework for member assessment and ranking in PCGs. Here, the long-term and short-term energy behaviours of members are assessed based on multiple evaluation criteria and the ranks of the prosumers are accordingly decided, whereby the higher-ranked prosumers are deemed to be more influential in enhancing the long-term sustenance of the PCG. The key highlights of the framework are as follows:

1. Four assessment criteria to assess the members' short-term and long-term energy behaviours within the PCG are defined, namely: Criterion A: meet the pre-qualification criteria; Criterion B: surplus energy contribution to receive incentives; Criterion C: social Responsibility to help fellow members to cover up their energy shortage; and Criteria D: quality of behaviours in membership duration. These criteria are prioritized using the method "weights from ranks" of MCDM techniques.

2. The points are allocated to the members based on their long-term and short-term energy behaviours that are assessed against the multiple criteria. These ranking points determine the degree of deviation between the expected and actual behaviour and provide a relative judgment for each of the member's behaviours. The ranking technique is developed following the concepts of the TOPSIS method of MCDM techniques.

3. The members with relatively higher ranks are considered as the subset of influential members.

4. The proposed member assessment and ranking framework was verified using MATLAB simulation, which proves that the suggested methodology that deals with multiple assessment criteria offers more effective ranking than the conventional ranking techniques that deal with single assessment criteria.

The current literature on similar research field of PCGs has no work investigating this issue, making our contribution novel.

10.3.5 Implementation of community-based energy sharing network in JADE platform

The final major contribution of this thesis is implementing the community-based energy sharing network in an agent-oriented platform.

In order to demonstrate the effectiveness of the overall community-based energy sharing network, in Chapter 7, we created a multi-agent community-based energy sharing network prototype system that combines the above-mentioned concepts of PCGs into a single platform. The proposed platform has the following highlights:

1. The overall platform for a community-based energy sharing network is designed as multi-agent systems using JADE, which was implemented in three phases: (i) initialization phase, (ii) PCG formation phase and (iii) energy sharing phase.

2. In the initialization Phase, the prosumer and the prosumer community coordinator specify the initial parameters needed for the prototype system to initialize the multi-agent community-based energy sharing network.

3. The PCG formation phase recruits the prosumers to the suitable PCGs and allocates optimized mutual goals.

4. The energy sharing phase involves local energy sharing among the members within a PCG as well as the external energy sharing that involves energy sharing with external energy buyers such as utility grid and other PCGs.

10.4 Future Works

The research work that has been carried out in this thesis has been published in peer-reviewed international journals, conferences and book chapters. Over the course of this research, 15 research papers have been published in 7 peer-reviewed international journals, 8 peer-reviewed conferences(in which 2 publications are presented as book chapters). Although a significant amount of effort has been invested in this research, there is still scope for future work, which we illustrate as follows:

- In this dissertation, four key challenges of developing PCGs are investigated and the frameworks are proposed. There are other challenges in the context of managing prosumers in PCGs such as developing member motivational schemes and incentive distribution schemes, which require further attention in future. However, some frameworks we developed in this thesis can be used as the initial building block to the aforesaid unaddressed issues. For instance, the member assessment and ranking framework can be used to find relatively influential members, which facilitate stepping-stones to the development of fair incentive distribution schemes.

- In this thesis, the definition of PCGs and the prosumer recruitment are done based on the homogeneity of the energy sharing capacity of prosumers; however, other categorical values such as prosumer's individual goals and short-term plans that affect the energy generation are not taken into account. This research can be further developed to define and form PCGs based on different influential factors.
- The goal programming model in a goal management and mutual goal definition framework can be extended for any number of conflicting goals.
- In the member assessment and ranking framework, the members are assessed based on four key criteria; however, they can be extended to any number of criteria to make it adaptable for any condition.

10.5 Conclusion

In this chapter, we have summarized the work that we have undertaken and documented in this dissertation. We first discussed the issues that we have addressed in the literature that prompted the research study done in this dissertation. We then highlighted the different contributions of this thesis. We then briefly described the future work that we intend to carry out in order to extend and further develop the approaches developed in this thesis.

The research study that we have undertaken in this dissertation has been published extensively in peer-reviewed seven international journals, and eight conferences. We have attached a complete list of all the publications arising as a result of the research study carried out in this thesis at the beginning of the thesis.

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