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SMART ENERGY DEMAND MANAGEMENT – A COLLABORATIVE APPROACH TOWARDS CONSUMERS' ACTIVE PARTICIPATION

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TABLE OF CONTENTS

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EXECUTIVE SUMMARY

Secured provision of energy is vital for the developments in all spheres. To cope with the rising energy demands and associated challenges, great attention is being given to the technological advancements that are capable of providing economically and environmentally sustainable energy solutions. In this regard, Smart Grids are considered as a solution to the sustainable energy provision as they enable efficient and reliable production, distribution, transmission and consumption of electricity.

In this context, we refer to the *electricity supply chain network* consisting of power stations (electricity generation), transmission system operators (electricity transmission), distribution network operators (electricity distribution) and customers (electricity consumption). This supply chain structure is significant because of its integrated processes and flows between the members. As exemplified, interconnected members incorporate the processes from main energy resource to the final consumption of electricity.

Presently, different trends can be observed in the electricity supply chain. First, considering the U.S. Energy Information Administration (EIA) future projections, the demand of energy is increasing and it may continue to increase and fluctuate (EIA, 2013: pp.1) in the next years. This pattern can be justified with the economic prosperity; furthermore, energy will play an important role in diminishing the carbon emissions through the electrification of various activities, processes, and products such as plug-in electric vehicles and building heating pumps.

Secondly, consumers' dynamic behavior towards electricity consumption forces utilities to constantly adjust the supply side to manage the peak demand variations, resultantly decreasing the supply efficiency. Therefore, meeting the increasing demands while balancing the operational constraints (supplemental production) put more stress on the entire electricity supply chain network (Marwan and Kamel, 2011; Molderink *et al.*, 2010).

From Centralized to Distributed Electricity Networks

The introduction of Smart Grids entails a paradigm shift from centralized electricity network to digitized, distributed grid infrastructure. This decentralization would have a profound impact on electricity supply chain network (Ipakchi and Albuyeh, 2009). First, it will allow secured bidirectional flow of energy along two-way communication and controlling capabilities. Secondly, it will intelligently integrate the actions of all connected members (from generators to customers).

Such coordination (of physical, information and financial flows) across the supply chain will provide sustainable, economic and reliable supply of electricity (Clastres, 2011; Al-Agtash, 2013; Bas, 2013). In particular, regarding the reliability aspect, electricity supply system reliability can be explained in terms of *supply adequacy* and *supply security*. Supply adequacy refers to the energy provision under normal conditions, whereas supply security refers to the system's ability to adequately respond to unpredicted disruptions (McCarthy *et al.*, 2007).

The current electricity network follows a centralized, top-down distribution approach with numerous improvement limitations, whereas smart grid infrastructure necessitates networked architectures with various enhancements. Looking at the supply-side, great attention is being given for the integration of distributed generation through renewable energy resources with the purpose of achieving sustainable energy.

With high significance, European Union has set the target to produce 20% of its energy from the renewable resources by the year 2020 (EU Commission, 2007) and the investments in the distributed generations through renewables are considered as a strong support towards achieving this target. Under the new paradigm of electricity systems, passive electricity distribution having one-way communication and flow of electricity is being transformed into an active two-way distribution between suppliers and consumers.

This transformation requires a strong collaboration and communication between supply and demand side participants, where a particular focus should be given on engaging the consumers as active participants in the electricity systems. This engagement is highly significant because it is estimated that contribution from the demand side (through demand response and renewable resources) will constitute from one-third to one-half of total smart grids benefits (Heffner, 2011).

Various approaches are being adopted for encouraging consumers and taking their inputs in terms of their energy demand management. Energy demand management (also known as demand side management) has always had a high weightage in the electricity supply systems. This is due to the fact that demand (consumption) should constantly be balanced with supply (production) to prevent supply disruptions and its associated technical, social and economic negative consequences.

Demand Side Management and the Role of the Consumers

Different demand side management and demand response programs exist, where the overall purpose of these initiatives is to reduce or shift demand in response to the supply constraints. The majority of these programs are mainly market-driven, environmental-driven, and network driven. In market-driven programs, the overall purpose is to reduce the energy supply costs, while in the environment-driven programs, the purpose is to reduce the energy usage as per supplier commitment to environment; finally, in network-driven programs, the focus is on maintaining the supply system reliability. Though, existing demand side management programs seek consumers' contributions towards energy savings and efficiency but most of these programs are driven by the goals of electricity utilities.

One key issue among these programs is that consumers play a passive role; that means, consumers are asked to respond by reducing/modifying their consumption patterns as per specific requirements of the electric utility. This approach makes consumers reactive rather than making them more proactive in managing their energy demand and resultantly they are left with limited participatory choices. Proactive management of consumers demand can be driven by the collaborative actions undertaken by electric utilities to directly engage their consumers. Collaborative actions suggest involving the stakeholders towards achievement of sustainable developments.

Consumers and their communities at large are becoming more environmental conscious. They are getting aware that their direct and collective positive actions can have higher contribution towards sustainability and can also push companies and businesses to bring change for the betterment of their society. However, consumers remain reluctant in their active participation because existing collaboration tools and platforms may not have an adequate fit with their perceived value proposition, while participating in the programs driven by electric utilities.

Emerging Role of Proactive Consumer

In pursuance of collaborative actions, Smart Grids widely acknowledge and encourage the active involvement of consumers and allow sustainable integration of proactive consumers (also known as *prosumers*). Proactive consumers actively participate by generating their own energy from renewable resources (e.g. photovoltaic panels and wind turbines) and also share the excess with others including other consumers and utility grids.

This user class transforms their passive role into the active role in the electricity generation and managing their demand, for the long-term sustenance of electricity infrastructure (Rathnayaka *et al.*, 2012). Proactive consumers can also assist electric utilities in managing the peak loads of electricity either by providing the supplemental capacity or by fulfilling the demand with their onsite-electricity generations.

There are different research studies in the domain of Smart Grids, explaining the benefits that can be achieved through consumers' involvement and their participations through demand response, and what challenges and barriers exist for them. However, in many of these studies, consumers are considered for changing consumption patterns for the sake of financial benefits (e.g. consumers response to different pricing and incentive mechanisms) (Mohsenian-Rad *et al.*, 2010; Gottwalta *et al.*, 2011; Hubert and Grijalva, 2011).

Dealing with sustainability challenges finds its roots in a shift of mindset towards the achievement of more efficient consumption patterns where consumers (along their communities at large) should be directly engaged. In our understanding, this shift in consumption patterns should not be limited to financial incentives; rather, the focus should also include participative and collaborative behaviors, factually realizing the collaborative consumption. This shift is better assisted with properly designed collaboration platforms establishing a mutual collaboration between producers and consumers.

Scope of the Research Work

By understanding the value and the necessity of consumers' active participation, we have considered a further step in demand-supply collaboration among proactive participants for their energy demand management. Accordingly, the research work described in this thesis focuses on collaborative activities on the demand side that could encourage consumers to be more active in their energy demand management while realizing the collaborative consumption strategy that is a technology enabled sharing of goods and services.

To proceed, we have identified and analyzed the characteristics and the key requirements of the demand resulting from a collaborative consumption process. Therefore, we refer to such a demand with the term Smart Demand, that is a demand signal coming from a collaborative environment. Identifying the challenges to smart demand helps us to examine the factor that can limit the active participation of consumers in different collaborative arrangements.

Further, to demonstrate consumers' engagement (and their demand flexibility) towards energy sustainability, we have envisioned the energy sharing among the group of consumers at their community level. In this model, we have considered proactive consumers who produce electricity through their solar photovoltaic panels for their own consumption, and share the excess with others in the community. Among different renewable resources, solar power (photovoltaic systems) is widely used renewable energy in some regions because of its abundance and relatively low initial setup costs (Wee *et al.*, 2012), and these systems and devices are easy to be deployed in domestic environments.

This collaborative framework encompasses an energy-sharing community network model that optimizes the energy sharing. The model also highlights the active participation of community members in terms of managing their demand for minimizing the costs along reduced electricity sourcing from the main electricity grid. In order to show the detailed working and to understand the complexity of the model, we have used a linear programing approach.

Consumers' activeness, or their engagement, will allow utilities to effectively manage the demand side that is ultimately beneficial for utilities, consumers, and society in general. To briefly highlight the results, our research suggests that increasing number of proactive consumers (*prosumers*) has a positive impact towards energy sustainability, as there are more renewable energy resources that can be shared among others.

In terms of proactive consumers, it provides increased capability and flexibility to manage their demand profile and also the reduced costs by selling back the electricity to the utility grid. In terms of electric utilities, consumers engagement can assist in reducing the operational costs by producing less electricity from expensive fossil based generation plants. With these improvements, society in general benefits with reliable supply with reduced electricity outages.

However, the potential role of proactive consumers is determined by various factors, ranging from self-interest layers to exogenous conditions that can induce the coordinated efforts of the users towards energy demand management. For actively engaging the consumers, electric utilities, service providers, governments, and regulators should take proactive actions and should also empower the consumers with essential collaborative tools and platforms.

Structure of the Thesis

This doctoral thesis consists seven chapters, and is organized as below:

Chapter 1: Introduction and Background

Chapter 1 introduces the research work illustrating the background for a systematic understating of electricity supply chain management. The overall purpose of this chapter is to explore and discuss the key issues at both the supply and demand side for effectively managing the energy demand. Therefore, the chapter starts by providing and overview of the current electricity supply chain and the electricity markets. Further, the concept of Smart Grid is presented along with its key drivers, challenges, different stakeholders involvement and their impacts on the value chain. Next, we discuss the consumers and prosumers required involvement in the Smart Grids developments. The chapter concludes by highlighting the emerging role of proactive consumers (prosumers) in the smart grids.

Chapter 2: Literature Review

This chapter discusses the existing work done from the perspective of demand side management. The aim of this chapter is to present the diverse views related to smart grids, and then narrow it down to the consumers' involvement and their participation. Therefore, it explores the technical, economic and social dimensions in the energy demand management. The chapter mainly scrutinizes the proposed models (quantitative and qualitative) in the literature from a consumer-centric view. Finally, it concludes by highlighting some of the key limitations that's needs to be addressed.

Chapter 3: Research Methodology

This chapter bridges the background and the existing work in order to analyze the research gaps. Accordingly, the chapter presents the problem statement in the context of renewable energy utilization for electricity demand and supply. Based on the related issues, research questions are presented that we aim to answer and also provides the justification for the selection of adequate research methodology.

Chapter 4: Smart Energy Demand Management

The detailed analysis of the literature provides the basis for this chapter. This chapter provides the answer to the 1st research question. It starts by providing the concept of Smart Demand, its ground definition and justifies the essentiality of smart demand in the context of energy demand. The chapter concludes by identifying the key requirements and the future challenges to the smart energy demand.

Chapter 5: Decision Models

In order to address the 2nd research question, this chapter proposes a mathematical model for the smart energy demand management. It starts by envisioning and explaining about the energy-sharing framework among the group of consumers. The goal of this model is to envision electricity sharing among the group of consumers at their community level and to demonstrate the impact of consumers' active participation in satisfying their electricity requirements. It allows us to characterize and understand the important flows and activities that can have a significant impact on the consumers' decisions in managing their demands. The mathematical model is based on the linear programming. Further, the chapter discusses the key assumptions, parameters, variables, and constraints. Finally, according to different cases along their subsequent scenarios, each objective function is formulated and solved by using the GAMS CPLEX optimizer.

Chapter 6: Test and Validation

This chapter includes the testing and the validation of the mathematical model. For the testing phase, we have implemented and solved the decisions models in the General Algebraic Modeling System. For this, we have presented the results of the solved mathematical model. Moreover, we have performed the design of experiments to test the model performance according to different sizes. To validate the model, we have contacted a company in the Italian health care industry. Therefore, using a real historical data of the company model is empirically validated. The chapter concludes by presenting and analyzing the experiment results along with the theoretical support.

Chapter 7: Conclusions and Future Research

We end the thesis with this final chapter of conclusion. The chapter highlights the key findings. It also includes the contributions of this research work covering the theoretical and managerial insights. Finally the chapter is completed with the proposed extension of our mathematical model (of smart energy demand management) as a future research work.

CHAPTER 1: INTRODUCTION AND BACKGROUND

Chapter Abstract

This chapter introduces the reader with the systematic understanding of electricity supply chain along its various issues and challenges. Therefore, the chapter starts by describing the electricity supply chain, electricity industry restructuring, electricity markets, and the expected changes. These changes are leading to the development of new advanced electricity system, such as Smart Grids. The concept of Smart Grid is further described from the vision to its impact on the electricity supply chain. Based on the strategic importance of electricity, the role of consumers and their required engagement in electricity system are discussed under Demand Side Participations. The chapter concludes by highlighting the emerging role and the importance of Proactive Consumers / Prosumers as active contributors, towards the improvement of Smart Grids.

1.1: Electricity Supply Chain

Supply chain management is a chain, consisting of suppliers and customers, which integrates and manages numerous processes and activities (including material, information and financial) to deliver products and/or services to the end customers. In this regard, electricity supply chain management is an upstream and downstream integration of different processes, and coordination of electricity flows along its information and financial flows from the suppliers to the final customers (Bas, 2013).

The main objectives in managing the electricity supply chain are to increase efficiency (with low outages), to reduce electricity costs, and to enhance the social benefits (emission reductions) through delivered electrical energy. Achieving such objectives necessitates scientifically rigorous and efficient modes in electricity supply chain processes along with increased coordination among electricity supply chain members (Fan and Cunbin, 2010).

The **main processes** in the electricity supply chain starts from sourcing of primary energy resources, generation, transmission, distribution (and retailing), and electricity consumption. Each process is carried out by performing multiple activities; resultantly, the output of each process will be served as an input to the next stage. Figure 1.1 depicts the simplified diagram of the electricity system by illustrating the main processes in the electricity supply chain. Moreover, each process along with its activities is further briefly explained in Table 1.1.

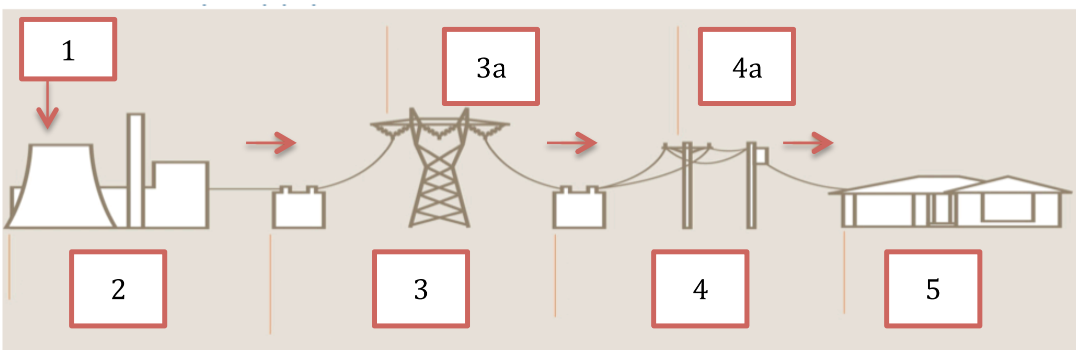


Figure 1.1: Electrcity supply chain (Source: adapted from http://eex.gov.au)

Table 1.1: Electrcity supply chain processes (Source: author)

	Main Process	Key Activity	Example
1:	Primary Energy Resources	Sourcing of different primary energy resources from operators in the supply markets.	ENI S.p.A., Italia (oil and gas)
2:	Electricity Generations	Power Plants that produce the electricity.	Enel, Edison, Edipower S.p.A.,

			Italia.
3:	Electricity Transmission	Transmission System Operators transmits the electricity.	Terna S.p.A., Italia.
3a:	Transmission Lines	Carrying high voltage electricity for the transmission over long distances.	
4:	Electricity Distribution	Distribution System Operators responsible for distributing and dispatching the electricity.	Enel Distribuzione, A2A S.p.A., Italia.
4a:	Distribution Lines	Carrying low voltage electricity for the distribution.	
5:	Electricity Consumption	Electricity consumed by customers that includes: agriculture, industry, service, and residential sector.	

1) Primary Energy Resources: At this stage different, types of energy resources are used to generate the electricity. These resources can include both non-renewable resources and renewable resources. Non-renewable resource includes fossil fuels such as oil, oil derivatives, gas, coal, coal derivatives, uranium, etc. Renewable resource includes such as wind, solar, biomass source, geothermal energy, etc. Accordingly, various supply markets as per resource types make this stage more complex. The single common activity performed with these resources is the extraction and refining the raw energy and then transferring this refined form of energy to the generators. To exemplify, natural gas accounts for the 42% share (being the largest primary energy resource used) in the electricity production in **Italy** for the year 2011 (TERNA,2011:pp4; GSE,2011:pp11).

2) Electricity Generation: The main activity performed during this process is related to the transformation of primary energy resource into the electrical power. Depending on the resource type, different types of Power Plants consisting of machines (such as steam and gas turbines, combustion engines etc.) are used for the conversion process. Examples include electricity generation through hydroelectric power plants, pumped-storage hydro plants, renewable resources, and fossil fuel based conventional power plants. In variety of power plants, fundamental process includes fuel conversion from the potential energy resource (such as oil, gas, coal, and nuclear) into the kinetic energy to drive the turbines. Resultantly, these turbines generate high voltage electrical energy (Sanderson, 1999).

3) Electricity Transmission: This stage involves bulk transmission of high voltage electrical energy through the transmission lines/wires. The interconnected transmission lines forming a transmission network transmit the electricity from its place of generation, over the long distances, to the regional distribution centers placed near the urbanized areas. Transmission amount of electrical power can vary according to various factors, including production capacity, dispatched quantity, structural constraints (transmission lines and equipment), and also the weather conditions. Transmission process in the electricity supply chain is highly complex, as it requires constant adjustments to accommodate the gap between electricity generation (supply) and its consumptions (demand). Therefore, inadequate supply chain planning (for generation and transmission) can create numerous challenges such as network congestions, electricity outages, fuel shortages, high production costs, and other environmental degradations (Wu *et al.*, 2006; PSC, 2013).

4) Electricity Distribution: The distribution process carries out the transfer of high voltage electricity from the transmission network to the local regional distribution network. These localized distribution networks reduce the electricity voltage in order to make it consumable in the domestic environments. Also in the electricity systems, more losses and interruptions of electrical energy occur in the distribution systems and subsystems (Eduardo *et al.*, 2006). In the distribution stage electricity is not directly delivered and sold to the consumers however; the electricity suppliers/retailers perform this function. Retailers (acting as final functional stage of electricity supply chain) purchase the electricity either from the pooling (of market participants) or the bilateral trades (direct contract with the generator) (Sanderson, 1999).

5) Electricity Consumption: Electricity suppliers / retailers deliver the electricity to its customers for their final consumption. Customers include agriculture, industry, services, and domestic/residential sectors. Each sector has different consumption trends. As an example of Italy, industrial sector (including transportation) has the highest share of electricity consumption for the year 2011 (TERNA, 2011). Retailers provide different value added services to customers for optimizing their electricity usage. These services include energy management systems, assistance services, home automation, time of use pricing contracts etc. Finally, to provide a reliable supply of electricity and to hedge against electricity price fluctuations, electricity retailers use various incentive programs to encourage customers in revealing their electricity demand values and their preferences in advance (Mahmoudi *et al.*, 2013).

1.2: Industry Restructuring and Electricity Markets

To deliver more value, (in terms of lower prices and improved services) to customers, organizations along the electricity supply chain are pushed further toward achieving the goals of improved energy efficiency. These actions are undertaken through restructuring of electricity delivery arrangements along its market liberalizations. The liberalization (also known as deregulation) is bringing reforms in the electricity supply chain from generation to consumption. It allows supply chain members to operate independently and also allows them to compete against others in the market at the same stage of supply chain.

The overall objective of the liberalization is to allow entry of various participants that should ensure a reliable electricity supply (for a short and long term) with lower prices and improved quality to all customers. Along increased competition, liberalization in the electricity industry could also assist in evading the capital-intensive investments for the technologies requiring longer development and construction periods (Foley *et al.*, 2010). Grilli (2010) and Tesauro (2001) highlighted the different motives behind bringing the changes in the electricity arrangements , that are:

- Economically and efficiently fulfill the customer demands. Satisfying customers' requirements by considering prices, choices, quality and supply reliability.
- Improve market competition and facilitate entry of new participants.
- Establish a trading arrangement that keep in balance supply and demand between generators and customers.
- Transparent and fair access to the energy resources without dominance of any single entity.
- Efficiently reduce and share various costs and risks; such as operations and maintenance costs with supply security.
- Improve transparency and accountability in the industry with compliance to government legislations.

During 1990s, several nations (such as USA, UK, and Norway) have deregulated and privatized their vertically integrated electricity industries to pursue the above-discussed motives. The process of deregulation of electricity industry in Italy started in 1992, by privatizing its sole concession of Ente Nazionale Energia Elettrica (ENEL). The process ended in 2007 with the establishment of Electricity Market where both supply and demand sides become liberalized that is allowing both sides to participate in the markets (Armando *et al.*, 2001; Grilli, 2010).

Conventionally, a monopolistic structure of the markets (electricity, gas, telecommunication, etc.) impedes the market competition with inefficient allocation of limited resources. This structure also improvises higher prices, inferior quality, and limits the product / service choices along restricting the innovations. In response to this, removing the market barriers for creating a rich competition through liberalization/deregulation is commonly considered as an effective solution for such problems (Böheim, 2005).

As per restructuring of the electricity industry, electricity markets include competitive wholesale markets and also the retail markets. There exist different electricity markets with various trading and pricing mechanisms. However, electricity markets are generally organized as multi-unit auctions with uniform prices (Grilli, 2010). These markets are run on daily basis and are controlled by Independent System Operators (ISOs). Trading between buyer and seller to procure electricity can be arranged by pooling (auction among market participants) or through bilateral trades (direct contracts).

Wholesale electricity markets are accessible to the participants trading (buying and selling) the larger quantities. Participants can include generators, independent power producers, transmission and distribution system operators, retailers and suppliers. In retail markets, consumers and businesses purchase low-voltage electricity power provided through local distribution systems. Retail electricity markets also contributes towards developing a competition in the wholesale markets (Goulding *et al.*, 1999). At present, Italian electricity system exhibits the varied market characteristics from monopoly to competition as shown in the Figure 1.2.

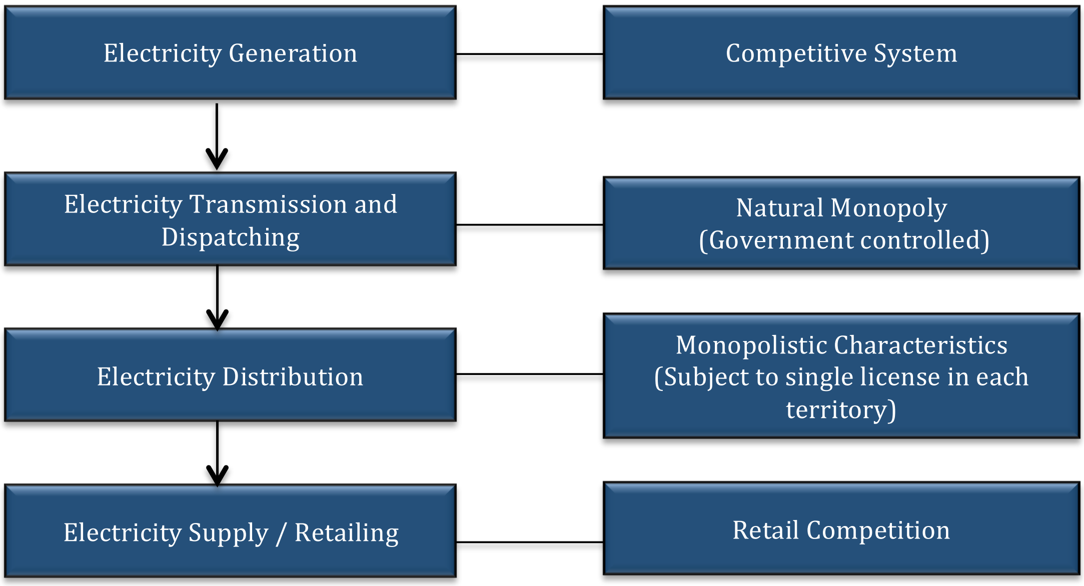


Figure 1.2: Market characteristics of the Italian electrcity system (Source: author)

1.3: Current Issues and Future Trends in Electricity Supply Chain

World electricity demand and its share in the energy market have shown a steady rise from last thirty years on yearly basis, with an average global growth rate of 3.6% (WEC, 2007: pp.19). It can also be acknowledged in another way as International Energy Agency stated that from 1973 to 2011, world electricity production has increased yearly with an average annual growth rate of 3.5% (IEA, 2013: pp.55). Moreover, such increase is growing beyond the efficient utilization of existing generation assets (Devabhaktuni *et al.*, 2013), resultantly having various implications on the environment, infrastructure, and supply reliability.

To cope with these, several improvements (from operations to architecture) are required in the entire electricity supply chain. Therefore as highlighted under the electricity markets, the deregulation of network industries like electricity is redesigned to initiate the required improvements ranging from electricity generation to consumption. These improvements can briefly be highlighted with distributed electricity generations through renewables, transmission and distribution grid management with real-time control, and demand management to monitor and control the consumptions.

1.3.1: Current Issues

The conventional electricity energy systems highlight a number of characteristics that requires substantial improvements at supply (generation) and demand (consumption) side. Traditionally, in most of the countries, electricity generation is carried out in large central power stations, which is subsequently transmitted and distributed through its networks (Wee *et al.*, 2012).

These plants are mainly dominated by fossil fuels (like oil, gas, and coal) usage, leading to a major source of greenhouse gas emissions (Vithayasrichareon *et al.*, 2012). Moreover, generation efficiency of the power stations varies according to power generation mix (fuel types). As exemplified, generation efficiency of the Italian power station varied between 46% (thermal plants) to 55% (modern gas combined cycle plants) for the year 2011. This efficiency further decreases, when 6% transmission and distribution losses are also considered (EU Commission,2013:pp.68; ABB,2013:pp.4).

Besides the supply side inefficiency, consumers' dynamic behavior towards electricity consumption is also adding more inefficiency to the power grids. Unlike any other commodities, large amount of electricity storage is neither feasible nor economical. Resultantly, the entire electricity supply chain is based around the balance where generation of electricity power has to be coordinated with total demand at each point in time. Such coordination of supply and demand is achieved by constantly adjusting the electricity production to the demand. If the demand increases, management and the control systems have to ensure that production of the electricity grids should also be increased accordingly, and vice versa.

An example of dynamic behavior is depicted in Figure 1.3 with hourly electricity loads. Figure highlights the hourly loads (gross domestic electricity consumption) on the Italian transmission grid (TERNA). It can be observed that during the night hours demand drops to the base load (minimum amount of electricity used), as some devices (e.g. fridge, microwave oven) continuously consume the electricity even at the standby mode. On the other side, variations of the peak load (maximum amount of electricity used) occur during the day. The first peak of the day can be observed in the morning hours when people start their day and the second peak can be seen in the evening when people are at home.

The stochastic nature of consumption (consumers demand profile) forced the electric utilities to constantly adjust the production capacity. Moreover, it also requires utilities to manage and control transmission and distribution capacity of the electricity grid under demand variations (between peak and low demands). Meeting the increasing demand while balancing the operational constraints (supplemental production and/or electricity imports) put more stress on the entire electricity supply chain network (Marwan and Kamel, 2011; Molderink *et al.*, 2010). Therefore, along improving the supply efficiency, it is equally important to understand the consumption patterns for the optimum use of generation assets.

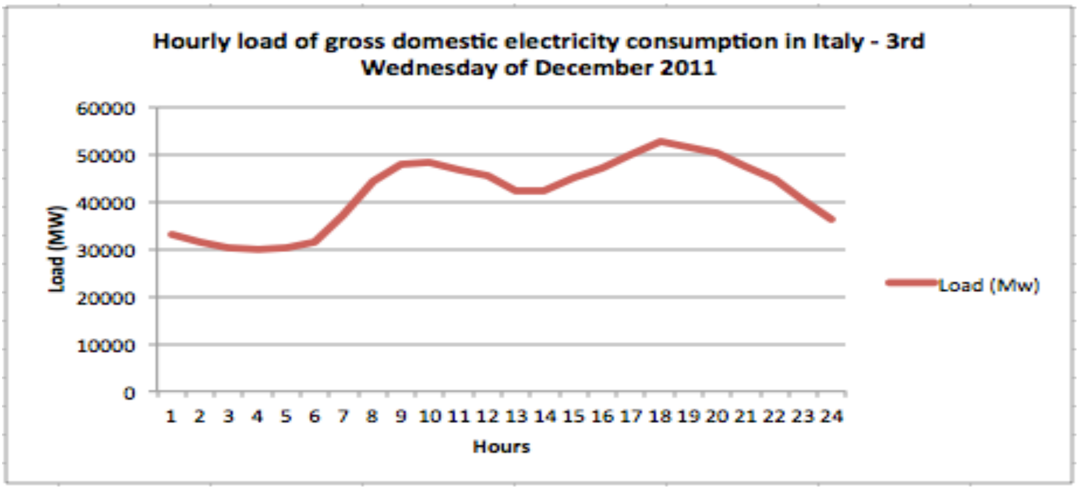


Figure 1.3: Hourly electricity loads in Italy on December 21, 2011
(Source: Adapted from TERNA, 2011)

1.3.2: Future Trends

There are different political, environmental and economic factors that are influencing the current conditions and also shaping the future of electricity supply chain. These can be highlighted with government energy policies, climate changes, supply security and affordability with market competitiveness, and required integration of renewable resources (Bekaert *et al.*, 2008; Gangale *et al.*, 2013). Gharavi and Ghafurian (2011) argued that future electricity systems are driven by three key factors that are government policies, customer needs and expectations, and intelligent technologies (including software and hardware).

In addition, sustainability concerns are driving the entire energy systems for the improvement of its efficiency and reliability to cope with the global growing demand for energy (Devabhaktuni *et al.*, 2013). It is expected that demand of electricity will continue to increase and fluctuate. Electricity will play an important role in diminishing the carbon emissions through electrification of many activities, for example electric passenger transportation (Lampropoulos *et al.*, 2010).

The electricity load, already dynamic, will be more dynamic with the mass diffusion of electric vehicles. Charging the batteries of these vehicles requires momentous amount of electric power and the charging rate of these batteries could double the average domestic load (Samadi *et al.*, 2010).

Conventional electricity delivery systems have some existing key characteristics that make its components, like generation, transmission, distribution, and customers, more isolated to each other. To meet the requirements of reliable, affordable, and sustainable electricity, new investments are being made in the context of transitioning to a future low carbon electricity system. Table 1.2 broadly outlines some key characteristics that will be required to change for the future electricity systems.

Table 1.2: Expected changes in the electricity supply chain (Source: author)

Existing Trends	Expected Changes
Centralized electricity generation from the fossil fuels.	Distributed electricity generation with small-scale technologies/devices (such as combined heat power, wind turbines).
One-way flow of electricity from the source of generation to customers.	Secured bidirectional flow of electricity by taking inputs from different renewable energy resources.
Real-time monitoring and controlling is mostly limited to power stations and	Technological advancements such as computing/communication technologies

transmission. Few electric utilities have extended real time control for its distribution systems (Gharavi and Ghafurian, 2011).	that will capture real-time data and provide predictive information about power transmission, substations, distribution grids, and consumptions to better manage the electricity power flow.
Customers' passive participation towards energy savings, and knowledge is mostly limited to electricity bills received at the end of month.	Widespread energy saving policies and programs for encouraging and also to actively engage customers towards energy savings, peak demand reductions, and renewable energy initiatives.
Existing electricity systems have limited operational flexibility and lacks interoperability between different systems and devices (Wakefield and McGranaghan, 2009; Schleicher-Tappeser, 2012). As example, at present it is difficult to inject electricity from alternative resource at any single point in the grids.	High attention is being given to improve the system flexibility by increasing adoption of renewable energy resources, interconnecting the power systems, energy storage devices, and integration of standardized communication and control technologies across the electricity energy systems.

1.3.3: Transition to Smart Grids

The complex setup of electrical energy provision is highly strategic oriented for the economy because it provides electricity through high dependence among entities and it has greatly contributed to our daily life by making many human activities' dependent on this power (Tsoukalas and Gao, 2008). Electricity system being strategic oriented needs to ensure well-advanced preventive measures for its safety and reliability issues.

According to the World Energy Outlook Report of 2010, nearly 70% of Europe's energy sector investments will be focused towards electricity between 2010 and 2035 (IEA, 2010 :pp.230). The trends, discussed above, require transition to modern electricity grids that should be capable of handling: 1) increasing electricity demands, 2) restricting greenhouse gas emissions, 3) diversification in the electricity generations, 4) optimal deployment and utilization of assets, and 5) Secured and reliable supply of energy.

To this end, electricity production through Smart Grids has been advocated a key component in delivering an efficient and low-carbon energy for the sustainable economic infrastructure (Ipakchi and Albuyeh, 2009; Farhangi, 2010). Information and communication technologies would facilitate the transition towards these new grids. It will allow developing a full visibility and pervasive control over the entire electricity supply chain.

1.4: Smart Grids

Existing electric grid infrastructure was designed more than a century ago by using the well-advanced technologies of that time. Those technologies were able to satisfy the 20th century requirements but are not capable enough to meet increasing energy consumptions of the present time with antiquated technologies and aging infrastructure. Accordingly, many nations are planning and investing to bring significant improvements in their electricity infrastructure using the modern technologies.

Inclusion of latest technologies (high intelligence) along innovative market structures (with increased member participations) lays the foundations of smart grids (Siirola and Edgar, 2012). Smart grid is an electricity delivery system that enhances its communication capabilities with sophisticated information technologies. The enhancement in these capabilities ensures highly efficient and reliable grid operations with cleaner environment and improved customer services (Samadi *et al.*, 2010).

There is a growing interest in the development of smart grids and its technologies from the diverse set of fields (like electrical engineering, information technology, economics and sociology) (Coll-Mayor *et al.*, 2007). Investing in the smart grids yields significant benefits including reduced environment impacts, people and communities' empowerment and economic vitality.

1.4.1: Smart Grid Vision – Restructuring from Centralized to Decentralized

Smart Grid vision entails a paradigm shift from centralized electricity network to digitized distributed grid infrastructure. The current electricity network follows a centralized and top-down distribution approach with numerous improvement limitations whereas smart grid infrastructure necessitates networked architectures with the ability to integrate distributed renewable energy resources, which is key requirement to alleviate sustainability impacts.

This new grid design enables the dissemination of new technological solutions (like plug in hybrid vehicles, automated load management strategies) for efficient control and management of electricity grids (like its reliability improvement, transmission loss reductions, disruption and maintenance cost savings) (Giordano and Fulli, 2012). Along this efficiency improvement, it also creates space for the new market players with the establishment of internal energy markets to support smart grid vision.

1.4.2: Defining the Smart Grid – Diverse Views

In simple, smart grid is a two-way communication network for optimizing the generation and distribution of electricity. However, smart grid can be portrayed under two approaches that are distinguished as the European perspective and the U.S.A. perspective.

EU Perspective:

The first approach, provided by the European Commission technology platform, defines smart grid as a network of electricity with the ability to intelligently integrate and coordinate the actions of its all connected users from generators to consumers. Such integration and coordination ensure delivery of sustainable, economical and reliable supply of electricity (EU-Technology-Platform, 2012).

U.S.A. Perspective:

The alternative approach, provided by the United States Department of Energy (US-DOE), does more to specify its objectives, features and the functional characteristics that are more inclined towards safety of the overall system. Under this definition, a smart grid employs different technologies, tools and techniques by which grid can work more efficiently in order to achieve different objectives simultaneously (US-DOE, n.d.).

Combining the above discussed perspectives; the main objectives and characteristics of smart grids includes; high reliability with self-healing capability for power interruptions, consumers participation with effective demand response programs, functions with high resilience to prevent physical and cyber attacks, high power quality in accordance to the needs of 21st century, ability to integrate distributed energy resources and storage devices, creates space for the new products, service and markets, and optimization of assets with high operational efficiency (Giordano and Fulli, 2012; Pipattanasomporn *et al.*, 2009; Gao *et al.*, 2012).

Smart grid is a communication network combined with the electricity grid that enables the management of extensive data communication between transmission, distribution and consumption in near-real-time. Such real time communications becomes the basis for the predictive analytic capabilities of smart grids. Basic principle of the smart grid requires high integration of the information and communication network with electricity infrastructure by which grid can actually become smart (Cisco, 2010).

In views of Wakefield and McGranaghan (2009) several definitions with broad scope are attached to smart grid concept by the authors, depending on their field of expertise. By collating the various dimensions of smart grids, it can be defined as a cost effective electricity delivery infrastructure, enhanced with data communication facilities and information technologies (including technologies that facilitate the efficient integration of intermittent renewable energy resources) to enable more efficient, reliable and secured grid operations with an improved customer service and a cleaner environment (Samad and Kiliccote, 2012; Ramchurn *et al.*, 2011; Gao *et al.*, 2012).

1.4.3: Driving Factors Towards Smart Grids

European Union in its energy policy framework aims to ensure a continued progress towards low-carbon economy. As shown in Figure 1.4, three main factors force to develop competitive and secured energy systems. Such systems would ensure affordable energy for all consumers, security of energy supply, and reduce dependence on the fossil fuels.

Likewise, in the view of strategic importance of electricity, the International Energy Agency has identified five key drivers that necessitate smart-grid initiatives in the electricity network which include 1) increase in demand, 2) diffusion of electric and hybrid vehicles, 3) usage of renewable energy resources, 4) ageing infrastructure and 5) variations in peak loads (Steve *et al.*, 2011:pp.7).

Currently, power grid systems have several limitations such as voltage drops and blackouts, and depreciation of electricity infrastructure with high share of carbon emissions (Gao *et al.*, 2012). These limitations create instability and inefficiency in the electricity system. To make changes in such unstable and inefficient system, smart grid deployment is highly essential by which system throughput can be maximized.

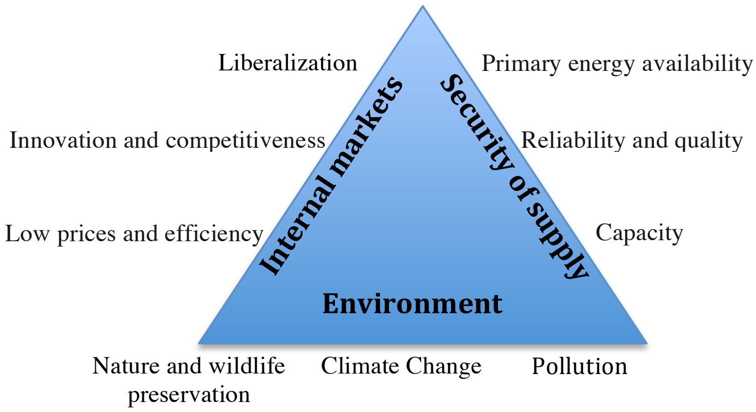


Figure 1.4: Driving factors towards smart grids deployment
(Source: Adapted from EU Commission, 2006:pp.13)

1.4.4: Impacts on Electricity Supply Chain

As discussed above, the deployment of smart grid is not only valuable in terms of bringing environmental sustainability, but it also significantly decreases the pressure on the electricity systems. The implementation of smart grid projects would bring considerable opportunities, potential gains for involved players and over all improvements in the electricity supply chain. Briefly discussing it would have an impact on:

Producers / Generators: With enhanced communication capabilities of smart grids, producers will have a high visibility of actual demand and production capacity flows on the distribution-networks. Control and management with such clear picture of demand provides means of optimizing production resources (Gao *et al.*, 2012).

Transmission Operators / Distributors Network: Smart grids would bring network traffic optimization, reduced downtimes and failures because of advanced fault detections, load management through balancing supply and demand, and monitoring the grid for reduced technical and non-technical losses with smart meters deployment (Clastres, 2011; Depuru *et al.*, 2011).

Suppliers / Utilities: With supply and demand adjustments (i.e. supply/demand-side management), utilities can adjust their offerings and can provide tailored energy services that better suits consumer profiles and their consumption schedules (Frei, 2008; Vassileva *et al.*, 2012; Giordano and Fulli, 2012).

Consumers: Smart grids will provide greater control to consumers for managing their power consumption plans and choices with increased cost reductions. Reductions in the length of outages, improved usage of storage devices and advanced fault detections are among many benefits that consumers will get with their active participatory role towards energy savings. (Gangale *et al.*, 2013; Siano, 2014)

1.5: Demand Side Participations

For efficient and smooth functioning of electric grids, Smart Grid requires highly sophisticated coordination tools and techniques with active participation from all its connected users. Along with the improvements at the supply side (e.g. distributed energy generations) it is also crucial to bring improvements at the demand side (e.g. demand-side energy efficiency). Customers are the integral part of the electricity systems and their active role is a prerequisite for the success of Smart Grids (Giordano and Fulli, 2012; Liu *et al.*, 2011).

Demand side is the totality of the consumers (households and businesses) that directly consume electricity. These end-users contribute by modifying their electricity consumption patterns, which allow efficient management of resources, electricity cost reductions, and contribute towards supply reliability through reduction/shifting the peak electricity loads (Soares *et al.*, 2014). Different programs and strategies are designed to engage consumers as participants in energy savings. This improved management of electricity demand termed as Demand Side Management is discussed further.

1.5.1: Demand Side Management

Demand Side Management (DSM) is a wide collection of various programs designed to improve the electricity energy systems from the consumption side. Electric utility companies implement the DSM programs to control and improve efficiency in the electricity consumption at the customer side (Foley *et al.*, 2010; Mohsenian-Rad *et al.*, 2010). These programs, an essential part of smart grids, induce consumers to lower/shift the electricity usage for energy savings/efficiency.

Collective benefits for utilities and consumers include improved system reliability, efficient resource usage for economic efficiency of electricity infrastructure, less power congestions and transmission bottlenecks, and energy savings with reduced prices (Marwan and Kamel, 2011). Electric power research institute has estimated 45,000MW savings with the implementation of demand management programs in U.S.A. (Walawalkar *et al.*, 2008).

DSM programs targets both short-term and long-term energy-efficiency behaviors/decisions of consumers. Energy efficiency describes using less energy for the same level of output or how much useful work can be done with each consumed unit of energy (Bertoldi *et al.*, 2013). A short-term program induces one time behavior such as purchasing energy-efficient equipment/appliances. Long-term programs are designed to promote repetitive efforts to reduce energy usage (Breukers *et al.*, 2011).

The overall objective is to reduce unnecessary energy consumptions and consumer should make the energy consumption decisions (including timing and quantity) based on the value and the supply of electricity. DSM can take various forms such as programs promoting the energy efficiency, educational programs to increase consumer awareness, and demand response programs. Among these, demand response programs are one of the most popular subgroup of the DSM because they rely on providing financial incentives to consumers.

1.5.2: Demand Response

The demand response (DR) programs (including incentive based and price based) are among the cheaper resources available to prevent system from being jeopardized during the peak load or under congested operations. Under these programs consumers are induced to change the electricity consumption in response to change in electricity prices, or as per agreed contractual incentives to consumers. Implementation of DR programs assist electric utilities to cope with the supply uncertainty in a short term as electricity demand can be redistributed from peak consumption hours to off-peak hours, and also the aggregate demand can be reduced altogether (Kim and Shcherbakova, 2011; Siano, 2014).

Different plans are attached with DR, which broadly can be categorized based on the usage time and incentives. Under the usage time that are time-based programs includes time of use (TOU), critical peak pricing (CPP), and real-time pricing (RTP). Incentives based programs mostly cover direct load controls (DLC), interrupted / curtailed (I/C) loads, demand bidding (DB), emergency demand response programs (EDRP), capacity market demand response, and ancillary service markets (A/S) programs.

According to ISO/RTO Council report, 5% to 15% load curtailment in peak times through demand response programs generate significant benefits in terms of reducing the need of additional resource requirements and lowering the real-time prices (ISO/RTO, 2007). Similarly, during the California electricity crisis in 2000-2001, 5% demand reduction through demand response have resulted 50% price reductions (Albadi and El-Saadany, 2008).

The basic phenomena correlate with the generation costs that ultimately lead to improved system reliability. Because small decrease in demand can cause a big reduction in the generation cost that in turn provides reduction of electricity price. Hence, energy saved during the load clipping can be used at more opportune time (Mohsenian-Rad *et al.*, 2010; Albadi and El-Saadany, 2008).

1.6: Emerging Role of Proactive Consumers

As explained under Demand Side Participations, electric utility companies have adopted various incentive programs for stimulating and facilitating consumers in energy management. Demand side participations can take various forms. However among these, three prominent types of measures (highlighted in Table 1.3) can be promoted through demand management.

Table 1.3: Demand management measures (Source: author)

Measures	Descriptions
Energy Efficiency	Discussed under the **Demand Side Management**, It includes promoting the use of technologies and behaviors that deliver improved energy services to consumers by using less/same level of energy inputs.
Load Management	Discussed under the **Demand Response**, these are the actions undertaken to influence the energy usage time to reduce peak electricity loads.
Distributed Energy Generation	These are the energy generation technologies integrated within the electricity network providing on-site electricity or to nearby local areas. It may also provide other services such as heating and cooling from the waste heat of electricity generation. Examples include photovoltaic panels, combined heat and power systems, and wind turbines.

In most of the DSM and DR practices, consumers play passive role. First, most of the actions are undertaken by electric utilities and consumers have less control over these actions. Secondly, consumers somehow respond passively to the price signals in deciding when and how much electricity should be consumed (AEMC, 2009).

Smart grids' bidirectional flow of energy and information between utility grids and consumers not only creates space for new market players but also acknowledges and encourages active involvement of consumers. Promoting and integrating the distributed energy generations at the customer side are giving rise to new form of user class that is proactive consumers (also known as prosumers). Smart grid framework for energy sharing requires sustainable integration of prosumers. Such role allows them to generate own energy from the renewable energy resources and also share the excess with others including consumers and utility grids.

Prosumers (the combination of producer/provider with consumer) in the domain of smart grids can be distinguished as those energy users who not only consume energy but they also produce energy from renewable energy resources that can be shared among downstream (consumers) and upstream (utilities/distributors) members. Such user class transforms their passive role into the active role in the electricity generation for the long-term sustenance of electricity infrastructure. Prosumers along with their distributed renewable energy inputs can have a significant impact on the smart grid infrastructure (Vogt *et al.*, 2010; Karnouskos, 2011; Schleicher-Tappeser, 2012; Lampropoulos *et al.*, 2010; Nee-Joo *et al.*, 2011:pp18).

Distributed electricity generation empowers small size electricity consumers to become potential producers. The resources of this energy class can be intelligently distributed among the neighborhoods in the community to boost energy efficiency. However, the potential role is dependent on the various factors (ranging from self-interested layer to exogenous conditions) that induce the coordinated efforts of the users (Lampropoulos *et al.*, 2010). Prosumers can be attached in the smart grid energy-sharing framework as a single entity or as a group. Under single-prosumer connection, energy is shared directly among prosumers and utility grids. However, this relationship may not induce effective participation.

Individual prosumers generally have a small capacity to produce the energy for the electric utility. Therefore, they will not have bargaining / negotiation powers to set their own selling price for the electric utilities. On the other side, prosumers in shape of groups are connected to grids. The group members individually produce energy but collectively sell to the electric utilities through auctions. Such aggregation of prosumers is an effective way to achieve the minimum targets of energy production, given by the utilities. However the ad-hoc nature of these groups prevent their long-term sustenance. It may include miss-matched behaviors and huge diversity that force the members to leave the group (Rathnayaka *et al.*, 2011).

Chapter Summary

In the existing electric grid infrastructure, designed more than a century ago, electricity is mainly centrally produced by following the demand. Since it is difficult to store electricity, grid balance is maintained by constantly adjusting the production (from fossil fuels) to demand. To economically fulfilling the demand and to ensure a reliable supply, the electricity industry was restructured, by allowing entry of new participants. However, the increasing energy prices and the environmental concerns require a more sustainable process for production, delivery and consumption of electricity. Alongside, electricity demand is increasing and is expected to continuously increase in the future. Consequently, it requires renewable and distributed energy generations. Smart grids allow efficient integration of distributed renewable energy generations and provide a pervasive control over the entire electricity supply chain. To maintain the grid reliability along providing affordable electricity to all, Smart grids require engagement of electricity consumers. Conventionally, this engagement is sought through promoting the energy efficiency and/or load management programs. Under these programs primarily consumers passively respond to the price signals. However, smart grids' bidirectional flows of electricity encourage the role of proactive consumers. These consumers can actively manage their own demand and can also share the excess with others including consumers and utilities, which in return offer reduced costs and greater independence.

CHAPTER 2: LITERATURE REVIEW

Chapter Abstract

The literature review for this study focuses on the Demand Side Management in Smart Grids. One of the key aspects of electricity grids is to maintain its stability. To this end, electricity supply and demand must remain in balance at any instant. Demand Side Management (DSM) helps to better manage the supply and demand with the support of consumer engagements in tailoring their consumptions. With the deployment of Smart Grids, DSM has taken the new forms for seeking consumers' participations. Along with tailored consumptions, consumers are being induced to actively participate in balancing the supply and demand. The main aim of this chapter is to present the diverse views related to DSM under Smart Grids, with respect to consumers' involvement and their participations. It broadly explores the technical, economic and behavioral perspectives in the demand side management. The chapter starts with the discussion related to necessity and forms of demand side management in smart grids. Then it proceeds with consumers' engagement in demand response programs, being one form of DSM. Further, the chapter discusses about the consumers engagements, required under the increasing integration of distributed renewable energy resources into the electricity grids. Finally, the chapter concludes by discussing about the proactive role of consumers as co-producers of electricity, and their contributions towards balancing the supply and demand.

2.1: Demand Side Management in Smart Grids

Environmental problems, carbon emissions, energy security, and increasing energy demands are among the key issues that are being actively addressed towards achieving the secured, reliable, and affordable energy supply. Accordingly, Smart Grids are conceived as an effective solution against such issues with various advantages. Among different benefits, it significantly improves physical and economic operations of the electricity grids, reduces losses and provides economic benefits to all its stakeholders (Verbong *et al.*, 2013).

Approaching towards sustainable and robust electricity system through smart grids necessitates various improvements ranging from electricity generation to electricity consumption. These improvements are targeted collectively from the technological dimensions as well as from the social dimensions. This collective consideration of smart grid proposes the new philosophy of operating the electricity supply system. In general, the traditional approach refers to supply all electricity demands whenever requested with less consideration towards efficient utilization of the operating system. With the new approach, it suggests that operations reliability and efficient utilization can be enhanced through minimizing the fluctuations at the demand side (Albadi and El-Saadany, 2008; Moslehi and Kumar, 2010).

Maintaining the operations reliability in the electricity system requires absolute, real time balance between supply and demand. Failing to do so can create electricity outages. Achieving this balance is considered as a complex challenge. It is because both supply and demand levels can change rapidly and unexpectedly. This unexpected change may occur from the failures at generation plants, transmission and distribution outages, and unexpected increase in the electricity loads (Albadi and El-Saadany, 2008). To prevent these unexpected changes, additional capacity can be built as a supply backup. However, it may require massive investments because electricity system infrastructure itself is a highly capital intensive.

Demand side management (DSM), also known as energy demand management, aims to better match the demand with the available supply, and it is one of the cheaper resources to manage and efficiently utilize the electricity supply system (Warren, 2014). For the sake of simplicity, we use only the term ‘demand side management’ instead of ‘energy demand management’ throughout this work. By definition, DSM consists of planning, implementing, and monitoring electric utility actions, which are primarily designed to influence and control the consumers’ electricity usage. These electric utility actions are taken to alter the consumer electricity usage that resultantly produces desired changes in the electric utility loads such as load magnitude and its time patterns (Gellings, 1985). Therefore, the main objective for utilizing the DSM programs is to encourage consumers to use less electricity power during the peak loads and/or to shift the usage to off-peak hours (Palensky and Dietrich, 2011; Bello *et al.*, 2012; Di-Giorgio and Pimpinella, 2012).

DSM is an umbrella term that can be broadly categorized into three main types. As shown in the Figure 2.1, these are energy efficiency, demand response, and distributed generation. Energy efficiency programs target to reduce the overall energy demands. Demand response aims to shift electricity consumption during peak-hours in order to balance the available supply with the demand. Distributed generations are initiated for smoothing the load curves to reduce electricity peaks. The primary objective while adopting each category is to engage consumers into the management of their energy usage, which yields mutual benefits for electric utilities and consumers. These benefits can include avoiding expensive generations, supply reliability, reduce outages, and lower electricity costs.

DSM has been considered since 1980s for controlling the electricity usage. However, its adoption for the households is relatively new (Verbong *et al.*, 2013; Gelazanskas and Gamage, 2014). The integration of DSM with smart grid technologies would provide a pervasive control for successful widespread implementation of DSM programs at the domestic levels. At present, consumers are provided with less information related to their consumption and they are not capable of adapting their demand according to price variations (Chao, 2011). Provisioning of this less information is happening because of two primary reasons, which are related to the regulatory and technical perspective. In a regulatory perspective, there is widespread enforcement of fixed regulated prices. These fixed prices do not allow any occurrence of demand elasticity, and it is considered as one of the operational problems in the electricity markets (Bergaentzlé *et al.*, 2014). Secondly from a technical perspective, it has been observed that the lack of advanced metering infrastructure obstructs sending the price signals to the consumers.

DSM programs along with the advanced metering infrastructure will induce consumers to change their electricity consumption practices according to electricity supply availability. Therefore, successful implementation of smart grids necessitates users and households support and their active engagement. To analyze this, next section will review different studies related to the effectiveness of DSM tools, which aim to seek consumers' engagement and participations such as in demand response programs. The review focuses on this aspect because electric utilities and consumers having a direct interaction can actively engage consumers towards changing their energy consumption behaviors and to accept the roll out of smart grids.

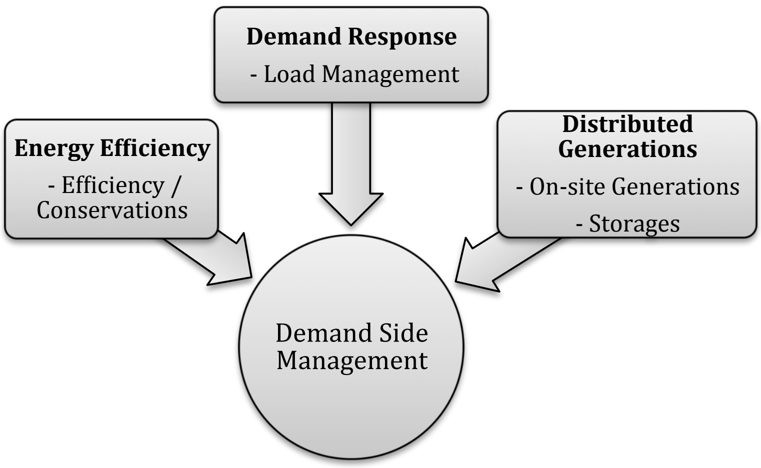


Figure 2.1: Categories of demand side management (Source: author)

2.2: Demand Response and Consumer Engagements

Demand response (DR) refers to the actions undertaken to alter the electricity usage from the existing consumption schedule in response to the changes in prices of electricity over the time or when electric grid reliability is in jeopardy (Faria and Vale, 2011; Fan, 2011; Gelazanskas and Gamage, 2014). In another way, DR are the incentives designed to induce consumers for lowering their electricity usage at times when the wholesale market prices are at the higher side (Siano, 2014). It is worth noting that, in some cases consumers are also asked to increase demand when excess production is available. Demand response helps to reduce or defer the costly investments for the electricity network expansion and in new fossil fuel based generations, by shifting the consumers' electricity loads to the times when excess supply is available and it is less costly to produced.

DR is generally seen as response to the price signals and, therefore, the key element towards DR implementation is the development of information and communication technologies (ICT) infrastructure (Darby and McKenna, 2012). In this regard, smart meters that are widely known ICT development in the electricity systems are the key enablers of the DR. These smart meters are the digital electricity meters that can rapidly and accurately measure and transmit the consumption data. The customer response, towards the electricity usage in the DR, is achieved and controlled by various programs with the support of smart meters. These programs are designed to coordinate the use of electricity as per electricity systems operations.

DR programs are generally classified into two main types that are incentive-based programs and time-based programs (Khajavi *et al.*, 2011). In literature some time-based programs are also termed as price-based programs (Nikzad and Mozafari, 2014). Time-based programs allow consumers to be responsive against the electricity prices they pay during a 24 hours period, and consumers can decrease or shift their consumptions. These programs use the dynamic pricing structure and the price changes following the real-time costs of electricity.

On the other side, incentive-based programs request consumer to reduce their consumption against some specific times, particularly under high price and/or supply constraints. Getting a response against these requests, electric utilities provide incentives to the consumers as participation payments (usually includes a credit bill or discount rate).

Customers, depending on their ability to offer load reductions, can adopt different DR programs. Accordingly, customers participate in different ways to modify their electricity consumption against the selected program. The literature review suggests three possible actions by which consumers' engagement can be achieved in the DR. Each of these actions contains specific benefits, costs, and the measures taken by the consumers. These actions are: (Albadi and El-Saadany, 2008; Aghaei and Alizadeh, 2013; Siano, 2014; Gelazanskas and Gamage, 2014)

- Load Reductions: These are the load curtailment strategies. A consumer reduces the electricity usage, without shifting to other times, during peak hours when prices are high. Consumer may loose some comfort e.g. adjusting the thermostat settings.
- Load Shifting: Under these strategies consumers respond to the higher electricity prices by shifting their consumption from peak hours to the lower cost off-peak periods. Residential consumer may not incur any costs in shifting their consumption, however industrial customers may experience rescheduling costs against their activities.
- On-Site generations: Third category under which consumers can be demand responsive is by using their on-site distributed generations and the storage devices. These customer-owned distributed generations can reduce their dependence on the main grids. Customers may experience no or very small change in their electricity usage patterns; however, electric utilities can significantly improve their load by getting less volatile demand (Valero *et al.*, 2007).

As highlighted by many authors (Siano, 2014; Albadi and El-Saadany, 2008; Aghaei and Alizadeh, 2013; Kirschen, 2003; Chao, 2011), demand response can yield significant benefits for electric utilities and consumers in terms electricity system operations, network expansions, market efficiency, environmental gains, and economic benefits. By reviewing the above-mentioned studies, Table 2.1 presents the potential benefits that can be achieved though the implementation of DR.

Table 2.1: Potential demand response benefits (Source: author)

Beneficiary	Benefits
Electricity Generators	• Help to avoid generation at the peak hours. • Reduce electricity production costs. • Reduce operating reserves for maintaining the supply reliability. Allow more penetration of renewable energy resources for electricity generations.
Transmission and distribution operators	• Relieve the network congestions. • Reduce electricity losses and outages. • Reduce and / or defer investment costs for the network backups and its expansions.
Retailers	• Retailers can avoid risks of demand and supply imbalance. • Benefits from the less price volatility in the market. • New products and improved choices for customers.
Consumers	• Electricity bill savings, lower electricity prices, reliable supply, lower carbon footprints, and improved options from retailers for managing electricity costs.

However, as per literature review, two types of instruments are used to implement the DR, where each instrument differently stimulates consumer engagements in terms of their electricity load reductions. Instruments include informational feedbacks and price-based programs with dynamic prices (McKerracher and Torriti, 2013; Bergaentzlé *et al.*, 2014).

In the informational feedbacks, consumers are provided with the information directly (such as energy display devices) and/or indirectly (such as educational programs for energy conservations), to change their electricity consumptions patterns. Informational feedbacks are primarily not targeted to shift the electricity demands. Rather, these are aimed to increase the overall energy efficiency. On the other side, price-based programs having dynamic pricing structure such as time-of-use prices, critical peak prices, real-time prices etc., seek consumers' engagement in terms of reducing/shifting their electricity consumptions.

Based on these instruments, different studies have been carried out to analyze and quantify the impact of demand response. Each study has highlighted different level of reductions achieved through consumers' engagements. The study of McKerracher and Torriti (2013) has suggested 3–5% energy conservations by providing the direct consumption feedbacks to the consumers. Similarly, Darby (2006) study has argued 5–15% savings by providing direct feed back to consumers. On the other side, some authors (Olmos *et al.*, 2010; Faruqui and Sergici, 2010; Faria and Vale, 2011) have advocated that consumers provide better response to the dynamic prices in the price-based programs. As exemplified, Olmos *et al.* (2010) study has shown 7.3–16.2% peak load reductions by applying the real-time pricing. However, impact of the demand response from the dynamic pricing varies from modest to substantial, which depends on the various factors including prices, demand elasticity, technological factors etc.

2.3: Distributed Renewable Energy Generations and Consumer Engagements

The production and consumption of energy are widely considered as key contributors towards climate change and thus present a core challenge for sustainability (Fuchs and Lorek, 2010; Warren, 2014). According to the International Energy Agency (IEA), approximately 68% of the world's electricity production was carried through burning of fossil fuels in the year 2011, which primarily included coal (41%) and gas (21%). This production significantly contributes towards the carbon dioxide (CO2) emissions and other greenhouse gases. On the other side, electricity consumption is increasing with the increase of national populations, especially in the emerging economies, and with the growing adoption of electrical devices and technologies in the societies (IEA, 2009, pp:19,27; IEA, 2013).

To manage the above-mentioned challenges, electricity production through smart grids is a possible solution for delivering an efficient and low-carbon energy. Smart grids deployment can efficiently accommodate the integration of renewable energy resources (RERs) in the electricity grids. It will allow to diminish the heavy reliance on the fossil fuels and to cope with growing energy demands. However, RERs (e.g., solar, wind) have intermittent and weather-dependent production supply. With this attribute, balancing the volatile electricity demand with the weather-dependent supply will make a more complex challenge. It is considered as a key issue in the shift towards low carbon emitting energy supply systems (Romer *et al.*, 2012; Schleicher-Tappeser, 2012).

To address the fluctuating attribute of the RERs, primarily two approaches can be adopted. These include storing the energy in the storage devices and, secondly increasing the demand flexibility by engaging consumers. Electricity storage can buffer the surplus energy, assist in balancing the supply and demand, and can increase the integration of

RERs without jeopardizing the grid stability (Moslehi and Kumar, 2010). Energy storage systems in a centralized way (connected to grids) and/or decentralized way (stand alone systems) are anticipated, but it is not yet clear which storage systems would be more suitable and economically efficient (Komor and Glassmire, 2012). Moreover, the growth potential of these energy storage systems is much smaller than the storage required to mitigate the demand variability (Moslehi and Kumar, 2010).

The study of Romer *et al.* (2012) suggested that economic applicability of decentralized electricity storage is not yet achieved and will further take years to be beneficial. The technologies and the devices that can be used for the energy storage are currently at the research and testing stages and still too expensive for most of the customers; hence yet not acquired to general use (Gelazanskas and Gamage, 2014; Romer and Lerch, 2010; Warren, 2014). Electric Vehicles (EVs) can also be used as decentralized electricity storage devices. But Giordano and Fulli (2012) argued that diffusion of EVs has so far fallen short of expectations. Also stakeholders are in a deadlock situation for the EVs' mass-market penetration; where customers are particularly waiting for the cheap and long-range EVs.

Consumers' participations at the demand-side could also help to effectively deal with the fluctuating attribute of the RERs. To do so, demand flexibility need to be increased by engaging consumers. Demand flexibility refers to shifting the consumption to the time when there is available supply and/or electricity production costs are lower. In this regard, consumers, through their energy management systems – equipped with advanced information and communication technologies – can create a temporal flexibility for their electricity consumptions. The energy management systems can provide a better control to consumers for realizing the flexible consumption.

Different studies have shown that, energy management systems with suitable controlling strategies for consumers can seek their active participations and can tailor their energy consumptions. The study of Becker *et al.* (2012) demonstrated that home energy management systems having an interactive monitor panel, enable residents to manage and control their energy consumptions according to supply conditions. Similarly, Molderink *et al.* (2010) proposed a three-step control methodology for a group of consumers under the presence of distributed generation and storage. Di-Giorgio and Pimpinella (2012) have designed an automated control strategy for the efficient management of electric energy in the domestic environments. Results shown that consumers can gain significant benefits with the use of local energy management systems, which centrally control the energy usage of home appliances. Vytelingum *et al.* (2010) study has favored the use of micro-storage energy devices for consumers. They claimed that consumers participating in terms of their storage profile optimization can allow them to better control energy consumptions and can save up to 13% on their electricity bills.

The efficient operations of electricity power grids require a perfect balance between electricity supply and the demand of all consumers at any instant. Currently, the grid operators and the electricity providers are only performing this task of balancing supply and demand. One of the aspects of the smart grid vision is to involve consumers and seek their active participation towards balancing problem of supply and demand. With the implementation of sophisticated intelligent information and communication systems, consumers are able to play active role in the management of their energy usage. The active participation of consumers will be an essential element for the smart grids deployment, and it is likely to bring many benefits for the stakeholders involved in the electricity supply chain.

To highlight the consumers active participation towards balancing supply and demand, Vasirani and Ossowski (2013) have proposed a consumer load balancing model. In their work, group of consumers share their estimated electricity demands to a market mediator, who buys electricity from the market. Results shown that coalition of consumers gain economic benefits from their participations. Similarly, the study of Vinyals *et al.* (2012) have shown that consumers participation in a coalitional energy purchasing results in a higher consumer gains. In the above-discussed studies, consumer participation is based on the coalitional groups that are mainly dependent on third parties, whereas consumers may also actively participate without depending on the market mediators.

2.4: Empowering the Proactive Consumers

Smart Grid vision entails a paradigm shift from centralized electricity network to digitized distributed grid infrastructure. This transformation will be necessary: to comply with the environment protection goals, to seamlessly integrate the RERs, distributed energy generations and storage capabilities, and to accommodate the greater emphasis on the demand-side management with active participatory role of consumers. Hubert and Grijalva (2011) have specified that consumers' active participation can be created with dynamic pricing policies, providing access to real-time information and controlling on the electricity usage, and the deployment of technologies (such as advanced meters and on-site distributed energy generations).

Smart grid enables the bidirectional flow of energy and information between the consumers and the utility grid. It will allow consumers not only to consume electricity but also to share the excess with the utility grid and other consumers. End-users are expected to shift their passive role 'as consumer of electricity' to 'proactive consumers' (also termed as prosumers). It suggests that the transition of passive role of small-size consumers towards a more active role in the electricity generation and distribution. In the smart grids literature, it has been often suggested that consumers are willing to play a more active role in the management of electricity supply and demand, and are able to also become producers (Schleicher-Tappeser, 2012).

Advancements in the technologies for emerging renewable energy systems allow consumers to become producers of electricity such as with the installation of residential photovoltaic solar systems. As households are able to locally produce the renewable energy, governments and private sectors are increasingly trying to involve residential consumers in the management of electricity supply and demand under smart grids (Belhomme *et al.*, 2008). Honebein *et al.* (2011) have argued that people within the smart grid are the only aspect that can be truly smart. In other words, consumers should be engaged and empowered, allowing them to accept their new role as active contributors in balancing the supply and demand of electricity in smart grids.

Gangale *et al.* (2013) in their study have reviewed different European Union smart grid projects to understand how consumers are engaged. They have argued that turning consumers into active energy users requires their engagement, which is dependent on building the trust and motivation. However, in their study, active participation is limited to improving the consumer energy efficiency. Extending this participation perspective towards active contribution, Geelen *et al.* (2013) have studied about the available products and services that can empower energy end-users to become co-producers (prosumers). Different products (such as micro-generators) and services (such as dynamic pricing) can have a different impact on co-producers (consumption / production) behavior. Therefore, in designing products and services co-producers interactions and behavioral perspective should be considered.

Based on the smart grid infrastructure, Karnouskos (2011) has explored the prosumer interactions and their contributions in the context of energy market places. He has suggested that prosumers resources (such as their electricity production through photovoltaic panels, and electricity storage through electric vehicles) could intelligently be distributed in the consumers' neighborhood that can yield significant economic as well as environmental benefits. Additionally, integrating the (residential/commercial) prosumers flexibility into the energy markets can assist seeking the equilibrium between supply and demand. Vogt *et al.* (2010) have studied the potential of a small office environment as a commercial prosumer-based participation in the smart grid. The results have shown that prosumer participation can assist in peak shedding of electricity consumptions.

Literature review suggested that prosumers can be integrated into the smart grids as individual prosumer and/or group of prosumers. Rathnayaka *et al.* (2011) have argued that prosumers coalitions could be arranged and integrated into the smart grids on the basis of similar interests and behaviors. They have termed such coalition as a goal-oriented community. However, in their study, they have grouped the prosumers only on the basis of similar technical capability (e.g. prosumers having same production capacity of photovoltaic panels). Apart from the integration perspective, the potential role of prosumers is dependent on the various parameters ranging from behavioral factors to exogenous conditions.

Some authors in the literature (Rathnayaka *et al.*, 2011; Rathnayaka *et al.*, 2012; Lampropoulos *et al.*, 2010) have mapped the factors that can influence behaviors and the management of electricity prosumers. Internal parameters of prosumer behaviors can broadly be categorized on the basis of personal domain (e.g. beliefs, values), behavioral domain (e.g. consumptions patterns), and contextual domain (e.g. demographic status). Exogenous conditions can greatly influence the behavioral parameters and can include many different factors. To exemplify the exogenous conditions, it includes government jurisdictions, policy and regulations, technical infrastructure, and energy market structures. However, literature review suggested that there is still lack of approaches in the prosumers management and their control. It can be exemplified with the suitable methodologies that can seamlessly integrate prosumers and consumers into a network perspective for locally balancing the energy supply and demand.

Chapter Summary

To maintain the electric grid stability, electricity supply must remain in balance with its demand in a real time. In the traditional approach, electric utilities have been asked to increase the supply capacity to meet the rising demands. Increasing the supply capacity with extensive usage of fossil fuels can be very costly and has negative impacts on the environment. Demand Side Management (DSM) works in another perspective; instead of adding more production capacity, energy users are asked to reduce their consumptions. Application of DSM in the electricity smart grids brings significant economic, environmental, and reliability benefits for both electric utilities and consumers. Literature review suggested that strong focus is being given on engaging the consumers in various DSM programs under Smart Grids. However, technological issues and economic incentives are dominant, such as development of automated energy management systems that can enable consumers to monitor and control their energy consumptions.

In particular, main focus in consumer engagement is providing them the consumption feedbacks for efficient energy use and/or their load scheduling controlled by external mediators. It may be argued that sophisticated technologies are required as key enablers of consumers' engagement, however, promoting the technological perspective alone may not yield active participations. Moreover, different studies have assumed that consumers demand flexibility can mainly be enticed with financial benefits. Along with financial benefits, consumers demand flexibility can also be increased by providing platforms that can empower them to act as co-producers of electricity. Some studies have started giving attention on empowering the consumers to become co-producers of electricity (i.e. prosumers). However, the literature review suggested that the management of proactive consumers is mostly overlooked, and thus requires different approaches and methodologies to motivate and manage the contribution of proactive consumers.

CHAPTER 3: RESEARCH METHODOLOGY

Chapter Abstract

This chapter starts by discussing the problem statement covering the main issue that need to be addressed. Following the problem analysis, the objectives of research are deliberated. Based on the literature review performed in the previous chapter, the research gaps are identified and discussed further. Accordingly, the research questions for this study are presented. Next, the research design and methodology of the thesis are presented and described. At the end of the chapter, it concludes by highlighting the boundaries of this research work.

3.1: Problem Statement

Electric utilities adopt the DSM techniques to optimize the power flows in the networks. This electricity load management is primarily initiated under specific circumstances such as to maintain economic/market stability, environmental stability, and network stability. Mostly in all these cases, consumers are requested to reduce/shift their consumption while providing them different incentives (Aghaei and Alizadeh, 2013). Normally, under DSM programs, utility companies take most of the decisions and actions, while consumers have little or no control. Contrary to this, engaging consumers in actively managing their demand with distributed renewable generation can provide more flexibility and stability to the power systems (Di-Giorgio and Pimpinella, 2012).

Traditionally in centralized electricity generation systems, supply side is responsible for maintaining the system flexibility by adjusting supply in real-time to match load requirements. However, it will be more difficult to manage constant supply under decentralized systems with renewable resources integration. Active participation of users, connected to the electric grid network, will become a fundamental requirement in maintaining the system balance between production, demand and inbuilt grid constraints (ETP-SmartGrids, 2012). This participation will not restrict them to be a demand side stakeholder; rather, it will allow them to be involved at the supply side as well. Hence, there is a strong need to exploit and efficiently utilize the demand flexibility (through consumer engagements) towards the provision of sustainable energy.

In this regard, Smart Grid implementation recognizes the required actions and interventions of various actors and stakeholders both at production and consumption side, in pursuit of sustainable developments. Consumer engagement is widely acknowledged, and their actions are central towards the accomplishment of Smart Grid goals. It has also been argued that people within the Smart Grids is the only part that can become truly smart (Honebein *et al.*, 2011). Therefore, consumers should be involved at the earlier development stage of Smart Grids, and they should be provided better choices to manage their demand. Providing better choices and services through smart girds require substantial collaborative efforts between utilities and their connected customers.

Extensive knowledge is available explaining the various opportunities for improving sustainability in the electricity production and consumption systems, with the involvement of various actors and consumers. Nonetheless, some authors have argued that in many cases the transformation of this knowledge into action is somehow less explained and this knowledge-to-action gap is more prominent in the case of consumers (Fuchs and Lorek, 2010). Similarly, various research studies have been performed explaining the pros and cons of different renewable energy resources and their usage in the residential / domestic purposes. However, under the collaborative arrangements, there exist a wide gap in terms of how these renewable energy resources can be integrated for the composition of electricity supply in the residential/domestic environments.

3.1.1: Research Aims and Objectives

Responding to above-discussed problem statement, the main goal of this research study is to analyze the impacts of integrating the various renewable energy resources (RERs) in the collaborative network. Along with this goal, the main objective is to explore the role of different participants in the collaborative network under the domestic/residential environment. This study focuses on the residential sector / small consumers equipped with photovoltaic panels (renewable energy resource) because of the following justifications:

Statistically: Residential sector is the third largest in European Union (EU 28 states) after transportation and industry and in Italy it is the 2nd largest final energy consumption sector after transportation sector (EU Commission, 2013, pp:52). Therefore, residential sector is expected to provide additional demand flexibility under the renewable energy generation mix.

Technically: Industrial and domestic energy users are subject to different rules and regulations. Industrial users have to forecast their renewable energy production capacity and this information has to be provided to electric utility in prior. Accordingly, small consumers are less constrained where prior information is not necessary because of less quantity. Secondly, based on the size and skills, industrial consumers have to deal with less market barriers compared to small consumers. Therefore, they are already possibly active in demand side management (He *et al.*, 2013). On the other side, in decentralized electricity generation more flexibility is required at the local level (Verbong *et al.*, 2013); and many small consumers connected to the distribution network can make up higher flexibility.

Renewable Energy Resource – Solar Power: Among different types of renewable energy resources, solar power is extensively used as renewable energy in some regions because of its abundance (Wee *et al.*, 2012). Photovoltaic systems are extremely scalable without having any impact on its efficiency, have a high reliability, have no moving parts, do not require fuels (Schleicher-Tappeser, 2012), and are easy to be deployed in domestic environments.

3.2: Research Gaps

Collaborative effort between utilities and consumers in the energy perspective is not limited to asking consumers and their communities for reducing/shifting energy consumptions. It is rather a process for changing consumers' perception and having their commitments towards energy sustainability. In this regard, provision of mutually beneficial collaborative platforms is required and essential to ultimately support and deliver the benefits of the collaborative consumption.

Accordingly, literature review suggested that endeavors for collaboration between electric utilities and consumers are generally limited to involving consumers for the participation in the DSM programs, particularly related to demand response. More specifically, the importance and utilization of proactive consumers in utility-consumer collaboration is mostly overlooked. Therefore, analysis of the literature review has identified that most of the research work in Smart Grids is mainly dominated towards the following aspects:

- In overall perspective, technological advancements and its economic benefits are the key research aspects. To highlight, studies have been focused towards developing the electricity system architectures and designing the market platforms for financial incentives (with software agent operations) (Al-Agtash, 2013; Bel *et al.*, 2009; Wang *et al.*, 2008; Lamparter *et al.*, 2010; Leloux *et al.*, 2012; Gao *et al.*, 2012).

- In consumers' perspective, main focus has been towards providing the consumption feedbacks regarding real time consumption and energy prices and / or load scheduling of home appliances (in centralized and decentralized way) (Simone *et al.*, 2013; Vytelingum, 2011; Vytelingum *et al.*, 2010; Ramchurn *et al.*, 2011;

Molderink *et al.*, 2010; Lamparter *et al.*, 2010; Mohsenian-Rad *et al.*, 2010; Faria and Vale, 2011).

- In different studies, consumers are treated as an entity that is asked to change the consumption patterns by enticing them with financial incentives only (Mohsenian-Rad *et al.*, 2010; Gottwalta *et al.*, 2011; Hubert and Grijalva, 2011).

- On the other side, few studies have considered the consumer collaboration that is limited to collective purchasing. More importantly, this collective purchasing is solely dependent on the third party, where consumers actually do not actively participate in managing their own demands (Vinyals *et al.*, 2012; Vasirani and Ossowski, 2013).

To summarize the above, this research work distinguishes from others as discussed further. The research work deeply focuses on the proactive consumers collaboration in energy demand management. We primarily considered the prosumer and consumer organization, interaction, and their collaboration towards energy sustainability in a holistic way, which is mostly overlooked in the research studies. This holistic approach can help in shifting the consumer energy demand towards collaborative consumption and it can also assist in improving the energy supply side.

From this point of view, we have analyzed and proposed the key requirements that simultaneously addressed may transform consumers from passive electricity users to more active consumers in managing their demand. Further, for improving the supply side, we have also demonstrated that the required presence of the proactive consumers in the social context (community) could facilitate consumers' engagement with electric utilities.

3.3: Research Questions

Considering the above research gaps, this research is focused on the exploration of the demand side flexibility with the support of proactive consumers. In our understanding, a collaborative approach implies influencing and managing the consumers demand among the group of proactive consumers, to achieve a predefined service level (i.e. demand satisfaction) and their energy costs. However, this participation requires changing the consumption patterns and having different nature of demand to be participatory. From this perspective, the following research questions are addressed in this research study:

3.3.1: Research Question 1:

How can we define smart demand and what are the key determinants?

- This question answers what is consumers' smart demand, why it is required and how it should be managed for their active participation.

3.3.2: Research Question 2:

How can growing smart energy demands be met efficiently through consumers' active participation?

- In order to answer this question, we develop a community energy-sharing model to describe a collaborative platform for a group of proactive consumers. We solve this model mathematically with linear programing approach.

3.4: Research Design and Methodology

This study starts by reviewing the state-of-the-art research within smart grids to understand the consumers' role and the importance of their engagement towards energy sustainability. For having such review, we mainly covered the research studies related to sustainable consumption, consumers' participation in sustainability, energy sustainability, electricity supply chain, electricity markets, smart grids, energy demand management, and related issues. This review process assisted us to frame the problem statement and to define our research goals and objectives. The complete research design, visualized in the **Figure 3.1,** is discussed next.

Devising the research goals and objectives lead us to develop the research questions. To address the **First Research Question**, we conducted an extensive literature review to evaluate the demand side participations in the electricity supply chain. In the literature review process, we used the keywords to draw the limits; key words mainly include demand-side management, smart grids, consumer engagements, consumer participation, consumer demand response, micro grids, electricity users, energy users behaviors, energy management systems, and renewable energy resources.

Based on the keywords, we reviewed the various research papers focusing on the consumer engagements and participations towards energy demand management. Through the analysis of the extensive literature review, the research gaps are identified. Accordingly, we developed a theoretical model, which provides answer to our first research question. It also explains how consumers demand should be managed and influenced for their active participation towards energy sustainability.

With the support of theoretical model, the first research question also addresses the key issues and challenges that potentially can obstruct consumers' participation in the collaborative arrangements. These identified challenges are related to consumers' internal parameters and also the external factors that can directly and / or indirectly affects the participation levels. Internal parameters covers the behavior related factors such as consumer awareness level, lifestyles, and their practices etc. On the other side, external factors (exogenous conditions) include technologies, infrastructure, and government policies etc.

To address the **Second Research Question**, we transformed the theoretical model into the analytical model. The model explains about the energy sharing among group of consumers. The analytical model is further classified into various energy sharing scenarios. These decision models are designed to deeply analyze consumers demand flexibility in different collaborative environments. Our analytical model is a discrete mathematical model and subsequently the decision models are formulated using the Linear Programming.

We adopted a quantitative research methodology to numerically explain the impact of consumers' contributions towards energy demand management. The selection of quantitative research methodology and particularly the development of analytical (i.e. mathematical) model assisted us to demonstrate the consumers' engagement and their demand flexibility based on the proposed theoretical model. It also facilitated us to explore the integration of prosumers and consumers in a network perspective, and how their contributions are affected in different collaborative arrangements with the addition of external entities.

To solve the mathematical model, we used General Algebraic Modeling System (GAMS) with CPLEX optimizer, because of its full license availability at university. After initial solution, the model is extended by using Python for two primary reasons. First, it helps to verify the computing efficiency of the model. Secondly, it helps to perform the design of experiments for detailed evaluation and analysis. Python is a computer programing language that assisted us to write our own programming code and to develop the script. This language was chosen because of the familiarity and also it frequently uses English keywords, which makes the programming code readable.

For the evaluation and analysis, we tested and validated our model through a historical data obtained from an Italian company in a health-care industry. The results are deeply analyzed according to the proposed energy decision models along with the theoretical support. As a future extension of our work, we presented a detailed discussion for developing the consumer control strategies in energy demand management.

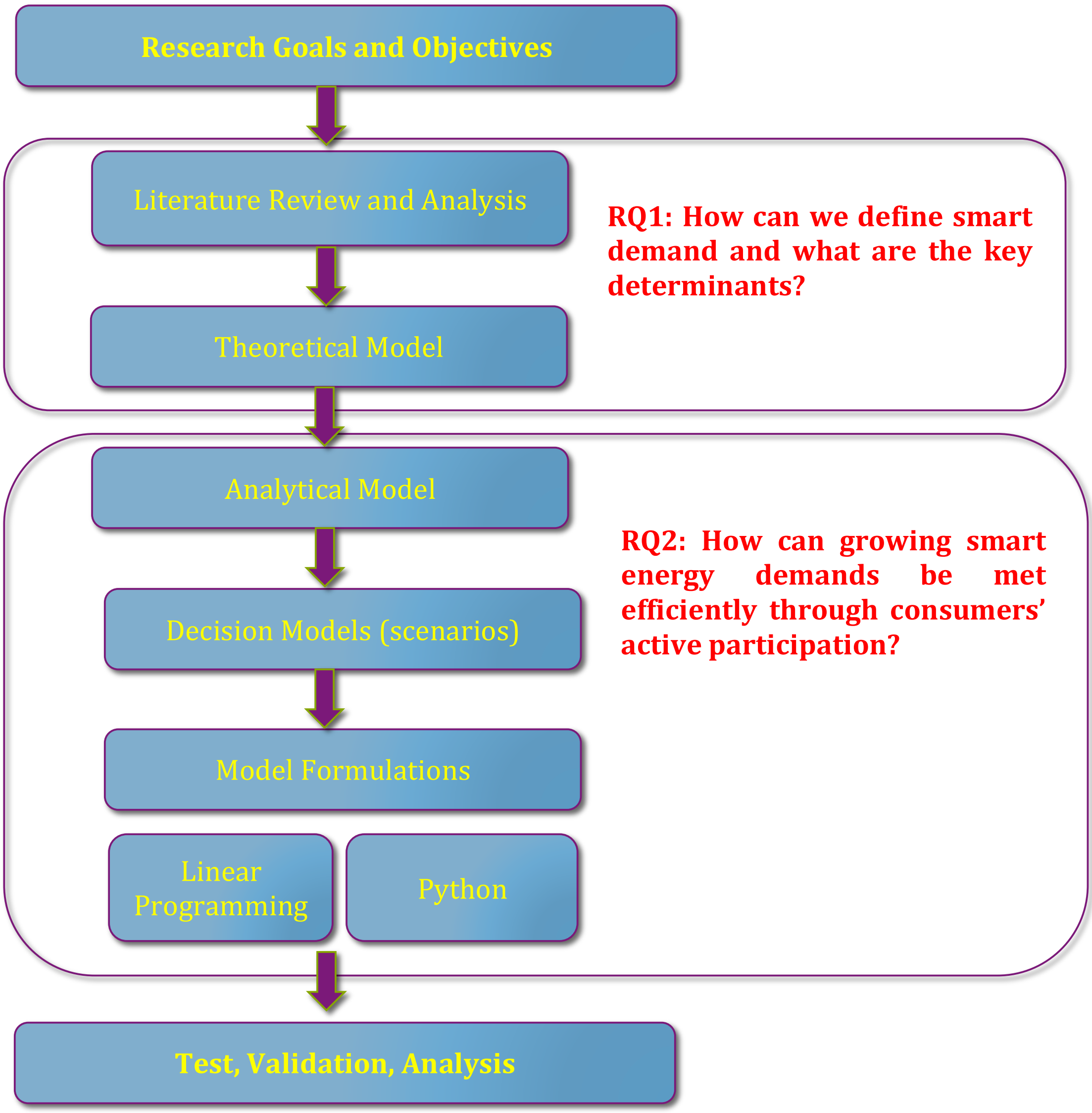


Figure 3.1: Research Design (Source: author)

3.5: Research Boundaries

The research study has following main boundaries:

Demand-Side Activities:

This thesis focuses on energy management as electricity use and its demand under the domestic/residential environment. It primarily includes demand side activities. With this focus, analysis is limited to demand side management without considering the supply-side improvements.

Behavioral interventions:

Research study demonstrates the proactive consumers participations (in terms of their demand flexibility) towards energy sustainability in the collaborative environments. Proactive participation of consumers can depend on internal parameters (behavioral issues) as well as on external parameters (exogenous conditions). Also, both set of parameters are identified and explained while answering the first research question.

Regarding the analytical model formulations to answer the second research question, the study would not consider further the impact of behavioral interventions. It is because this thesis is based on the electricity supply chain management approach, which is more focused towards understanding and evaluating the technical and economic dimensions in the network perspective. Therefore, the social dimension is not considered, as this research is focuses towards studying the network perspective of consumers and prosumers integration. Considering the social dimension (such as personal and behavioral domain) may have some impact in the different collaborative arrangements.

Chapter Summary

One of the Smart Grid goals is to ensure reliable operations of the electricity system through perfectly balancing the supply and demand. This balance is not easily achievable because both supply and demand levels can frequently as well as unexpectedly fluctuate due to number of reasons such as generation unit outages and sudden increase in the electricity loads from the demand side. Moreover, balance will be more difficult to achieve with the increasing share of variable renewable energy resources into the electricity networks. Therefore as a cheaper resource for system operations, equal consideration is being given to involve consumers for increasing their flexibility and changing their perceptions towards energy consumption. In this perspective, most of the work has been focused towards seeking the consumers' response to the electricity prices only.

However in addition to above, focus should also include providing consumers adequate collaborative tools and platforms that can increase the capability of their response. Presence of collaborative platforms can allow them to proactively manage their demand by having more choices. Therefore, in this regard the *First Research Question* addresses how consumers demand should be induced and influenced to have their active participation in the collaborative environments. The *Second Research Question* demonstrates how their demand flexibility (i.e. response) in the social context (community) can be beneficial for them. For this, we developed an analytical model to evaluate and analyze the benefits and costs of proactive participation in which consumers give up some of their electricity consumption. The model is mathematically solved through linear programming.

CHAPTER 4: SMART ENERGY DEMAND MANAGEMENT

Chapter Abstract

The smart grids implementation ensures to bring profound technological, economic, and environmental improvements in the existing electricity system. Along with these improvements, pervasive information and control technologies of smart grids will also influence the households' daily routines. Consumers would play a vital role towards smoother operations of electricity systems through demand side management, energy storage, and distributed energy generations. The extent to which consumers are engaged and are encouraged to be an active player would have a considerable impact on the smart grids success.

This chapter provides the answer to the first research question that is "How can we define the Smart Demand and what are the key determinants?" For this consideration, the chapter starts by discussing about the changing consumption preferences and the required engagement of consumers. Next, the chapter talks about how the demand resulting from the collaboration environment differs and therefore, it define Smart Demand and its dimensions. Enabling intelligent technologies along with encouraging social nature of consumption in mutually beneficial collaboration platforms can foster consumers' active participation towards smart grids. For such explanation, smart demand for energy demand management is deliberated to highlight the importance of proactive consumers collaboration. Integrated consideration of smart demand dimensions based on the collaborative arrangements is explained. Finally, the chapter concludes by explaining the key determinants / challenges to the smart energy demand and its possible remedies.

4.1: Changing Preferences and Required Measures at Demand-Side

Cultural, social, and economic factors are increasingly transforming the consumption patterns, shifting the consumers' behaviors from a mere individual attitude to satisfy the personal needs to a more collaborative process. This collaborative process with involved consumers is resulting in a sustainable value creation encompassing the economic, environmental, and social developments (Nuttavuthisit, 2010). Sustainable consumption has become a core issue on the environmental agenda of many nations and thus, government institutions are increasingly paying attention to sustainable consumption to achieve more sustainable development (Seyfang, 2007). With this growing motivation in promoting the sustainable consumption patterns, individuals are more conscious of their role in their communities, and are aware that their direct and collective participation can affect the current and future life of their society.

Conversely, many sustainability strategies and corporate social responsibility (CSR) practices mainly address environmental aspects (Berns *et al.*, 2009), neglecting the impact of global over-consumption (Sheth *et al.*, 2011), and overlooking the role of the consumer and the societal involvement (Huang and Rust, 2011). Moreover, European consumer policy mainly assumes that consumer is a rationally acting individual who is competent to deal with the provided information to take rational decisions (Gangale *et al.*, 2013). The explanation suggests that consumers are mostly considered as an individual entity towards changing their consumption patterns. Whereas, the collective dimension of consumer behavior i.e. in a societal context is largely set aside and studies suggests that behavioral change should occur at collective, social level (Jackson, 2005).

Dealing with sustainability challenges finds its roots in a shift of mindset towards the achievement of more efficient consumption patterns. A holistic approach, accompanied by shared norms and values and adequate technologies, is required to effectively deal with the current challenges posed by the sustainable development principles. For this, consumers (and their communities at large) should be explicitly encouraged to be directly engaged through a more participative and collaborative behaviors, factually realizing a collaborative consumption strategy. Collaborative consumption, a technology enabled sharing of goods and services, is one of the ways to initiate consumer engagements accompanied with community involvements. The studies of Allcott (2011) and Huijts *et al.* (2012) have highlighted that societal dimension (i.e. community involvements) can assist shaping the consumer behaviors by engaging them. As an example, considering the community energy comparison (social norm information) in shaping the consumer behaviors can induce people to preserve energy, leading to improved social and/or environmental conditions.

Considering the above discussion, it can be argued that consumers should be encouraged and engaged towards efficient consumption patterns (for their sustainable consumption). Also, this consumer engagement should be unfolded in a broader societal perspective. Considering this perspective would assist:

- Developing a more collaborative platform to satisfy the individual needs
- May have a profound impact towards consumers' active participation

It can be supported with the argument of Breukers *et al.* (2013), who have stated that individual behaviors are deeply ingrained within the societal processes and people learn much from their immediate environment. Also, this contextual (societal) domain influences the consumers' behavioral domain in different attributes including cultural, social and economic factors (Lampropoulos *et al.*, 2010), leading to satisfy the individual needs through a sustainable collaborative process.

Consumers (along with their communities) engagement provided by properly designed collaboration platforms would increase the possibilities for producers and consumers to establish a mutual collaboration. This consumer-producer collaboration would seek equilibrium between supply and demand both in time (e.g. finding a customer when products are available, finding suppliers when demand upsurges) and space (e.g. finding a supplier close to a customer, or vice versa). As a result, the demand resulting from a collaborative consumption process differs substantially from the traditional forms of demand as usually conceived.

To summarize, changing the consumption patterns, moving towards a collaborative and sustainable process involving different participants, with distinct requirements and interests, requires a completely new approach to demand management. Under this premise, the nature itself of the demand changes, requiring a different connotation. Therefore, we refer to such a demand with the term Smart Demand. In this regard, this chapter answers the *First Research Question* that is **"How can we define Smart Demand and what are the key determinants?"**

4.2: Defining the Smart Demand

In views of Thomson and Perry (2006), collaboration is a process of combining the personal choices/preferences into the collective choices. The implementation of these shared preferences is carried out through a self-interested bargaining. Accordingly, collaborative consumption is a collaboration process in which participants have a shared access to products or services, through self-interested bargaining (as opposed of paying more to own products or services). This collaboration process is often enabled by information and communication technologies. Economic pressures, environmental concerns, community considerations, and technological innovations are among the main drivers of collaborative consumption.

The demand resulting from a collaborative consumption process differs substantially from the traditional forms of demand as usually conceived. Therefore, the term Smart Demand is considered as a simple yet comprehensive term expressing the main characteristics of the demand signal expressed in a collaboration environment. In this environment, the individual demand can be shifted in time and/or compensated through other participatory efforts of the community. The "smartness" of the demand depends upon the smartness of the actions undertaken to reduce/shift/redistribute its profile under the collaborative systems by considering the mutual gains. As shown in the Figure 4.1, **three main dimensions** are envisioned along which smart demand is contextualized.

In the next sub-sections, dimensions necessity and importance are discussed, explaining its support to the smart demand.

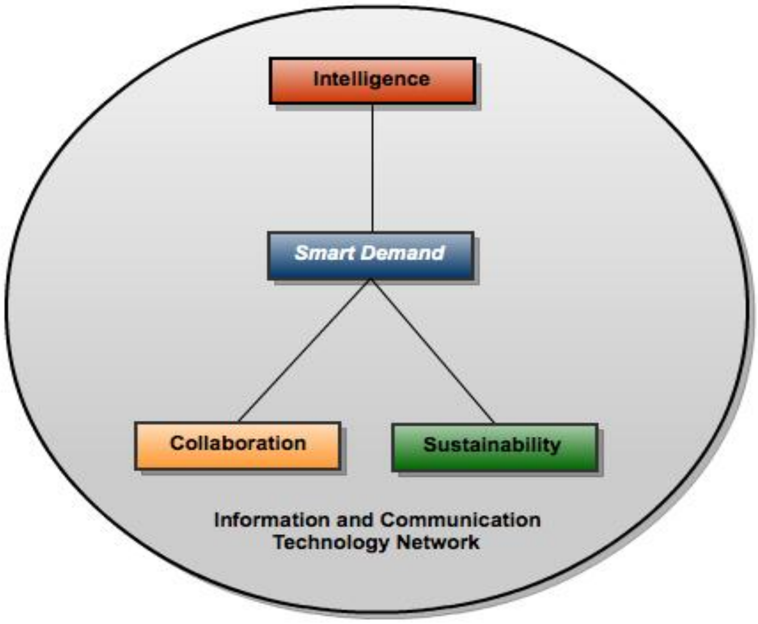


Figure 4.1: Smart demand tripod (Source: author)

4.2.1: Sustainability

Consumption and production, together, can be considered as a source of all stress on the natural environment originated by humans. This stress on the environment can be exemplified with the production wastes, generation of pollution, natural resource depletions etc. To reduce this stress, strong focus is required to incorporate sustainability both at the production and at the consumption side. In this regard, sustainable consumption refers to the consumption of goods and services to fulfill human needs along better quality of life. This has to be done by minimizing the depletion of natural resources, reduced toxic materials, wastes and emissions over the life cycle of products and services; so that the needs of the future generations cannot be endangered (Zhan *et al.*, 2010).

Conventionally, most of the attention has been given for promoting the sustainability design for production and its related impacts. These sustainability designs were primarily targeted to promote sustainable methods to tackle engineering related issues such as to minimize the production wastes. Alongside, the sustainability design trends have been shifting towards promoting those technologies and products that play a significant role for moderating the over all consumption level and its concerned impacts, such as promoting the use of energy-efficient products (Thorpe, 2010).

Moderating the consumption requires understanding about consumers and their behaviors. To have such detailed understanding, different research methods and the ways of approaching users are being adopted from multi-disciplinary fields. To exemplify, behavior-based approaches (based on cognitive and environmental psychology) towards sustainability includes applying the persuasive product designs and intelligent technologies. These product designs and their technologies have a clear influence on consumers' behavior and increasing their awareness towards sustainable consumption (Scott *et al.*, 2012).

However, a systematic and holistic approach to address the social nature of consumption is still lacking in the user-centered and behavior related design efforts. In view of this, there is a growing interest in accommodating the social-technical dimension towards consumption by applying social practices in the technical-design process (Scott *et al.*, 2012). Social-technical dimension considers that technology and humans are conjoined, where they are influenced by each other and are developed in cooperation.

To tackle the issues related to social and systematic nature of consumption in sustainability efforts, designers are adopting practice-oriented designs (Lilley, 2009; Azapagic *et al.*, 2006). In simple understanding, practice-oriented designs help in shifting the focus from products to practices. Practice-oriented designs facilitate consumers' engagement in terms of their resource intensive behaviors over resource efficient behaviors and technologies (i.e. assisting consumers towards their sustainable consumption). Practice-oriented designs and innovations can be exemplified with car sharing as an alternative mode of transportation.

Influencing consumers' behavior in a social dimension enables them to develop an active perception of their required engagement towards sustainable developments (Schweizer-Ries, 2008). Moreover, Heiskanen *et al.* (2005) have argued that consumers must be engaged in the development and assessment of the technologies for sustainable consumption. Their resistance can otherwise hinder the implementation, and resultantly can hamper the accomplishment of sustainable development goals.

4.2.2: Collaboration

The changing dimensions of social and economic developments necessitate the modification and restructuring in the consumption patterns as not only what we are consuming but also how we should consume (Brokaw, 2011). To push society towards more sustainable path, disseminating eco-efficient services are considered to be more viable rather than products only (Bartolomeo *et al.*, 2003). Such services can be exemplified with collaborative consumption aiming towards the shared use of products or services.

Collaborative consumption is a technology-enabled sharing of goods and services with a mindset of lesser/efficient resource usage to bring sustainability through customer-centric approach. Such mindset of lesser/efficient resource usage induces the creation of shared values that requires enhanced arrangements of collaborations (Porter and Kramer, 2011). Botsman and Rogers (2010) have conceptualized the collaborative consumption as a system of organized dissemination of products and services including sharing, swapping, trading, lending, renting and so on.

Adopting such consumption patterns, people gets the ownership benefits with less personal burden, cost savings and lower impact on environment, hence showing more captivating alternative to standard and traditional buying and ownership styles. Collaborative consumption focus is not limited to the communal use of products and services, but the primary objective is to promote and encourage the active role of consumers towards sustainable communities. These communities (either new or existing) collaborate to foster the sustainable development in different sectors such as infrastructure, mobility, energy, waste, and food (Rae and Bradley, 2012).

Consumers, as well as their communities, need to be empowered with adequate collaborative platforms to play their dynamic role towards sustainable developments. For such platforms, three primary systems are created that are redistribution markets, collaborative lifestyles, and product service systems (Brokaw, 2011; Dillard, 2012). To achieve vast cultural and commercial implications, a trust and user experience plays a vital part in the collaborative platforms (Porter and Kramer, 2011).

The consumers' participation in the collaborative platforms can yield benefits in all sustainability dimensions. To characterize the benefits, shared usage of resources reduces the excess consumption and resultantly lowers consumption impacts on the environment (such as reduced wastes). Consumer participations in the collaborative platforms also generate social benefits including improved quality standards, improved health conditions, employment generations, and sense of community. Economic benefits includes such as new products/service innovations, more choices to consumers and financial incentives.

4.2.3: Intelligence (through products and systems)

Intelligent products, smart objects, and smart products are often associated to each other in the literature, and Meyer *et al.* (2009) have described that these terms can be used interchangeable. Likewise, concept realization of smart products also varies according to the number of terms used to describe or relate to them (Lopez *et al.*, 2012). Accordingly, in this research study, smart products and intelligent products are used as interchangeable.

McFarlane *et al.* (2003) have defined intelligent products as the products that are able to represent physical and information based identities. Smart products can be defined as the products having the following characteristics (McFarlane *et al.*, 2003; Meyer *et al.*, 2009; Lopez *et al.*, 2012):

- Have its distinctive identity.
- Sensing and storage ability towards measurement of systems i.e. it can sense and store measurements with its associated sensors and transmitters.
- Have an ability to identify and sense other relevant attributes of external entities, such as weather conditions, location identifications, etc.
- Can have an interconnection and communication power with other smart objects.
- Have a decision power i.e. they can make the decisions about themselves and external objects.

Meyer *et al.* (2009) have discussed about the literature perspective of the intelligent products and categorized the intelligent products according to three main classifications. These classifications help in evaluating their prominent features, limitations and future potentials. These include (as shown in the Figure 4.2) location of intelligence, level of intelligence and aggregation level of intelligence.

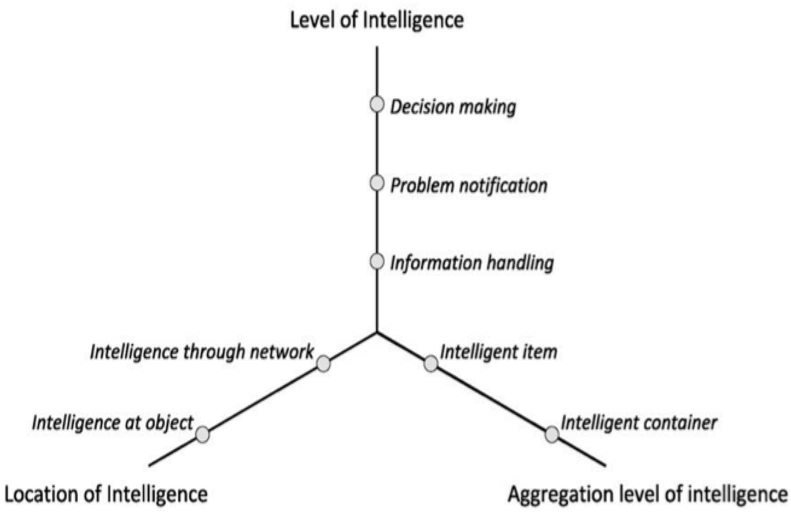


Figure 4.2: Product classification according to intelligence (Source: Meyer *et al.*, 2009)

The goals and benefits of the intelligent products are context dependent. They can be employed to specific contexts such as in manufacturing managing the supply networks, and also for managing the consumption side. *From a consumer perspective:* smart products and services can assist consumers in using the collaborative platforms and can help them to analyze their demand and consumption patterns. Presence of such products automates the repetitive tasks and assists consumers in decision-making procedures, helping them to manage their consumption (i.e. how much should be consumed) (Meyer *et al.*, 2012).

From a system perspective: smart products and services will provide producers / suppliers higher visibility over the demand side (such as for planning process) and will enable a better demand management. Higher visibility allows sensing the demand shifts and acting accordingly to reduce the impact of demand variations. Producers / suppliers can better adjust their capacity constraints with the support of consumer engagements, enabled through intelligent products and systems in the collaborative platforms.

4.2.4: Summarized Discussion

Following points can summarize the discussions made in the dimensions (Sustainability, Collaboration, Intelligence), and help us to demarcate the term smart demand onwards.

- **Sustainability:** should be socially contextualized as a matter of social practice towards sustainable consumption. It may help to directly engage consumers (along with their communities) in pursuit of sustainability at a broader societal perspective.
- **Collaboration:** a process of shared value creation would be better assisted with the properly designed collaboration platforms. These platforms should be designed based on the mutual gains and trusts between producers and consumers.
- **Intelligence**: through instrumentation, automation, infrastructure, play an integral role in enabling a collaborative platform for the system and flows integration. These technological solutions should be designed by providing more control to consumers (e.g. more control over own energy usage).

4.2.5: Smart Demand Definition

Collectively considering the dimensions along with its key points, help us to define the term Smart Demand as:

> **"Smart Demand is a sustainable collaborative demand received through embedded product / system intelligence, under the network of information and communication technology"** (Tariq *et al.*, 2013).

Such a demand, with adequate support of information and communication technology network and smart/intelligent objects, provides the sensing ability to observe the collaborative demand shifts/variations.

Smart demand interpretation visualizes the implementation of intelligent systems for the demand compensation in such a way that yields mutual gains and trust in collaborative platforms. These platforms equipped with smart/intelligent products at customer side enable the transparent access of demand information, which is essential to get the sustainable collaborative demand. To get this right information and to act timely are favorable from consumer point of view (in terms of their sustainable consumption) and also for manufacture / producer perspective (in terms of sustainable production).

4.3: Smart Demand for Energy Demand Management

Energy sustainability has a key influence in the domain of sustainable developments. It requires a shift from the traditional energy resources towards renewable ones such as wind, solar energy, biomass etc. All such renewable energy resources, without producing emissions, support the energy sustainability. Electricity generation through Smart Grids is a key element towards delivering an efficient and low-carbon energy for the sustainable economic infrastructure (Samad and Kiliccote, 2012; Gao *et al.*, 2012). Smart grid implementation facilitates the incorporation of decentralized and fluctuating renewable energy resources along with the effective management of electricity supply and demand towards achieving the energy sustainability.

Smart grid assists in reducing the excess load burdens on the electricity grids by managing the electricity demand and supply (Ramchurn *et al.*, 2011). Smart grid facilitates the development of sophisticated collaboration tools and intelligent techniques, so that its connected members can actively participate towards managing the excess electricity load burdens. With the technological support, electricity supply and demand can be adjusted through effective demand side management (DSM) programs and with the efforts of proactive participants.

DSM programs are designed to reduce and manage the electricity loads in the situations such as emergency and / or under high production costs. Normally under these programs, consumers play passive role because most decisions (actions) are taken (performed) by utilities, and consumers have little or no control (Belhomme *et al.*, 2008). In contrast to this, consumers can play dynamic role as proactive consumers, provided availability of such intelligent collaborative energy systems that induce their active participations towards achieving the energy sustainability. Intelligent collaborative energy systems may refer to the presence of alternative renewable energy systems and energy markets where proactive consumers play central role for its sustenance.

In this manner, smart grid concept supports the functioning of such energy systems that accommodate the integration of proactive consumers (prosumers). Proactive consumers can contribute to the energy generation through their own systems (such as solar photovoltaic systems for electricity generation), and share the excess with other consumers and utility grids. In this regard, prosumers (the combination of producer with consumer) user class transforms their passive role into the active role towards electricity generation. Their active role would facilitate the long-term sustenance of electricity infrastructure (Vogt *et al.*, 2010; Karnouskos, 2011). Strong presence of prosumers along with their active roles can assist their neighborhood to fulfill the energy demands, supporting utilities to manage peak load reductions (Karnouskos, 2011).

Achieving sustainability through proactive consumers is dependent on the creation of sophisticated intelligent collaborative platforms. Under these platforms, connected users harmonize their combined efforts to fulfill their energy demands, leading to energy autonomous prosumer communities. Energy autonomy or energy self-sufficiency refers to the ability of the energy system where it functions through its local generation, storage and distribution systems without taking the energy inputs from the external sources. This reaps numerous benefits such as secured supply, energy cost reductions and less carbon emissions associated with the particular region and / or community (Rae and Bradley, 2012).

Smart grid intelligent tools and techniques (such as advance electricity metering infrastructure) would enable the collaborative platforms, allowing consumers to have more choices in managing their consumption through alternative sources. With improved customer services, consumers can better manage their electricity usage, storage, and its sharing. To achieve the true capability of smart grids bidirectional flow of energy and information between utility grids and users, consumers (along with their communities) need to be encouraged for their involvement. It is projected that consumers' contributions towards energy efficiency (through demand side management and renewable resources) will comprise from one-third to one-half of total smart grids benefits (Heffner, 2011).

Efficiency in energy sustainability refers to the curtailment in energy consumption without following the reductions in energy supply. However, it also caters the changes in the energy consumption by considering the alterations (in the lifestyle and alternative production resources) (Schweizer-Ries, 2008). As discussed in the smart demand definition, adopting the social nature of consumption, shitting from product-based approach to a practice-oriented approach (for collaborative systems) can also significantly strengthen these alterations in the energy consumption.

Seeking energy sustainability in a broader societal perspective with the support of proactive consumers empowers energy sustainable communities. To narrow down this broad concept, energy sustainable communities (ESCs) are the communities that opt for the renewable energy over traditional sources (fossil based) and seek to realize energy efficiency (Schweizer-Ries, 2008). Achieving the sustainability targets in a larger social context with the support of proactive consumers requires consumption modification along-with socially connected community efforts. This community effort stimulates sustainable consumption as a social sustainable practice, leading to sustainable behaviors.

Therefore, consumers should be encouraged for their active participation towards achieving the sustainability targets (with mutual gains consisting of economic, social and environmental benefits) through collaboration (creating the demand flexibility) with the help of intelligence (as intelligent products and systems). This vision illustrates that *demand of energy is becoming a sustainable collaborative process*, involving different players with distinct requirements, where all the connected members collaborate to get the mutual benefits in terms of their sustainable energy consumptions.

By this explanation, smart demand for energy demand management is envisioned as a tripod of sustainability, collaboration and intelligence (as shown in the Figure 4.3). Increased level of collaboration along with intelligent tools and techniques can demonstrate improved efforts towards sustainable developments. The figure is further explained and discussed under the integrated considerations.

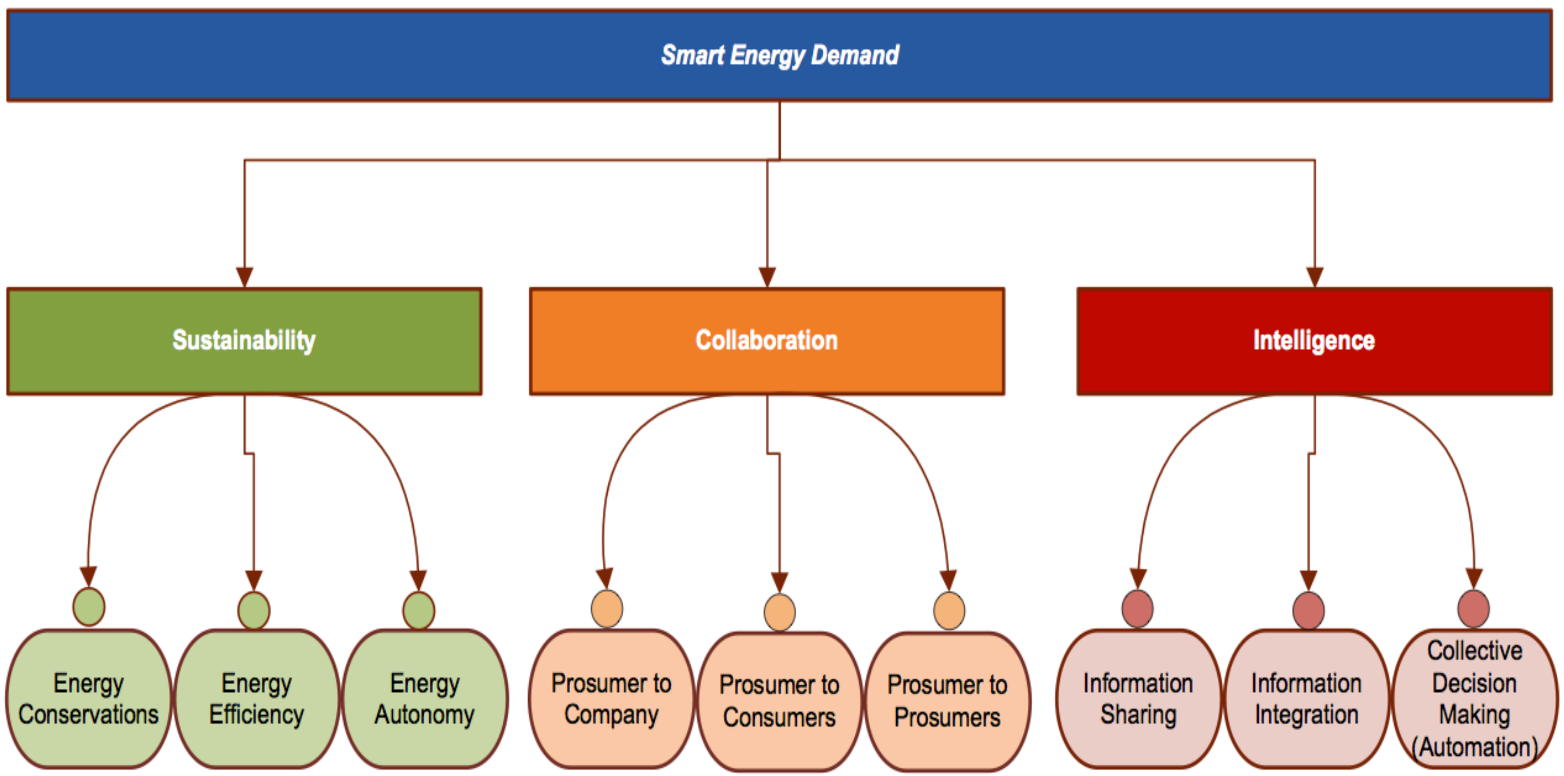


Figure 4.3: Smart demand for energy demand management (Source: author)

4.4: Integrated Consideration of Smart Energy Demand Management

Enabling the end-users participation as electricity prosumers in the platforms such as deregulated energy marketplaces requires the infusion of network intelligence (through systems and products). Such network intelligence can facilitate prosumers to optimize their energy consumption and / or production. Literature review has suggested that prosumer management domain is mostly overlooked in the smart grids research studies, and it requires a careful consideration to foster the long-term development for the grids infrastructure.

As more and more consumers enter into the dynamic prosumers domain the more significant impact they can have on the smart grid infrastructure. It can be exemplified as if a large network of prosumers having distributed renewable resources halts their energy inputs to their vicinity. In such case, it can intensify the electricity load burdens on the utilities and in worst-case utilities may not be able to fulfill the whole demand of consumers without the support of prosumers input (Rathnayaka *et al.*, 2011). In views of Vogt *et al.* (2010) grid becomes smart when all endpoints contribute to its operations. Whereas, endpoints should not be restricted only to generators but it must also include electricity end-users (like consumers and prosumers).

Along with the tripod vision of smart demand for energy demand management, the collaborative arrangements in the energy context are strongly intertwined with the expected level of sustainability. Depending on the contributions, pro-active consumers integration through their smart energy demand can have different implications for managing the energy demand that are discussed further in Table 4.1.

However, detailed implementation of smart demand management into a specific system model requires its extensive analysis in terms of tangible as well as intangible factors. Tangible factors can include such as pricing, and incentives etc. and intangible factors can be exemplified such as behavioral, cognitive, and motivational factors in consumers' collaboration towards energy consumption and sharing. As per literature analysis, most work related in this perspective overlooks the comprehensive analysis and hence partially comments these dimensions (sustainability, collaboration, intelligence) in collective way as a consumers' participation towards electricity peak load saving strategies.

Consumers are primarily motivated for their collaboration by emphasizing the environmental benefits alone. A recent survey conducted by Gangale *et al.* (2013) have highlighted that, most of the European smart grid projects use environmental concern as a primary motivational factor to seek consumers engagement. On the other side, the work of Vinyals *et al.* (2012) and Vasirani and Ossowski (2013) have focused only on the collaboration as a collective energy purchasing by overlooking the consumers proactive participation and other determinants such as behavioral factors in creating the demand flexibility under energy sharing perspective.

Table 4.1: Energy demand management through smart demand (Source: author)

Collaborative arrangements	Integrated considerations
Prosumer to company	Prosumers collaborate with electric utilities through their energy demand information sharing and having a detailed feedback on their energy consumption. It will allow them to have a better control on their energy flows through their distributed generations. This controlling can help to avoid consumption during peak hours, being beneficial for prosumers (as savings) and for utility (as low production costs). Both foster the sustainability as energy savings / conservations.

Prosumer to consumers	Prosumer to consumers' collaboration seek energy efficiency (i.e. efficient usage of energy and / or opting alternative supply sources). For such demand side management participants integrate the network information (e.g. prosumers supply constraints) into their decision making towards consumption alterations.
Prosumer to prosumer	Collaboration for demand side management by involving and promoting the role of prosumers in the network perspective. This prosumers network aiming to provide incremental capacity of the supply side may lead to energy autonomy. It requires intelligent automation systems that enable fully autonomous decision-making against diverse self-interests.

4.5: Challenges to Smart Energy Demand

Smart grids provide greater control to consumers for managing their electricity consumption with increased cost reductions. Reductions in the length of outages, improved usage of storage devices and advanced fault detections are among many benefits that consumers will get with their active participatory role. Long-term sustenance of the new grid infrastructure requires a strong collaboration from all its connected members, particularly a strong emphasize is being given on collaborating with the consumers as demand side management.

Smart energy demand management is consumers' sustainable collaboration which range from collaborating with company to the more advanced collaboration of prosumers networks with the utilities. However, different factors can contribute towards shaping the smart energy demand patterns. Based on the extensive review of literature, key factors ranging from self-interested layers to exogenous conditions that may impact consumers' smart demand are discussed in Table 4.2. Comprehensive consideration of these factors, into specific system modeling, may induce prosumers and consumers to use the collaborative platforms with intelligent tools for their sustainable prosumption and consumption respectively.

Table 4.2: Challenges to smart energy demand (Source: author)

Smart energy demand		
Intervention	**Challenges**	**Possible remedies**
Sustainability	Investment costs regarding renewable energy resources, storage devices and system implementation costs can create hindrance for the participation towards energy efficiency.	There must be a government support through their policies and subsidiaries against the investment costs for the technologies and equipment. Ramping up the sustainable developments through mandatory community targets can also induce consumers required participation.
	Consumers limited knowledge regarding their energy usage patterns, its sustainability impacts and electricity market knowledge can lead to slow adoption of sustainable collaborative demand patterns (Bel *et al.*, 2009).	The coordinated policy efforts through educational along advertising efforts can help to promote consumers sustainability awareness level and their market knowledge. Set of regulations regarding mandatory community efforts towards energy efficiency goals can help to influence and shape social behaviors towards energy efficient consumptions patterns. Community involvement should be encouraged through strong social and economic benefits, which eventually increase community pressure on the consumers and can intervene individual behaviors and routines (Breukers *et al.*, 2011; Kim and Shcherbakova,
	Embedded social practices, lack of societal pressures, consumer habits, skills and opportunities, lack of self-efficacy awareness level, and sense of responsibility (Breukers *et al.*, 2011) can lead to poor participation.	
	Consumers' satisfaction towards existing electricity	

	services does not allow them to pursue sustainable change in their demand patterns.	2011). Energy audits can also be linked towards community and individual sustainability efforts. It may force consumers to actively participate and collaborate in the prosumers network for their energy demand from sustainable sources.
Collaboration	Non-availability of tools that can induce and help consumers to evaluate their demand flexibility against technical and economic benefits and costs (Bel *et al.*, 2009). Inappropriate incentive pricing mechanism and feed-in tariff to pay back the efforts, and poor synchronization of collaborators' self-interests also act as key determinants.	Highlighting only the environmental benefits may not induce consumers for their active participation. There must be convenient intelligent tools that can clearly depict technical benefits (such as appliance loads reductions) and economical benefits (such cost benefit analysis). Attractive feed-in-tariff schemes would also stimulate prosumers for using and producing renewable energy.
	Electricity market structures, legislative, administrative and regulatory barriers can suppress the consumer participatory efforts.	Restructuring of electricity markets increase the market competition (Bel *et al.*, 2009). The increasing presence of prosumers and their networks can mitigate the potential power of the supply side agents. Market entry barriers should be eliminated through increased deregulation, which eventually promotes market innovations and gives more choices for consumer participations.

		Moreover based on the societal and structural differences, market strategies (promoting local energy markets establishment) should be designed in accordance to such differences rather than looking for an uniform market strategy (Samad and Kiliccote, 2012; Giordano and Fulli, 2012).
	Consumer response fatigues and required attention to individual products / electrical appliances could also have adverse impacts on demand shifts and lead to poor participation.	These issues can be rationalized with the wide spread of the intelligent techniques at the product (electrical appliances) as well as at the system level (i.e. connecting them either in centralized way such as home area networks or in a decentralized way such as appliances taking autonomous decisions according to their environment).
	Information security and data privacy concerns can impede the required trust among participants for the collaboration. Moreover, such unauthorized access of data can also hinder successful implementation of collaborative platforms (Giordano and Fulli, 2012; Verbong *et al.*, 2013).	Distributing the intelligence at the consumer side is required for their active participation. However at the same time, consumers should be given more control over own energy usage and they should have freedom in selecting the nature, timing, and the amount of data they want to share in the collaborative arrangements.
Intelligence (products and systems)	Lack of user-friendly technologies can otherwise foster high participation and willingness to collaborate with others in the network.	Technologies help to automate the processes and assist consumers to perform the tasks with minimum required efforts. The user-friendlier these technologies are, the less

		efforts (minor knowledge background) are required to actively participate.
	Lack of energy information feeds regarding price and consumption, poor and costly access of information, and overload of information with it's required processing efforts are among those factors that creates hindrance for the consumers and their active participation.	It is argued that if consumers can see the shape of their consumption patterns and its sustainability impact, they may be able to change their consumption behavior (Kim and Shcherbakova, 2011). Provide cheaper and balanced information access. Seeking electricity usage and price information with the real-time information feeds through in house display devices can effectively reduce costly access of information and can encourage consumers to create flexibility in their demand patterns.
	Lack of technologies that can monitor real time detailed electricity usage and supply patterns assisting consumers to create flexibility in their demand patterns.	
	Technology costs and their financing options (such as smart meters). Without such technologies consumer participation is not possible. These cost barriers can obstruct and limit the effective participation (Kim and Shcherbakova, 2011).	Government and utilities partnerships play central role for reducing the technological infrastructural costs. Financing options offered by governments against the consumer collaborative efforts could greatly assist consumers to reduce carbon footprints in their communities. Rebates, discounts, cost-sharing agreements may promote consumers willingness to actively participate in energy sustainable communities.

Chapter Summary

Smart grids through its technologies will connect the entire electricity supply chain from generation to consumption. Attaining the different benefits against the investments of smart grid technologies requires increased collaboration among the connected members of electricity supply chain. Particular strong emphasize is being given on collaborating with the consumers to seek their active participation towards smoother grid operations. Active participatory roles necessitate a shift of mindset towards efficient consumption trends. Changing the consumption trends through the dynamic role and proactive participation of consumers and communities can have a significant contribution towards sustainable development. Concurrently, there is a growing interest for shifting the consumption trends towards collaborative consumption. An application of collaborative consumption is not limited to the communal use of products and services, but more importantly it can be another way of sharing the responsibilities among consumers and their communities towards sustainable path.

Smart grid technologies would provide intelligent techniques and collaborative platforms. It would allow consumers to better manage their consumption through the collaboration in terms of creating a possible flexibility in their demand patterns, resulting a smart demand. It rationalize that consumption process is becoming a sustainable collaborative process where individual demand can be shifted in time and/or compensated through other participatory efforts (such as prosumers in the community). By this, smart demand is a tripod of sustainability, collaboration and intelligence. This tripod of the smart energy demand has an organic unity among them that harmoniously contribute towards it. Certainly consumers' smart energy demand has different challenges that range from self-interested tangible factors, intangible factors, to exogenous conditions. Comprehensive consideration can remove the hindrance towards consumers' active participation in the collaboration arrangements.

CHAPTER 5: DECISION MODELS

Chapter Abstract

The previous chapter has discussed about the Smart Demand and its consideration for Energy Demand Management. It has also been explained in the previous chapter, that consumers should be encouraged for their active participations towards energy sustainability along with the provision of mutually beneficial collaborative platforms. Accordingly, this chapter focuses on the second research question that is "How can growing smart energy demands be met efficiently through consumers' active participation?" To address this research question, the chapter presents the Decision Models aiming to facilitate the active participations among groups of consumers in a collaborative environment.

The chapter starts by justifying the necessity of proactive consumers collaboration and the need to develop an analytical model. Subsequently, an energy-sharing model is presented to demonstrate consumers' active engagement towards energy sustainability at their community level. For this, the model is categorized into three main cases, where each case includes different scenarios having certain restrictions for community members. These cases are designed / formulated to represent the proactive consumers participation towards energy demand management, and this participation depends on their level of collaboration. The chapter concludes by formulating all the cases along with its scenarios into the linear programming optimization model.

5.1: Necessity of Proactive Consumers Collaboration

The challenges and issues for the future electricity grids arise from both sides of the electricity supply chain. At the supply side, increasing integration of the distributed renewable energy resources (RERs) into the electricity grids is emanating two significant challenges. First, these RERs have less stability for the provision of electricity because of the fluctuating nature of the resource. This fluctuation occurs on daily and also on the seasonal basis, leading to increased electricity power and frequency volatility on the electric grid (Moslehi and Kumar, 2010; Verbong *et al.*, 2013) Secondly, an increase in distributed generation will also introduce issues related to the reverse electricity power flow from the generation unit (MIT, 2011). These reverse flows originates from the surplus of solar, wind, or any other RERs, when demand is particularly low.

On the other side, increasing attention is turning towards managing the demand side. It is because of the fact that in the future, use of electricity (as a form of energy) will increase with the electrification of various activities, processes, and products (Ramchurn *et al.*, 2011; Lampropoulos *et al.*, 2010). It can be exemplified with the extensive usage of heat pumps for space and water heating powered by electricity, and also mass diffusion of electricity vehicles (EVs).

In the European Union, residential sector accounts for 25% of total electricity consumption (EU Commission, 2013, pp:62). This figure is expected to double by the year 2030 (Hansla *et al.*, 2008). According to the World Bank, electricity consumption per capita in Italy was measured at 5,393 kWh (Kilowatt hour) for the year 2011. With the addition of EVs, this electricity demand of the household is expected to be approximately double on average (Samadi, 2010). Resultantly, the more and more features of the home are electrified, the more significant peaks of electricity loads are expected.

In summary, existing grids are being challenged with the electricity power and frequency volatility (caused by RERs) and with the production capacity constraints (caused by increasing electricity demands and peak load variations). Additionally, the grids itself currently rely on the ageing infrastructure including the transmission lines and distribution systems. In this regards, Smart Grid ensures an effective solution to tackle these challenges with the shift from demand driven generation systems to a more supply driven generation systems. Currently production of the generation system is always adjusted according to the changes at the demand side (i.e. demand driven). Contrary to this, electricity demand (and its consumption) will be modified according to the production of the generation system (i.e. supply driven) (Meyer *et al.*, 2012).

The transformation, where demand should follow supply, introduces the need of local generation where supply and demand should be more locally balanced. Moreover, it also requires active involvement of consumers where they can contribute by lowering (and/or shifting) their consumption. Their active involvement can assist in mitigating the supply variability, peak loads, expensive generations, and also facilitate in locally balancing the supply and demand. As highlighted by Neely *et al.* (2010), coupling the supply variability with the demand-side flexibility (consumers inputs) can help to mitigate RERs generation variability along with expensive system backup investments.

With the support of smart grid systems, responsibility of providing reliable and uninterrupted electricity power does not only rely on the producers, but now it is also being shared with the consumers by seeking their proactive participations. The incremental capacity building for the supply side can be extremely expensive for the utilities (Kim and Shcherbakova, 2011). Concurrently, reliability issues (such as supply constrains) could also be effectively sought out with the strong emphasis on the demand side management by involving and promoting the prosumers network.

To increase the consumer participations, some of the renewable energy resources (such as photovoltaic panels) will be directly installed at the end-user locations, transforming their passive role to active contributors (i.e. prosumers). Smart grid technologies for distributed energy generations will empower prosumers to integrate their energy consumption and generation into the energy networks. Prosumers can share the excess supply capacity with others including consumers and electric utilities. Managing the demand side by combining the prosumers flexibility along with their local energy resources is highly anticipated. Depending on the incentives, the efforts of proactive participants can help to reduce supply side agents' market power with improved market operations. Active demand side participation would likely to improve consumers demand flexibility, as they will be provided with more choices to fulfill their demand (Bel *et al.*, 2009; Karnouskos, 2011).

The future smart grids will have a distributed nature of operations; where the coordination of energy consumptions will become the highest priority. Smart grids' two-way flow of the electricity and data, to and from prosumers, will require a new form of coordination mechanisms, (collaborative) service designs, and social processes (community interactions). Accordingly, the vision of community grid energy system that mostly relies on local energy resources is gaining acceptance. In this new form of social innovation, consumers owning renewable energy resources will be allowed to integrate their production into their local grid.

However, successful implementation of this collaboration process requires efficient coordination mechanisms, aiming to assist members in their decision-making process for optimal energy consumption and production. The efficient coordination mechanism among the group of prosumers can enable them to create and operate local marketplaces for trading energy between the community members. Accordingly, by considering the above-discussed benefits and the necessity of proactive consumers collaboration, the next section will describe the coordination mechanism for community based energy-sharing. Different proposed decision models could facilitate in improving the prosumers and consumers' engagement towards their community, as well as with the electric utilities.

5.2: Energy Sharing Model

By considering the importance of the proactive consumers and their active role in the smart grids, we envision the energy sharing among the group of consumers at their community level. The framework presents an energy-shared community network model that optimizes the energy sharing through Smart Energy Demand Management.

In other words, this energy-shared community strikes for the balance between service levels (i.e. demand satisfaction) and costs of the network, considering the alternative energy resources. It suggests seeking out the efficient means of energy distribution so that members can meet their maximum energy demand with the available resources of renewable energy in the network, and resultantly acquires less energy from the power plant.

We consider groups of consumers, referred to as communities. Community includes consumers (which consume energy) and proactive consumers (which both produce and consume energy). Proactive consumers (also termed as prosumers) integrate renewable energy resources (in our case, photovoltaic panels that do not require specific planning activities, decisions and cost for turning them on and off) into their premises. Renewable energy resources allow the prosumers to generate own electricity, theoretically store it for their later consumption, and share the excess with others in the network.

Consumers can fulfill their energy demand from the resources available within their community that are prosumers and community aggregator. Community aggregator is a third party agent that can act as a broker between two communities, and can buy electricity collectively for the community members. The main role of the aggregator is to aggregate consumers' demands and to decide how to fulfill the demands from internal sources (prosumers in the other communities) and the electric utility. With this aggregation, both aggregator and community members will share the profits in the community network. Energy demand is specifically assumed as electricity requirements.

Our work has introduced the role of aggregator for managing the local energy generation and consumption. In the literature, the role of aggregator is limited to a mediator between electricity customers and electricity market. Likewise in practice, electricity energy aggregation is only for the large business customers in Italy and, currently aggregator for the residential environment does not exist (Chimenti, 2010). However, we assume that in the future the aggregator activities would be extended to the residential environment. Therefore, we have considered the aggregator role to analyze the importance of this new actor in managing the renewable energy supply and demand among the group of proactive consumers in a residential environment.

In addition to buying electricity from prosumers and aggregator, community members can fulfill their demand by using the energy being supplied by external sources (electric utility company). Figure 5.1 provides a visualization of the network consisting of communities, an aggregator, the electric utility and the power grid.

RERs (such as solar power and wind energy) have intermittent energy supplies (being sensitive to weather conditions). With this fluctuating attribute of RERs, it is more difficult to completely fulfill the electricity demand under all situations (Ibrahim *et al.*, 2008; Ramchurn *et al.*, 2011). Therefore, it is important to control the energy consumption as per electricity production, storage, and its distribution under the presence of renewable energy resources. This controlling can be achieved by reducing/shifting/redistributing the demand profile under the collaborative systems by considering the mutual gains.

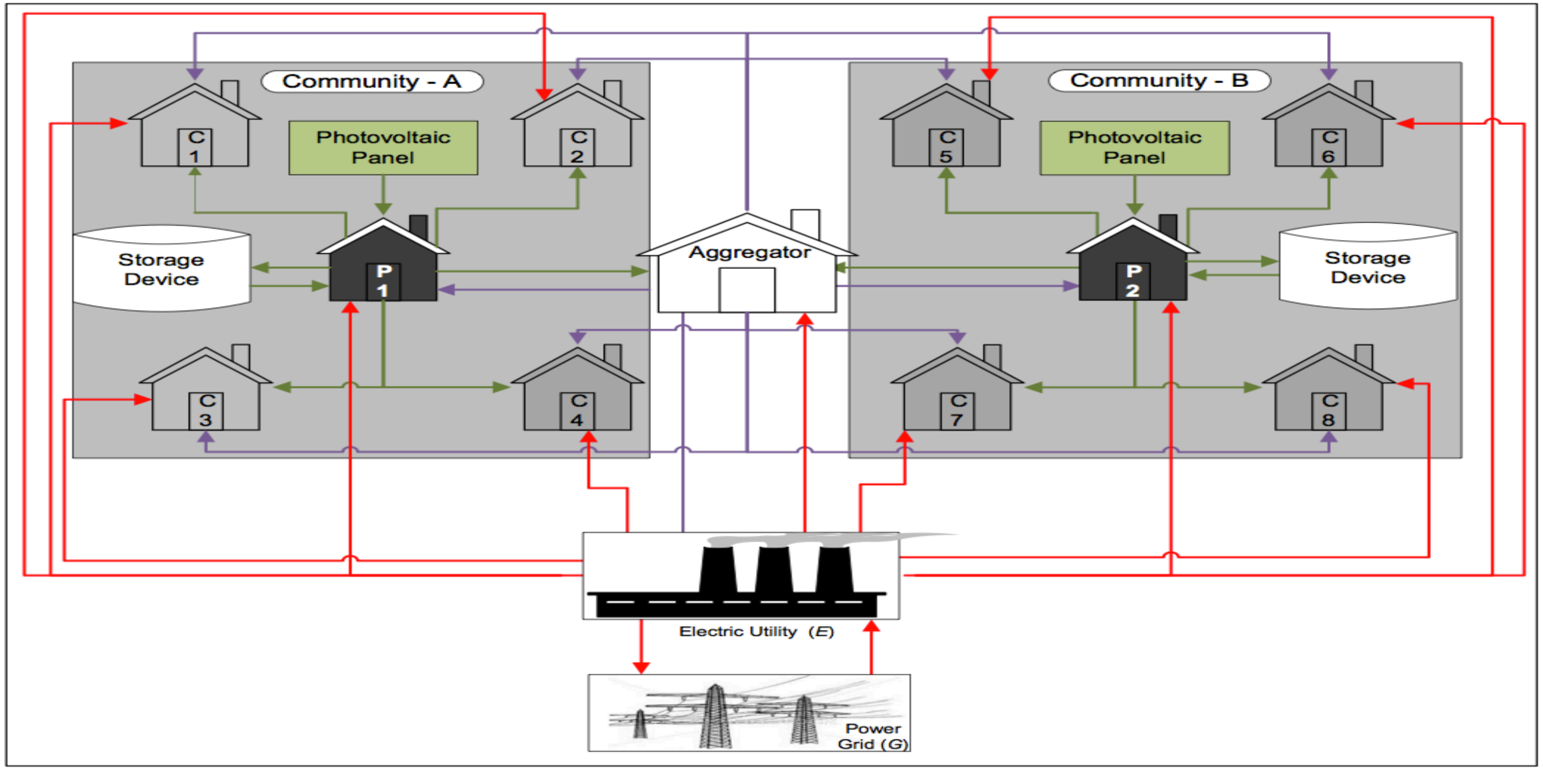


Figure 5.1: Network of energy-shared communities (Source: author)
Green Lines: Electricity supply from the prosumers renewable resource
Purple Lines: Electricity supply from the aggregator
Red Lines: Electricity supply from the electric utility and power grid

5.2.1: Proposed Cases

To recapitulate about the Smart Demand tripod, discussed in Chapter 4, collaborative arrangements in the energy context are strongly linked with the expected level of sustainability and the form of intelligence required. Therefore, in this Energy Sharing Model we have presented three cases. Each case represents proactive consumers participation towards energy demand management depending on their level of collaboration. Further, each case includes different scenarios having certain restrictions for prosumers, consumers, and/or aggregator.

Cases includes:

1) Prosumer-to-Company
2) Prosumer-to-Consumer and
3) Prosumer-to-Prosumer.

Depending on the case selection, the network optimization vision is translated into specific different objective functions. Network is primarily designed in view of prosumers perspective, however the objective functions include cost minimization and/or profit maximization of prosumer(s), community (ies) and the whole network.

We consider a multi-period problem, where the planning horizon is divided into T discrete time slots t = 1…T. As shown in Figure 5.2, the beginning of each time slots represents the instant in which it is possible to make a decision about the energy sourcing. Each participant has its respective demand (exogenous parameter). For the time discretization (refer Figure 5.2), we have considered the following:

- Planning horizon (the time period we want to plan) is considered as two days.
- Each day is discretized into 4 slots that give us total 8 slots in the planning horizon.
- Since each day has total 4 slots therefore, every slot has a timespan of 6 hours.

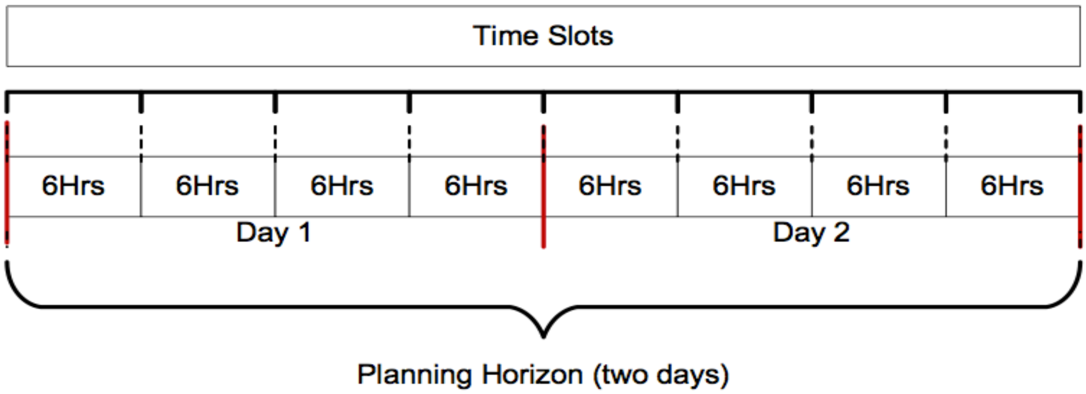


Figure 5.2: Time discretization (Source: author)

All the prices are exogenously determined, and are currently fixed in the problems. The prices are considered deterministic with two reasons. First it is considered as a simplifying assumption to handle the network-designing problem along with the complexity of the model, which has many different attributes (related to electricity consumption, production, and distribution). It helps us to address the important features of prosumers and consumers integration and their management in a network perspective, without being distracted by all of the details. Secondly, deterministic prices are considered because our model is based on the linear problem with the objective to minimize the total costs for the participants. Also, all the future prices (price in the subsequent time slots) come from short-term forecasting the Italian spot electricity market (that is GME - Gestore dei Mercati Energetici SpA). Since our planning horizon is short therefore we considers the price forecasts are accurate.

At the moment, electric utility and electricity power grids are assumed as a black box, that means no constraints (technical/non-technical) are considered. Moreover, power grid has an infinity supply capacity and electric utility has infinity distribution capacity. Table 5.1 highlights the involved members and their key role.

Table 5.1: Summarized description of members' activities (Source: author)

Who	What	When	Where
Consumer	Electricity consumption	As per demand.	Supply from: Prosumers, aggregator, and electric utility
Prosumer	Electricity consumption and production	Consumption as per demand. Production as per production slot.	Supply from: Aggregator and electric utility Production Source: Renewable resource (photovoltaic panels)
Aggregator	Third party supplier agent between communities	As per consumers demand.	Supply from: Prosumers, and electric utility
Electric Utility	Electricity supplier	As per aggregator and consumers demand.	Supply from: Power Grid
Power Grid	Electricity producer	Constant supply to electric utility	Supply to: electric utility only.

5.3: Model formulation

The Energy Sharing Model is formulated and presented as a linear programming optimization model. Optimization process and the model are adopted to reflect the complex varieties of the multiple attributes (such as production, energy losses, demands, electricity loads shift able and non-shift able and so on). In the next section, cases descriptions along with their formulations will be presented. We present increasingly complex models, to illustrate the complexity involved moving from the simplest one to the following. Some of these models are not meant to be used directly, but represent intermediate passages to more complete models.

5.4: Case 1 – Prosumer-to-Company

- This case refers to the situation where a community contains only a single prosumer *P1*, the electric utility *E*, and no other participants (consumers).

5.4.1: Case Description

- For the sake of generalization of the model, we used the index *i* to represent the prosumers and index *t* to represent time slots as follows:

Set of Indices		
I	Prosumers	$i \in I, \quad \mathrm{I} = \{P1\}$
T	Set of time slots	$t \in T, \quad T = \{1,2,3,4,5,6,7,8\}$

- Prosumer *i* is equipped with photovoltaic panels with an estimated maximum production capacity Li_i^t over the time slots. Since we are considering photovoltaic panels, the production capacity Li_i^t may be estimated considering the weather forecast of the next days.

- Producing the electricity through photovoltaic panels has a fixed production cost hi_i^t.
- Prosumer i possesses a cumulative storage devices (i.e. batteries) with total capacity Ei_i. Storing the electricity implies a fixed storage cost ci_i per period (slot).
- The following two parameters for electricity production and its storage into the device are considered:
  - wi_i is the rate of energy lost during electricity production by the renewable resource of prosumer i where $wi_i \in (0,1)$
  - ai_i is the rate of energy lost during charging process in the storage device of prosumer i where $ai_i \in (0,1)$
- Prosumer i has a total demand Di_i. The total demand of the prosumer i represents the demand over the planning horizon. To meet his total demand, Decision Model would propose an efficient allocation of electricity Ldi_i^t over the planning horizon for the prosumer i, so that $Di_i = \sum_{t=1}^{T} Ldi_i^t$. To exemplify, if prosumer i has a total demand $Di_i = 80kW$ (over the planning horizon of two days), decision model may propose prosumer i that it is best to use $Ldi_i^t = 10kW$ in each time slot, which will minimize his costs while satisfying his total demand.
- This specific electricity requirement of the prosumer i can be fulfilled in three ways:
  - Utilizing only own production and storage, if enough to cover the requirement.
  - Buy the entire quantity from the Electric Utility E, in a case of no production and storage.
  - Mixing the above strategies, as smartly managing the demand that allow prosumer i to buy only fraction of energy (unfulfilled amount at a certain time) from the electric utility (E).
- Prosumer i can buy unlimited electricity from the electric utility E at a unit price pie_i^t. Prices change from time to time, but are always given (or forecasted) in advance with sufficient accuracy. Prosumer i can also sell excess energy to the electric utility E at a unit price $piie_i^t$

To summarize, prosumer i, optimizes his energy usage by having a best allocation of electricity to the different time slots. This electricity allocation (represented by Ldi_i^t) would maximize his objective function. Figure 5.3 visualizes this network.

5.4.2: Case Scenarios

Under this case, the following scenarios are proposed

Scenario 1: Prosumer does not share his resource with the electric utility E

Scenario 2: Prosumer share his resource with the electric utility E providing the excess energy

5.4.3: Case 1 – Scenario 1

Scenario 1: No sharing is allowed with electric utility *E*	Objective: Minimize prosumer total cost (Refer Figure 5.3)

In this scenario

- There is only one prosumer and renewable energy is not shared with the electric utility.

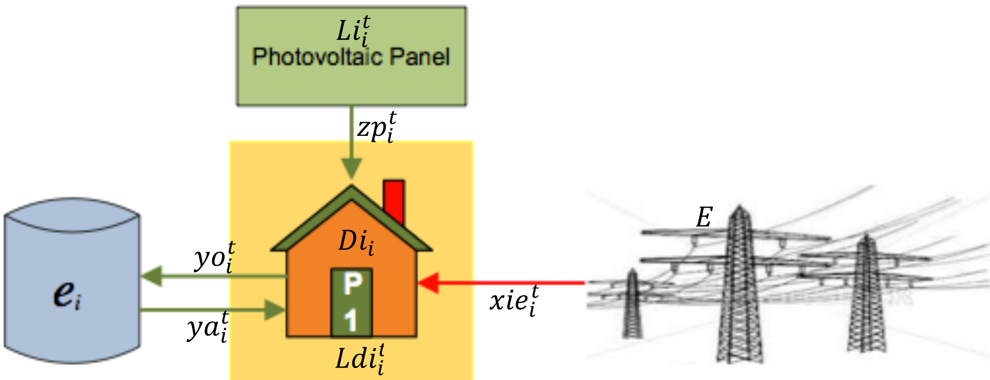


Figure 5.3: Prosumer-to-company network (Scenario: 1) (Source: author)

5.4.3A: Parameters and Descriptions

ci_i	Unit cost of electricity storage for prosumer *i*
Ei_i	Total storage capacity of storage device of prosumer *i*
wi_i	Rate of energy lost during electricity production process of prosumer *i* ($wi \in (0,1)$)
ai_i	Rate of energy lost during charging-storage process of prosumer *i* ($ai \in (0,1)$)
hi_i^t	Unit production cost of electricity for prosumer *i* in time period *t*
Li_i^t	Electricity production capacity of the renewable resource for prosumer *i* in time period *t*
Di_i	Total demand of prosumer *i* during a planning horizon
pie_i^t	Unit price of electricity kw per hour bought from electric utility by prosumer *i* in time period *t*

5.4.3B: Variables and Descriptions

zp_i^t	Quantity produced from the renewable resource by prosumer *i* in time slot *t*
za_i^t	Quantity available after production loss for prosumer *i*
yo_i^t	Quantity transferred to storage device in time slot *t* by prosumer *i*
ya_i^t	Quantity acquired from storage device in time slot *t* by prosumer *i*
sa_i^t	Actual storage inside the device in time slot *t* by prosumer *i*
Ldi_i^t	Proportion of total demand satisfied in period *t* for prosumer *i* (load allocations)
xie_i^t	Quantity bought by prosumer *i* from electric utility

5.4.3C: Objective Function

Objective Function is to minimize total cost for the prosumer

min	$\sum_{t}^{T} zp_i^t . hi_i^t$	$+ \sum_{t}^{T} sa_i^t . ci_i$	$+ \sum_{t}^{T} xie_i^t . pie_i^t$
	Production costs	Storage costs	Prosumer cost of buying from electric utility

5.4.3D: Constraints

$zp_i^t \leq Li_i^t \ \forall \, t \in T$	Quantity produced in time period *t* must be less than or equal to the production capacity per time slot of the renewable resource.
$za_i^t = zp_i^t * (1 - wi_i) \ \forall \, t \in T$	Quantity available is equal to quantity produced minus its loss.
$sa_i^t = sa_i^{t-1} + (yo_i^t * (1 - ai_i)) - ya_i^t \ \forall \, t \in T$	Current energy available in storage device at the end of time *t*
$sa_i^t = Ei_i \quad \forall \, t \in T$	Quantity stored must not exceed the capacity of the storage device
$\sum_{t}^{T} Ldi_i^t = Di_i$	Sum of all load allocations must be equal to the total demand.
$za_i^t + ya_i^t + xie_i^t = Ldi_i^t + yo_i^t \ \forall \, t \in T$	Balance constraints: all prosumer's inflows are equal to outflows
$zp_i^t, za_i^t, yo_i^t, ya_i^t, sa_i^t, Ldi_i^t, xie_i^t \geq 0$	Non-negativity constraints

5.4.4: Case 1 – Scenario 2

Scenario 2: Sharing with electric utility is allowed	Objective: Maximize the total profits of prosumer (Refer Figure 5.4)

In this scenario

- Prosumer i can share his excess renewable energy (through photovoltaic panels) with the electric utility E, in addition to self-consumption. (Refer Figure: 5.4).
- Prosumer i sells the electricity $xiie_i^t$ to the electric utility at the price $piie_i^t$

5.4.4A: Assumption

In addition to the above descriptions, we considered the following assumption:

- Electric utility E has an unlimited demand ($D_E = \infty$) that it can absorb prosumer i electricity at any time.

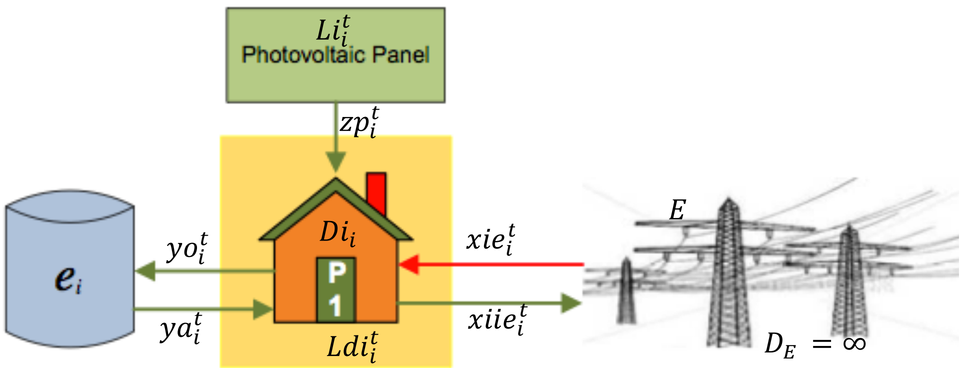


Figure 5.4: Prosumer-to-company network (Scenario: 2) (Source: author)

5.4.4B: Parameters and Descriptions

ci_i	Unit cost of electricity storage for prosumer *i*
Ei_i	Total storage capacity of storage device of prosumer *i*
wi_i	Rate of energy lost during electricity production process of prosumer *i* ($wi \in (0,1)$)
ai_i	Rate of energy lost during charging-storage process of prosumer *i* ($ai \in (0,1)$)
hi_i^t	Unit production cost of electricity prosumer *i* in time slot *t*
Li_i^t	Electricity production capacity of the renewable resource for prosumer *i* in time slot *t*
Di_i	Total demand of prosumer *i* during a planning horizon
pie_i^t	Unit price of electricity kw per hour bought from electric utility by prosumer *i* in time slot *t*
$piie_i^t$	Unit price of electricity kw per hour sold to electric utility by prosumer *i* in time slot *t*

5.4.4C: Variables and Descriptions

zp_i^t	Quantity produced from the renewable resource by prosumer *i* in time slot *t*
za_i^t	Quantity available after production loss for prosumer *i*
yo_i^t	Quantity transferred to storage device in time slot *t* by prosumer *i*
ya_i^t	Quantity acquired from storage device in time slot *t* by prosumer *i*
sa_i^t	Actual storage inside the device in time slot *t* by prosumer *i*
Ldi_i^t	Proportion of total demand satisfied in time slot *t* for prosumer *i* (load allocations)
xie_i^t	Quantity bought by prosumer *i* from electric utility in time slot *t*
$xiie_i^t$	Quantity sold by prosumer *i* to electric utility in time slot *t*

5.4.4D: Objective Function

Objective Function is to maximize the total profits for the prosumer

max	$\sum_{t=1}^{T} xiie_i^t . piie_i^t$	$-\sum_{t}^{T} xie_i^t . pie_i^t$	$-\sum_{t}^{T} zp_i^t . hi_i^t$	$-\sum_{t}^{T} sa_i^t . ci_i$
	Prosumer revenues from selling to electric utility	Prosumer cost of buying from electric utility	Production costs	Storage costs

5.4.4E: Constraints

$zp_i^t \leq Li_i^t \ \forall\, t \in T$	Quantity produced in time period *t* must be less than or equal to the production capacity per time slot of the renewable resource.
$za_i^t = zp_i^t * (1 - wi_i) \ \forall\, t \in T$	Quantity available is equal to quantity produced minus its loss.
$sa_i^t = sa_i^{t-1} + (yo_i^t * (1 - ai_i)) - ya_i^t \ \forall\, t \in T$	Current energy available in storage device at the end of time *t*
$sa_i^t = Ei_i \quad \forall\, t \in T$	Quantity stored must not exceed the capacity of the storage device
$\sum_{t}^{T} Ldi_i^t = Di_i$	Sum of all load allocations must be equal to the total demand.
$za_i^t + ya_i^t + xie_i^t = Ldi_i^t + yo_i^t + xiie_i^t \ \forall\, t \in T$	Balance constraints: all prosumer's inflows are equal to outflows
$If \sum_{t}^{T} Li_i^t \geq Di_i \ then\ xie_i^t = 0$ $\textbf{ElseIf} \sum_{t}^{T} Li_i^t \leq Di_i \ then\ xiie_i^t = 0$	If sum of all production is greater than total demand, then electricity cannot be bought from outside and vice versa. Since both Li_i^t

	and Di_i are known data, these constraints can be easily implemented.
$zp_i^t, za_i^t, yo_i^t, ya_i^t, sa_i^t, Ldi_i^t, xie_i^t, xiie_i^t \geq 0$	Non-negativity constraints

5.5: Case 2 – Prosumer-to-Consumers

This case refers to the situation where proactive consumers collaborate with other consumers in the community.

5.5.1: Case Description

- Under this case, we have considered a group of consumers, referred to as a community. A single prosumer *P1* in the community shares the excess energy with the group of consumers *C1* – *C4* and can also share with the electric utility *E.*
- For the sake of generalization of the model, we used the index *i* to represent the prosumers, index *j* for the consumers, and index *t* to represent time slots. In this case, following indices are used:

Set of Indices		
I	Prosumers	$i \in I, \quad I = \{P1\}$
J	Consumers	$j \in J, \quad J = \{C1, C2, C3, C4\}$
T	Set of time slots	$t \in T, \quad T = \{1,2,3,4,5,6,7,8\}$

- Prosumer *i* has a total demand Di_i and consumer *j* has a total demand Dj_j.
- The total demand of the prosumer *i* and consumer *j* represents their demand over the planning horizon.
- To best meet their total demands, Decision Model would propose an efficient allocation of electricity Ldi_i^t over the planning horizon for the prosumer *i* and Ldj_j^t for the consumer *j*. Decision model will ensure that prosumer *i* total demand is equal to

$Di_i = \sum_{t=1}^{T} Ldi_i^t$ and the total demand of consumer j is equal to $Dj_j = \sum_{t=1}^{T} Ldj_j^t$ over the planning horizon.

- This specific electricity requirement of the **prosumer *i*** can be fulfilled in three ways:
    - Utilizing only own production and storage, if enough to cover the requirement.
    - Buy the entire quantity from the Electric Utility *E*, in a case of no production and storage.
    - Mixing the above strategies, as smartly managing the demand that allow prosumer i to buy only fraction of energy (unfulfilled amount at a certain time) from the electric utility (E).
- This specific electricity requirement of the **consumer *j*** can be fulfilled in three ways:
    - Buy the entire quantity from the prosumer *i,* if enough to cover the requirement.
    - Buy the entire quantity from the Electric Utility *E*, in a case of no supply from prosumer *i*.
    - Mixing the above strategies, as smartly managing the demand that allow consumer j to buy fraction of energy from prosumer *i* and from the electric utility *E*.
- Prosumer *i* sells electricity $xij_{i,j}^t$ to consumer j at the price $pij_{i,j}^t$.
- Prosumer *i* sells electricity $xiie_i^t$ to electricity utility *E* at the price $piie_i^t$.
- Consumer j can buy electricity xje_j^t from the electric utility *E* at a price of pje_j^t and can buy $xij_{i,j}^t$ from prosumer *i* at a price of $pij_{i,j}^t$.
- Prosumer *i* can buy electricity xie_i^t from the electric utility *E* at a price of pie_i^t.
- In this case, a uniform pricing strategy is adopted where, prosumer i sells identical quantity of energy for the same price to each consumer j.
- **Figure 5.5** visualizes the prosumer to consumer network along with its abbreviations. In the figure red lines show electricity drawn from the electric utility *E* and green lines refer to the prosumer activities.

5.5.2: Case Scenarios

Under this case, following scenarios are proposed

Scenario 1: Profit maximization of a prosumer, who shares the energy resource in his community with the restriction of selling out to the electric utility.

Scenario 2: Profit maximization of a prosumer, who shares the energy resource within his community and also with the electric utility.

Scenario 3: Profit maximization of the whole community, considering the alternative energy resource.

5.5.3: Case 2 – Scenario 1

Scenario 1: Sharing in single community without selling outside to the electric utility	Objective: Profit maximization of the prosumer (Refer Figure 5.5)

In this scenario

- Prosumer *i* can share his renewable energy (generated through photovoltaic panels) only within his community. As shown in the Figure 5.5, selling outside to the electric utility is not allowed.

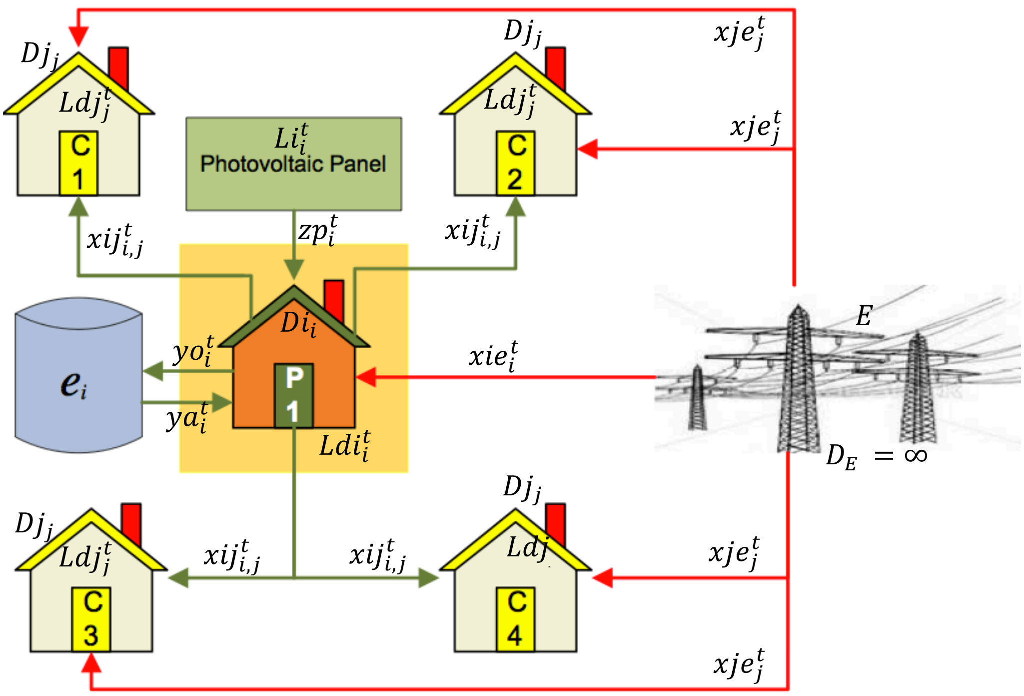


Figure 5.5: Prosumer-to-consumer network (Scenario: 1) (Source: author)

5.5.3A: Parameters and Descriptions

Prosumer Parameters	
ci_i	Unit cost of electricity storage for prosumer *i*
Ei_i	Total storage capacity of storage device of prosumer *i*
wi_i	Rate of energy lost during electricity production process of prosumer *i* ($wi \in (0,1)$)
ai_i	Rate of energy lost during charging-storage process of prosumer *i* ($ai \in (0,1)$)
hi_i^t	Unit production cost of electricity per time slot of prosumer *i*
Li_i^t	Electricity production capacity of the renewable resource per time slot for prosumer *i*
Di_i	Total demand of prosumer *i* during a planning horizon

$pij_{i,j}^{t}$	Unit price of electricity kw per hour sold to consumer *j* in time *t* by prosumer *i*
pie_{i}^{t}	Unit price of electricity kw per hour bought from electric utility in time *t* by prosumer *i*
Consumers Parameter	
Dj_{j}	Total demand of each consumer in the community

5.5.3B: Variables and Descriptions

zp_{i}^{t}	Quantity produced from the renewable resource by prosumer *i* in time slot *t*
za_{i}^{t}	Quantity available after production loss for prosumer *i*
yo_{i}^{t}	Quantity transferred to storage device in time slot *t* by prosumer *i*
ya_{i}^{t}	Quantity acquired from storage device in time slot *t* by prosumer *i*
sa_{i}^{t}	Actual storage inside the device in time slot *t* by prosumer *i*
Ldi_{i}^{t}	Proportion of total demand satisfied in period *t* for prosumer *i* (load allocations)
$xij_{i,j}^{t}$	Quantity sold by prosumer *i* to community consumer in time *t*
xie_{i}^{t}	Quantity bought by prosumer *i* from electric utility in time *t*

5.5.3C: Objective Function

Objective Function is to maximize the total profits for the prosumer in the community.

$\boldsymbol{max}$	$\sum_{t=1}^{T}\sum_{j=1}^{J} xij_{i,j}^{t}.pij_{i,j}^{t}$	$-\sum_{t=1}^{T} xie_{i}^{t}.pie_{i}^{t}$	$-\sum_{t=1}^{T} zp_{i}^{t}.hi_{i}^{t}$	$-\sum_{t=1}^{T} sa_{i}^{t}.ci_{i}$
	Prosumer revenues from selling directly to consumers	Prosumer cost of buying from electric utility	Production costs	Storage costs

5.5.3D: Constraints

$zp_i^t \leq Li_i^t \;\; \forall\, t \in T$	Quantity produced in time period *t* must be less than or equal to the production capacity per time slot of the renewable resource.
$za_i^t = zp_i^t * (1 - wi_i) \, \forall\, t \in T$	Quantity available is equal to quantity produced minus its loss.
$sa_i^t = sa_i^{t-1} + (yo_i^t * (1 - ai_i)) - ya_i^t \;\; \forall\, t \in T$	Current energy available in storage device at the end of time *t*
$sa_i^t = Ei_i \quad \forall\, t \in T$	Quantity stored must not exceed the capacity of the storage device
$\sum_t^T Ldi_i^t = Di_i$	Sum of all load allocations must be equal to the total demand.
$\sum_t^T xij_{i,j}^t \leq Dj_j \;\; \forall\, j \in J$	Supplied quantity to consumer should be less than or equal to the consumer total demand
$za_i^t + ya_i^t + xie_i^t = Ldi_i^t + \sum_{j=1}^J xij_{i,j}^t + yo_i^t \quad \forall\, t \in T$	Balance constraints: all prosumer's inflows are equal to outflows
$\boldsymbol{If} \sum_t^T Li_i^t \geq Di_i \; \boldsymbol{then} \; xie_i^t = 0$ $\boldsymbol{ElseIf} \sum_t^T Li_i^t \leq Di_i \; \boldsymbol{then} \; xij_{i,j}^t = 0$	If sum of all production is greater than total demand, then electricity cannot be bought from outside. Else if sum of all production is less than total demand, then prosumer cannot fulfill the consumer demand.
$zp_i^t, za_i^t, yo_i^t, ya_i^t, sa_i^t, Ldi_i^t, xie_i^t, xij_{i,j}^t \geq 0$	Non-negativity constraints

5.5.4: Case 2 – Scenario 2

Scenario 2: Sharing in single community and selling outside	Objective: Profit maximization of the prosumer (Refer Figure 5.6)

In this scenario

- Prosumer i can share his renewable energy within the community as well outsider with the electric utility as well. Figure 5.6 visualizes the network.

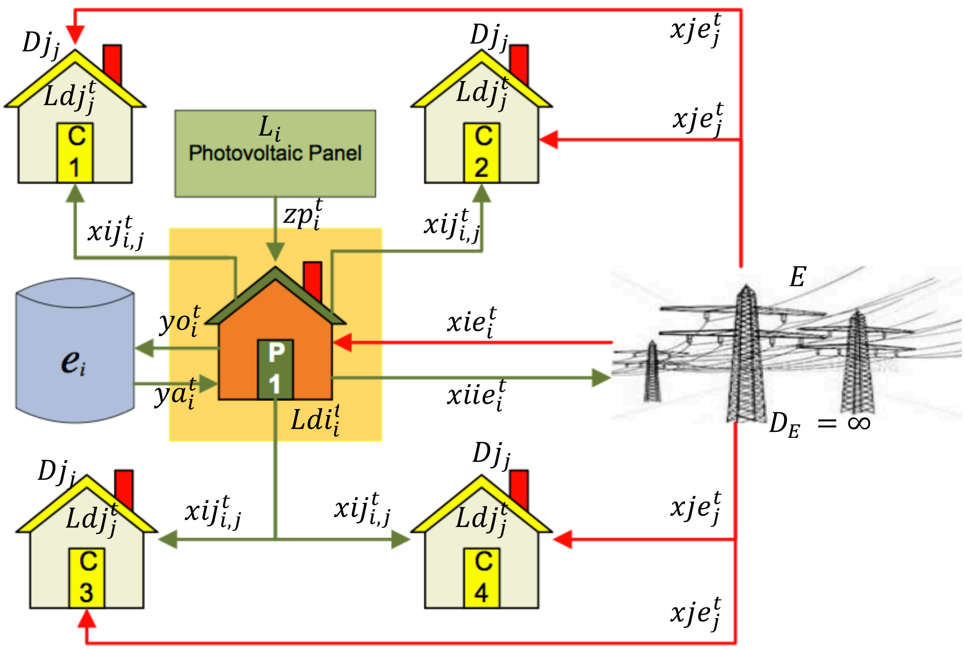


Figure 5.6: Prosumer-to-consumer network (Scenario: 2) (Source: author)

5.5.4A: Assumptions

Under this scenario, we have considered the following assumptions:

- Electric utility E has an unlimited demand ($D_E = \infty$) that it can absorb prosumer i electricity at any time.

- Prosumer gains an incentive to sell electricity to its community consumers because $pij_{i,j}^{t} > piie_{i}^{t}$

5.5.4B: Parameters and Descriptions

Prosumer Parameters	
ci_i	Unit cost of electricity storage for prosumer *i*
Ei_i	Total storage capacity of storage device of prosumer *i*
wi_i	Rate of energy lost during electricity production process of prosumer *i* ($wi \in (0,1)$)
ai_i	Rate of energy lost during charging-storage process of prosumer *i* ($ai \in (0,1)$)
hi_i^t	Unit production cost of electricity per time slot of prosumer *i*
Li_i^t	Electricity production capacity of the renewable resource per time slot for prosumer *i*
Di_i	Total demand of prosumer *i* during a planning horizon
Prosumer Selling Prices	
$pij_{i,j}^t$	Unit price of electricity kw per hour sold to consumer *j* in time *t* by prosumer *i*
$piie_i^t$	Unit price of electricity kw per hour sold to electric utility in time *t* by prosumer *i*
Prosumer Buying Prices	
pie_i^t	Unit price of electricity kw per hour bought from electric utility in time *t* by prosumer *i*
Consumers Parameter	
Dj_j	Total demand of each consumer in the community

5.5.4C: Variables and Descriptions

zp_i^t	Quantity produced from the renewable resource by prosumer *i* in time slot *t*
za_i^t	Quantity available after production loss for prosumer *i*
yo_i^t	Quantity transferred to storage device in time slot *t* by prosumer *i*
ya_i^t	Quantity acquired from storage device in time slot *t* by prosumer *i*
sa_i^t	Actual storage inside the device in time slot *t* by prosumer *i*
Ldi_i^t	Proportion of total demand satisfied in period *t* for prosumer *i* (load allocations)
Prosumer Selling Quantities	
$xij_{i,j}^t$	Quantity sold by prosumer *i* to community consumer in time *t*
$xiie_i^t$	Quantity sold by prosumer *i* to electric utility in time *t*
	Prosumer Buying Quantities
xie_i^t	Quantity bought by prosumer *i* from electric utility in time *t*

5.5.4D: Objective Function

Objective Function is to maximize the total profits for the prosumer in the community.

max	
$\sum_{t=1}^{T}\sum_{j=1}^{J} xij_{i,j}^t . pij_{i,j}^t$	Prosumer revenues from selling directly to consumers
$+\sum_{t=1}^{T} xiie_i^t . piie_i^t$	Prosumer revenues from selling to electric utility
$-\sum_{t=1}^{T} xie_i^t . pie_i^t$	Prosumer cost of buying from electric utility

$-\sum_{t=1}^{T} zp_i^t . hi_i^t$	Production costs
$-\sum_{t=1}^{T} sa_i^t . ci_i$	Storage costs

5.5.4E: Constraints

$zp_i^t \leq Li_i^t \;\forall\, t \in T$	Quantity produced in time period *t* must be less than or equal to the production capacity per time slot of the renewable resource.
$za_i^t = zp_i^t * (1 - wi_i) \;\forall\, t \in T$	Quantity available is equal to quantity produced minus its loss.
$sa_i^t = sa_i^{t-1} + (yo_i^t * (1 - ai_i)) - ya_i^t \;\forall\, t \in T$	Current energy available in storage device at the end of time *t*
$sa_i^t = Ei_i \quad \forall\, t \in T$	Quantity stored must not exceed the capacity of the storage device
$\sum_t^T Ldi_i^t = Di_i$	Sum of all load allocations must be equal to the total demand.
$\sum_t^T xij_{i,j}^t \leq Dj_j \;\forall\, j \in J$	Supplied quantity to consumer should be less than or equal to the consumer total demand
$za_i^t + ya_i^t + xie_i^t = Ldi_i^t + \sum_{j=1}^{J} xij_{i,j}^t + xiie_i^t + yo_i^t \quad \forall\, t \in T$	Balance constraints: all prosumer's inflows are equal to outflows
$\boldsymbol{If} \sum_t^T Li_i^t \geq Di_i \;\boldsymbol{then}\; xie_i^t = 0$ $\boldsymbol{ElseIf} \sum_t^T Li_i^t \leq Di_i \;\boldsymbol{then}\; xij_{i,j}^t, xiie_i^t = 0$	If sum of all production is greater than total demand, then prosumer cannot buy the electricity from outside. Else if sum of all production is less than total demand, then prosumer cannot fulfill the consumer

	demand as well as cannot sell to electric utility.
$zp_i^t, za_i^t, yo_i^t, ya_i^t, sa_i^t, Ldi_i^t, xie_i^t, xij_{i,j}^t, xiie_i^t \geq 0$	Non-negativity constraints

5.5.5: Case 2 – Scenario 3

Scenario 3: Sharing in single community and selling outside	Objective: Profit maximization of the single community (Refer Figure 5.7)

In this scenario

- Prosumer *i* and Consumers *j* participate towards energy demand management to collectively optimize the community profits. Prosumer *i* share his energy resource with community members and electric utility. Figure 5.7 depicts the network structure.

5.5.5A: Assumptions

This scenario holds the following assumptions:

- Electric utility E has an unlimited demand ($D_E = \infty$) that it can absorb prosumer *i* electricity at any time.
- Prosumer gains an incentive to sell electricity to its community consumers because $pij_{i,j}^t > piie_i^t$
- Consumers pay less price if they buy from prosumer compared to electricity utility $pji_{j,i}^t < pje_j^t$

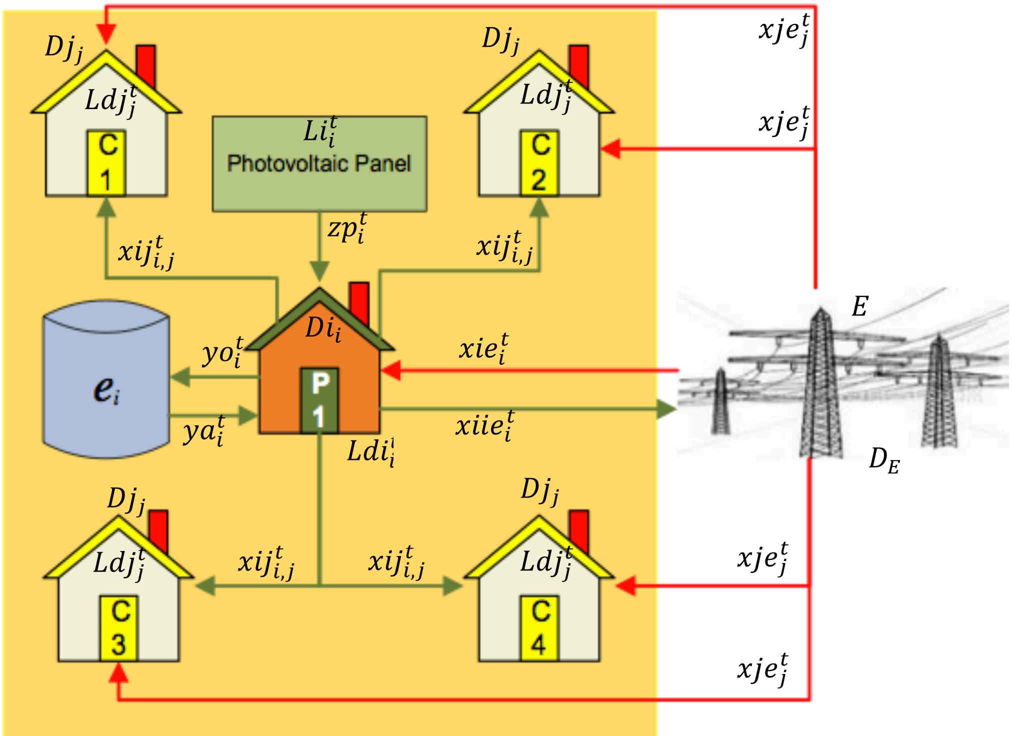


Figure 5.7: Prosumer-to-consumer network (Scenario: 3) (Source: author)

5.5.5B: Parameters and Descriptions

Prosumer Parameters	
ci_i	Unit cost of electricity storage for prosumer *i*
Ei_i	Total storage capacity of storage device of prosumer *i*
wi_i	Rate of energy lost during electricity production process of prosumer *i* ($wi \in (0,1)$)
ai_i	Rate of energy lost during charging-storage process of prosumer *i* ($ai \in (0,1)$)
hi_i^t	Unit production cost of electricity per time slot of prosumer *i*
Li_i^t	Electricity production capacity of the renewable resource per time slot for

	prosumer *i*
Di_i	Total demand of prosumer *i* during a planning horizon
Prosumer Selling Prices	
$pij_{i,j}^t$	Unit price of electricity kw per hour sold to consumer *j* in time *t* by prosumer *i*
$piie_i^t$	Unit price of electricity kw per hour sold to electric utility in time *t* by prosumer *i*
Prosumer Buying Prices	
pie_i^t	Unit price of electricity kw per hour bought from electric utility in time *t* by prosumer *i*
Consumers Parameter	
Dj_j	Total demand of each consumer in the community
$pji_{j,i}^t$	Unit price of electricity kw per hour bought by consumer *j* from prosumer *i* in time *t*
pje_j^t	Unit price of electricity kw per hour bought by consumer *j* from electric utility *E* in time *t*

5.5.5C: Variables and Descriptions

Prosumer Variables	
zp_i^t	Quantity produced from the renewable resource by prosumer *i* in time slot *t*
za_i^t	Quantity available after production loss for prosumer *i*
yo_i^t	Quantity transferred to storage device in time slot *t* by prosumer *i*
ya_i^t	Quantity acquired from storage device in time slot *t* by prosumer *i*
sa_i^t	Actual storage inside the device in time slot *t* by prosumer *i*
Ldi_i^t	Proportion of total demand satisfied in period *t* for prosumer *i* (load allocations)
Prosumer Selling Quantities	
$xij_{i,j}^t$	Quantity sold by prosumer *i* to community consumer in time *t*

$xiie_i^t$	Quantity sold by prosumer *i* to electric utility *e* in time *t*
Prosumer Buying Quantities	
xie_i^t	Quantity bought by Prosumer *i* from electric utility in time *t*
Consumers Variables	
Ldj_j^t	Proportion of total demand satisfied in period *t* for consumer *j*
$xji_{j,i}^t$	Quantity bought by consumer *j* from prosumer *i* in time *t*
xje_j^t	Quantity bought by consumer *j* from electric utility *e* in time *t*

5.5.5D: Objective Function

Objective Function is to maximize the total community profits.

max $\sum_{t=1}^{T}\sum_{j=1}^{J} xij_{i,j}^t . pij_{i,j}^t$	Prosumer revenues from selling directly to consumers
$+\sum_{t=1}^{T} xiie_i^t . piie_i^t$	Prosumer revenues from selling to electric utility
$-\sum_{t=1}^{T} xie_i^t . pie_i^t$	Prosumer costs of buying from electric utility
$-\sum_{t=1}^{T}\sum_{j=1}^{J} xje_j^t . pje_j^t$	Consumer costs of buying from electric utility
$-\sum_{t=1}^{T}\sum_{j=1}^{J} xji_{j,i}^t . pji_{j,i}^t$	Consumer costs of buying from prosumers
$-\sum_{t=1}^{T} zp_i^t . hi_i^t$	Prosumers production costs
$-\sum_{t=1}^{T} sa_i^t . ci_i$	Prosumers storage costs

5.5.5E: Constraints

$zp_i^t \leq Li_i^t \; \forall \, t \in T$	Quantity produced in time period *t* must be less than or equal to the production capacity per time slot of the renewable resource.
$za_i^t = zp_i^t * (1 - wi_i) \; \forall \, t \in T$	Quantity available is equal to quantity produced minus its loss.
$sa_i^t = sa_i^{t-1} + (yo_i^t * (1 - ai_i)) - ya_i^t$ $\forall \, t \in T$	Current energy available in storage device at the end of time *t*
$sa_i^t = Ei_i \quad \forall \, t \in T$	Quantity stored must not exceed the capacity of the storage device
$\sum_t^T Ldi_i^t = Di_i$	Sum of all load allocations must be equal to the prosumer's total demand.
$\sum_t^T Ldj_j^t = Dj_j \; \forall \, j \in J$	Sum of all load allocations must be equal to the consumer's total demand.
$xij_{i,j}^t = xji_{j,i}^t \; \forall \; t \in T, \; j \in J$	Prosumer selling quantity is equal to consumer buying quantity (as there is only one prosumer)
$Ldj_j^t = xji_j^t + xje_j^t$ $\forall \, t \in T, j \in J$	Electricity loads required in time *t* by consumer *j* is equal to sum of electricity purchases from prosumer and electric utility.
$za_i^t + ya_i^t + xie_i^t + \sum_j^J xje_j^t = Ldi_i^t + \sum_{j=1}^J Ldj_j^t + xiie_i^t + yo_i^t \quad \forall \, t \in T$	Balance constraints: all prosumer's and consumer's inflows are equal to outflows
$\boldsymbol{If} \sum_t^T Li_i^t \geq Di_i \; \boldsymbol{then} \; xie_i^t = 0$ $\boldsymbol{ElseIf} \sum_t^T Li_i^t \leq Di_i$ $\boldsymbol{then} \; xij_{i,j}^t, xji_{j,i}^t \; xiie_i^t = 0$	If sum of all production is greater than total demand, then prosumer cannot buy the electricity from outside. Else if sum of all production is less than total demand, then prosumer cannot fulfill the consumer demand

	as well as cannot sell to electric utility.
$zp_i^t, za_i^t, yo_i^t, ya_i^t, sa_i^t, Ldi_i^t, xij_{i,j}^t,$ $xiie_i^t, xie_i^t, xji_{j,i}^t, xje_j^t \geq 0$	Non-negativity constraints.

5.6: Case 3 – Prosumers-to-Prosumers

This case refers to the situation where multiple communities are considered. In this network of prosumers, distributed renewable resources are shared among their vicinity and in other communities through the third party agent (aggregator).

5.6.1: Case Description

- Compared to the previous cases, in this case we have considered two communities where, each community consist one prosumer and number of consumers.
- For the sake of generalization of the model, we used the following indices in this case:

I	Prosumers in community-A	$ia \in I, \quad \text{I} = \{P1\}$
M	Prosumers in community-B	$ib \in M, \quad \text{M} = \{P2\}$
J	Consumers in community-A	$ja \in J, \quad \text{J} = \{C1, C2, C3, C4\}$
N	Consumers in community-B	$jb \in N, \quad \text{N} = \{C5, C6, C7, C8\}$
T	Set of time slots	$t \in T, \quad T = \{1,2,3,4,5,6,7,8\}$

- Prosumer *P1/P2* in the community-A/B shares the energy among their respective group of consumers and the same can also be shared with the other community through aggregator, and aggregator further can sell to the electric utility.
- To manage the interaction between two communities, the role of aggregator is introduced in the network. As discussed in the start, renewable resources have some variability in their production supply. Therefore, it may not always be possible to match

and / or fulfill the total demand within both communities through sharing the electricity. In such situation, aggregator plays the required role in terms of aggregating the consumers' demands and decides how to fulfill the demands from the internal sources (prosumers of other community) and/or from electric utility *E*.

- Community aggregator can act as:
  - Agent between two communities to fulfill each other demand
  - Acts as a buyer who buys electricity from the electric utility *E* for the communities, to satisfy their demand that is unable to be met from the internal sources.
- Consumers can satisfy their unfulfilled demand from the aggregator, where paying less prices and avoiding the demand charge of electric utility incentivize them. Demand charge is an additional billed amount charged by electric utility companies that covers the difference between the electric power consumers expects to have available and the electricity that consumers actually use. In both roles of aggregator, he earns his profit (commission) in terms of the difference between buying and selling prices (selling price > buying price).
- Prosumers and consumers have their respective total demand, which is demand over the planning horizon. To best meet their total demands, decision model would propose an efficient allocation of electricity over the planning horizon for the prosumers (prosumer ia of community–A and prosumer ib of community–B) and consumers (consumer ja of community–A and consumer jb of community–B). Decision model will ensure that sum of all electricity load allocations are equal to respective total demand of prosumers and consumers. For example: for community-A prosumer $\sum_t^T Ldia_{ia}^t = Dia_{ia} \; \forall \; ia$ and for community-A consumer $\sum_t^T Ldja_{ja}^t = Dja_{ja} \; \forall \; ja$.
- This specific electricity requirement of the prosumer *i* can be fulfilled in following ways:
  - Utilizing only own production and storage, if enough to cover the requirement.
  - Buy the entire quantity through aggregator A from the prosumer of another community, if enough to cover the requirement.
  - Mixing the above strategies, that allow prosumer *i* to buy fraction of energy (unfulfilled amount at a certain time) from the aggregator A and electric utility (E).

- This specific electricity requirement of the consumer *j* can be fulfilled in following ways:
  - Buy the entire quantity from the prosumer *i*, if enough to cover the requirement.
  - Buy the entire quantity through aggregator A from the prosumer *i* of another community, if enough to cover the requirement.
  - Buy the entire quantity from the electric utility (E), in a case of no supply from prosumer *i* and aggregator A.
  - Mixing the above strategies, that allow consumer *j* to buy fraction of energy from prosumer *i*, aggregator A and from the electric utility (E).

Figure 5.8 visualizes the network whereas, Table 5.2 explains the buying and selling of electricity within the network

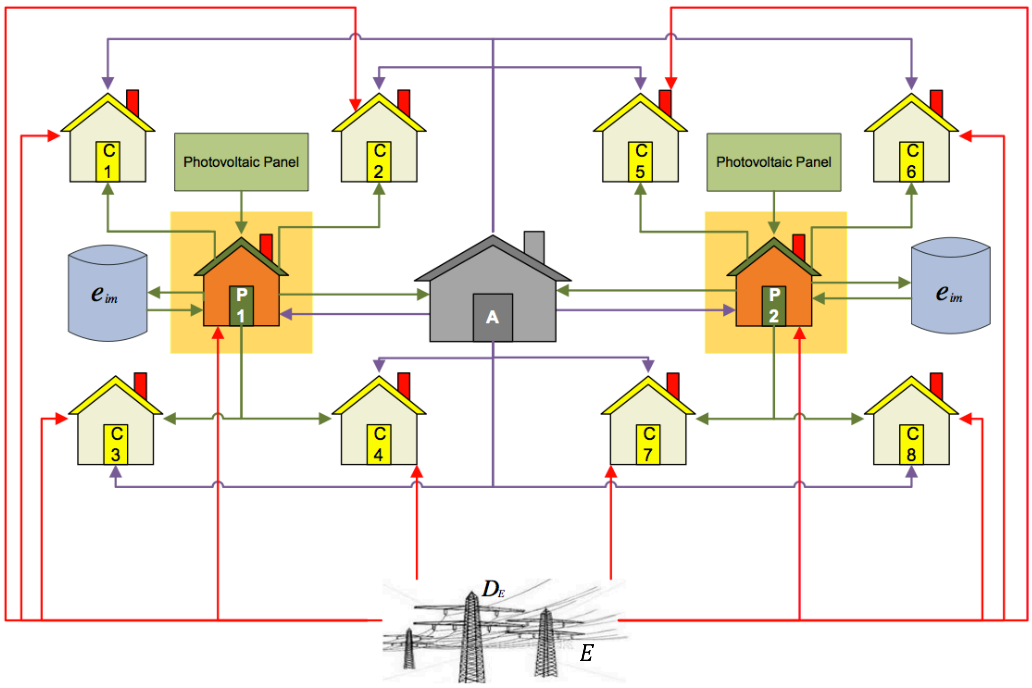


Figure 5.8: Prosumer-to-prosumer network (Source: author)

Table 5.2: Electricity buying selling in prosumer-to-prosumer network (Source: author)

Prosumer *i*		
	Sell to	Buy from
Consumer *j*	Allowed	–
Aggregator *A*	Allowed	Allowed
Electric Utility *E*	–	Allowed
Consumer *j*		
	Sell to	Buy from
Prosumer *i*	–	Allowed
Aggregator *A*	–	Allowed
Electric Utility *E*	–	Allowed
Aggregator *A*		
	Sell to	Buy from
Prosumer *i*	Allowed	Allowed
Consumer *j*	Allowed	–
Electric Utility *E*	Allowed	Allowed
Electric Utility *E*		
	Sell to	Buy from
Prosumer *i*	Allowed	–
Consumer *j*	Allowed	–
Aggregator *A*	Allowed	Allowed

5.6.2: Case Scenarios

Under this case, following scenarios are proposed:

Scenario 1: Profit maximization of a prosumers; with the restriction to sell outside.

Scenario 2: Profit maximization of individual communities excluding the aggregator; with the restriction to sell outside.

Scenario 3: Profit maximization as a societal perspective; only aggregator is allowed to sell outside.

5.6.3: Case 3 – Scenario 1

Scenario 1: Sharing in two communities through aggregator without selling outside (to electric utility *E*)	Profit maximization of prosumer(s) (Refer Figure 5.9)

In this scenario, electricity sharing between the two communities is allowed through aggregator. Prosumers of both communities can only sell in their local as well as in other community, but cannot sell to the electric utility. Moreover, aggregator A does not buy electricity for prosumers, and prosumers have to buy themselves from the electric utility.

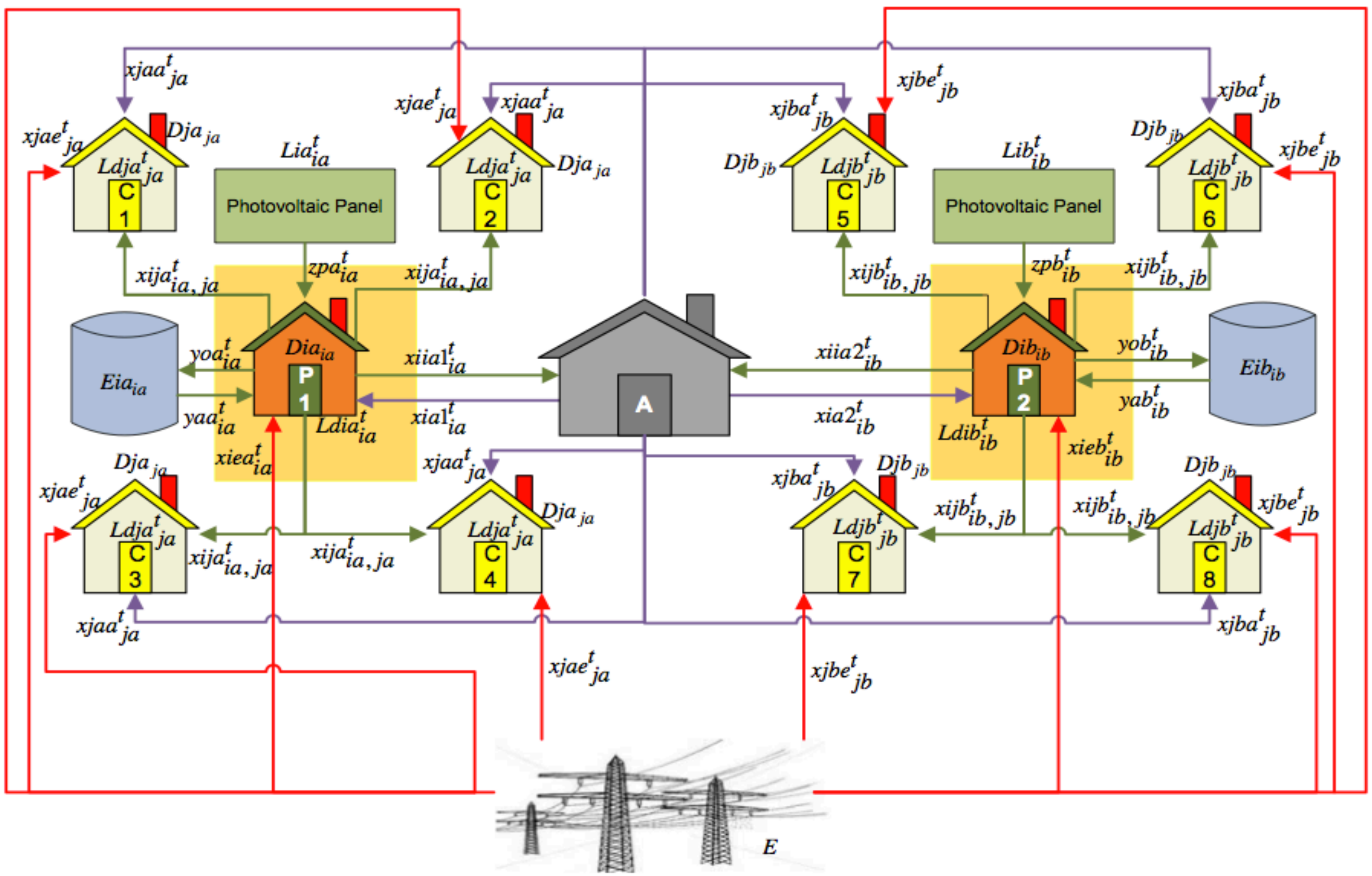


Figure 5.9: Prosumer-to-prosumer network (Scenario: 1) (Source: author)

5.6.3A: Assumptions

This scenario holds the following assumptions:

- Prosumer gets higher selling price for the quantity he sold to its own community consumers as compared to selling to the aggregator. Similarly, buying from community prosumer is less than the buying from aggregator and from the electric utility.
    - For prosumer selling: consumer price > aggregator Price
    - For consumer buying: prosumer price < aggregator price < electric utility price.
- In this case, a uniform pricing strategy is adopted where, prosumer i sells identical quantity of energy for the same price to each consumer *j*.

5.6.3B: Parameters and Descriptions

cia_{ia}	Unit cost of electricity storage for prosumer *ia* of community-A
cib_{ib}	Unit cost of electricity storage for prosumer *ib* of community-B
Eia_{ia}	Total storage capacity of storage device of prosumer *ia* of community-A
Eib_{ib}	Total storage capacity of storage device of prosumer *ib* of community-B
wia_{ia}	Rate of energy lost during production process for prosumer *ia* of community-A
wib_{ib}	Rate of energy lost during production process for prosumer *ib* community-B
aia_{ia}	Rate of energy lost during charging-storage process for prosumer *ia* of community-A
aib_{ib}	Rate of energy lost during charging-storage process for prosumer *ib* of community-B
hia_{ia}^{t}	Unit production cost of electricity in period *t* for prosumer *ia* of community-A

hib_{ib}^{t}	Unit production cost of electricity in period *t* for prosumer *ib* of community-B
Lia_{ia}^{t}	Electricity production capacity of the renewable resource in period *t* for prosumer *ia* of community-A
Lib_{ib}^{t}	Electricity production capacity of the renewable resource in period *t* for prosumer *ib* of community-B
Dia_{ia}	Total demand of prosumer *ia* of community-A
Dib_{ib}	Total demand of prosumer *ib* of community-B
Dja_{ja}	Total demand of consumer *ja* of community-A
Djb_{jb}	Total demand of consumer *jb* of community-B
Prosumer Selling Prices	
$pija_{ia,ja}^{t}$	Price of electricity kw per hour sold to consumer *ja* of community-A by its prosumer *ia* in period *t*
$pijb_{ib,jb}^{t}$	Price of electricity kw per hour sold to consumer *jb* of community-B by its prosumer *ib* in period *t*
$piia1_{ia}^{t}$	Price of electricity kw per hour sold to aggregator by prosumer *ia* of community-A in period *t*
$piia2_{ib}^{t}$	Price of electricity kw per hour sold to aggregator by prosumer *ib* of community-B in period *t*
Prosumers Buying Prices	
$pia1_{ia}^{t}$	Price of electricity kw per hour bought from aggregator by prosumer *ia* of community-A in period *t*
$pia2_{ib}^{t}$	Price of electricity kw per hour bought from aggregator by prosumer *ib* of community-B in period *t*
$piea_{ia}^{t}$	Price of electricity kw per hour bought from electric utility by prosumer *ia* of community-A in period *t*
$pieb_{ib}^{t}$	Price of electricity kw per hour bought from electric utility by prosumer *ib* of community-B in period *t*

5.6.3C: Variables and Descriptions

zpa_{ia}^{t}	Quantity produced from the renewable resource by prosumer *ia* of community-A in period *t*
zpb_{ib}^{t}	Quantity produced from the renewable resource by prosumer *ib* of community-B in period *t*
zaa_{ia}^{t}	Quantity available after production loss for prosumer *ia* of community-A in period *t*
zab_{ib}^{t}	Quantity available after production loss for prosumer *ib* of community-B in period *t*
yoa_{ia}^{t}	Quantity transferred to storage device in period *t* by prosumer *ia* of community-A
yob_{ib}^{t}	Quantity transferred to storage device in period *t* by prosumer *ib* of community-B
yaa_{ia}^{t}	Quantity acquired from storage device in period *t* by prosumer *ia* of community-A
yab_{ib}^{t}	Quantity acquired from storage device in period *t* by prosumer *ib* of community-B
saa_{ia}^{t}	Actual storage inside the device in period *t* for prosumer *ia* of community-A
sab_{ib}^{t}	Actual storage inside the device in period *t* for prosumer *ib* of community-B
$Ldia_{ia}^{t}$	Proportion of total demand satisfied in period *t* for prosumer *ia* of community-A (load allocations)
$Ldib_{ib}^{t}$	Proportion of total demand satisfied in period *t* for prosumer *ib* of community-B (load allocations)
Selling Quantities	
$xija_{ia,ja}^{t}$	Quantity sold by Prosumer *ia* of community-A to its consumer *ja* in period *t*

$xijb^t_{ib,jb}$	Quantity sold by prosumer *ib* of community-B to its consumer *jb* in period *t*
$xiia1^t_{ia}$	Quantity sold by prosumer *ia* of community-A to aggregator in period *t*
$xiia2^t_{ib}$	Quantity sold by prosumer *ib* of community-B to aggregator in period *t*
$xjaa^t_{ja}$	Quantity sold by aggregator to community-A consumer *ja* in period *t*
$xjba^t_{jb}$	Quantity sold by aggregator to community-B consumer *jb* in period *t*
Prosumer Buying Quantities	
$xia1^t_{ia}$	Quantity bought by prosumer *ia* of community-A from aggregator in period *t*
$xia2^t_{ib}$	Quantity bought by prosumer *ib* of community-B from aggregator in period *t*
$xiea^t_{ia}$	Quantity bought by prosumer *ia* of community-A from electric utility in period *t*
$xieb^t_{ib}$	Quantity bought by prosumer *ib* of community-B from electric utility in period *t*

5.6.3D: Objective Function

Objective Function is to maximize the total profits of prosumers of both communities.

max $\sum_{ia}^{I}\sum_{ja}^{J}\sum_{t}^{T} xija^t_{ia,ja}.\,pija^t_{ia,ja} + \sum_{ib}^{M}\sum_{jb}^{N}\sum_{t}^{T} xijb^t_{ib,jb}.\,pijb^t_{ib,jb}$	Prosumers revenues from directly selling to respective community consumers
$+\sum_{ia}^{I}\sum_{t}^{T} xiia1^t_{ia}.\,piia1^t_{ia} + \sum_{ib}^{M}\sum_{t}^{T} xiia2^t_{ib}.\,piia2^t_{ib}$	Prosumers revenues from selling to aggregator

$- \sum_{ia}^{I} \sum_{t}^{T} xia1_{ia}^{t} . pia1_{ia}^{t}$ $- \sum_{ib}^{M} \sum_{t}^{T} xia2_{ib}^{t} . pia2_{ib}^{t}$	Prosumers cost of buying electricity from aggregator
$- \sum_{ia}^{I} \sum_{t}^{T} xiea_{ia}^{t} . piea_{ia}^{t} - \sum_{ib}^{M} \sum_{t}^{T} xieb_{ib}^{t} . pieb_{ib}^{t}$	Prosumers cost of buying electricity from electric utility
$- \sum_{ia}^{I} \sum_{t}^{T} zpa_{ia}^{t} . hia_{ia}^{t} - \sum_{ib}^{M} \sum_{t}^{T} zpb_{ib}^{t} . hib_{ib}^{t}$	Production costs
$- \sum_{ia}^{I} \sum_{t}^{T} saa_{ia}^{t} . cia_{ia} - \sum_{ib}^{M} \sum_{t}^{T} sab_{ib}^{t} . cib_{ib}$	Storage costs

5.6.3E: Constraints

1	Quantity produced in time period *t* is less than or equal to total production capacity of the renewable resource.
	$zpa_{ia}^{t} \leq Lia_{ia}^{t} \quad \forall\, ia, t \in I, T$ $zpb_{ib}^{t} \leq Lib_{ib}^{t} \quad \forall\, ib, t \in M, T$
2	Quantity available is equal to quantity produced minus loss in time period *t*.
	$zaa_{ia}^{t} = zpa_{ia}^{t} * (1 - wia_{ia}) \quad \forall\, ia, t \in I, T$ $zab_{ib}^{t} = zpb_{ib}^{t} * (1 - wib_{ib}) \quad \forall\, ib, t \in M, T$
3	Storage availability – i.e. what is available inside the storage device in time period *t*.
	$saa_{ia}^{t} = saa_{ia}^{t-1} + (yoa_{ia}^{t} * (1 - aia_{ia})) - yaa_{ia}^{t} \quad \forall\, ia, t \in I, T$ $sab_{ib}^{t} = sab_{ib}^{t-1} + (yob_{ib}^{t} * (1 - aib_{ib})) - yab_{ib}^{t} \quad \forall\, ib, t \in M, T$
4	Storage capacity in time period *t*.
	$saa_{ia}^{t} \leq Eia_{ia} \quad \forall\, ia, t \in I, T$ $sab_{ib}^{t} \leq Eib_{ib} \quad \forall\, ib, t \in M, T$
5	Sum of all load allocations for each community prosumers must be equal to their total demand.

	$$\sum_{t}^{T} Ldia_{ia}^{t} = Dia_{ia} \quad \forall\, ia \in I$$ $$\sum_{t}^{T} Ldib_{ib}^{t} = Dib_{ib} \quad \forall\, ib \in M$$
6	Supplied quantity to consumers is less than or equal to the consumer total demand.
	$$\sum_{ia}^{I}\sum_{t}^{T}(xija_{ia,ja}^{t} + xjaa_{ja}^{t}) \le Dja_{ja} \quad \forall\, ja \in J$$ $$\sum_{ib}^{M}\sum_{t}^{T}(xijb_{ib,jb}^{t} + xjba_{jb}^{t}) \le Djb_{jb} \quad \forall\, jb \in N$$
7	Prosumers balance constraint – all prosumer's inflows are equal to outflows in time period *t*.
	$$zaa_{ia}^{t} + yaa_{ia}^{t} + xia1_{ia}^{t} + xiea_{ia}^{t} = Ldia_{ia}^{t} + \sum_{ja}^{J} xija_{ia,ja}^{t} + xiia1_{ia}^{t} + yoa_{ia}^{t} \quad \forall\, ia, t \in I, T$$ $$zab_{ib}^{t} + yab_{ib}^{t} + xia2_{ib}^{t} + xieb_{ib}^{t} = Ldib_{ib}^{t} + \sum_{jb}^{N} xijb_{ib,jb}^{t} + xiia2_{ib}^{t} + yob_{ib}^{t} \quad \forall\, ib, t \in M, T$$
8	Aggregator balance constraint – all aggregator's inflows are equal to outflows in time period *t*.
	$$\sum_{ia}^{I} xiia1_{ia}^{t} + \sum_{ib}^{M} xiia2_{ib}^{t} = \sum_{ia}^{I} xia1_{ia}^{t} + \sum_{ja}^{J} xjaa_{ja}^{t} + \sum_{ib}^{M} xia2_{ib}^{t} + \sum_{jb}^{N} xjba_{jb}^{t} \quad \forall\, t \in T$$
9	If-else conditions (If prosumers in each community have total production greater than their total demand then no external purchasing is allowed from electric utility and aggregator and else if it is lower then no selling to consumers and aggregator is allowed.)
	Prosumer-A $$\boldsymbol{If} \sum_{t}^{T}\sum_{ia}^{I} Lia_{ia}^{t} \ge \sum_{ia}^{I} Dia_{ia} \;\; \boldsymbol{then}\; xiea_{\boldsymbol{ia}}^{\boldsymbol{t}}, xia1_{\boldsymbol{ia}}^{\boldsymbol{t}} = 0$$

	$$\boldsymbol{Else\ If} \sum_{t}^{T}\sum_{ia}^{I} Lia_{ia}^{t} \leq \sum_{ia}^{I} Dia_{ia}\ \boldsymbol{then}\ xija_{\boldsymbol{ia,ja}}^{\boldsymbol{t}}, xiia1_{\boldsymbol{ia}}^{\boldsymbol{t}} = 0$$ Prosumer-B $$\boldsymbol{If} \sum_{t}^{T}\sum_{ib}^{M} Lib_{ib}^{t} \geq \sum_{ib}^{M} Dib_{ib}\ \boldsymbol{then}\ xieb_{\boldsymbol{ib}}^{\boldsymbol{t}}, xia2_{\boldsymbol{ib}}^{\boldsymbol{t}} = 0$$ $$\boldsymbol{Else\ If} \sum_{t}^{T}\sum_{ib}^{M} Lib_{ib}^{t} \geq \sum_{ib}^{M} Dib_{ib}\ \boldsymbol{then}\ xijb_{\boldsymbol{ib,jb}}^{\boldsymbol{t}}, xiia2_{\boldsymbol{ib}}^{\boldsymbol{t}} = 0$$
10	Non-negativity
	$$zpa_{ia}^{t}, zpb_{ib}^{t}, zaa_{ia}^{t}, zab_{ib}^{t}, yoa_{ia}^{t}, yob_{ib}^{t}, yaa_{ia}^{t}, yab_{ib}^{t}, saa_{ia}^{t}, sab_{ib}^{t},$$ $$Ldia_{ia}^{t}, Ldib_{ib}^{t}, xija_{ia,ja}^{t}, xijb_{ib,jb}^{t}, xiia1_{ia}^{t}, xiia2_{ib}^{t}, xjaa_{ja}^{t}, xjba_{jb}^{t}$$ $$xia1_{ia}^{t}, xia2_{ib}^{t}, xiea_{ia}^{t}, xieb_{ib}^{t} \geq 0$$

5.6.4: Case 3 – Scenario 2

Scenario 2.1: Sharing in two communities through aggregator without selling outside (to electric utility *E*)	Profit maximization of community (ies) (Refer Figure 5.10)
Scenario 2.2: Sharing in two communities through aggregator where aggregator is allowed to sell outside (to electric utility).	Profit maximization of community (ies) (Refer Figure 5.11)

In this scenario, electricity is shared between two communities through the aggregator. Aggregator acts as an agent between two communities and can also buy the electricity from electric utility for the community members. Aggregator does not possess any storage device. Community is considered as a group of consumers and prosumers only, excluding the aggregator.

In scenario 2.1, Aggregator can share community-A electricity only with community-B, which means he is not allowed to sell out side to the electric utility. Figure 5.10 represents the network flows. **In scenario 2.2**, Aggregator is allowed to sell prosumers electricity outside to the electric utility. Figure 5.11 represents the network flows of this scenario.

5.6.4A: Assumptions

In addition to the assumptions that are discussed in case 3 scenario 1, this scenario assumes that aggregator *A* yields higher return by selling to the prosumer *i* and consumer *j* rather than selling to the electric utility *E*. Therefore, for aggregator selling; prosumer/consumer price > electric utility price.

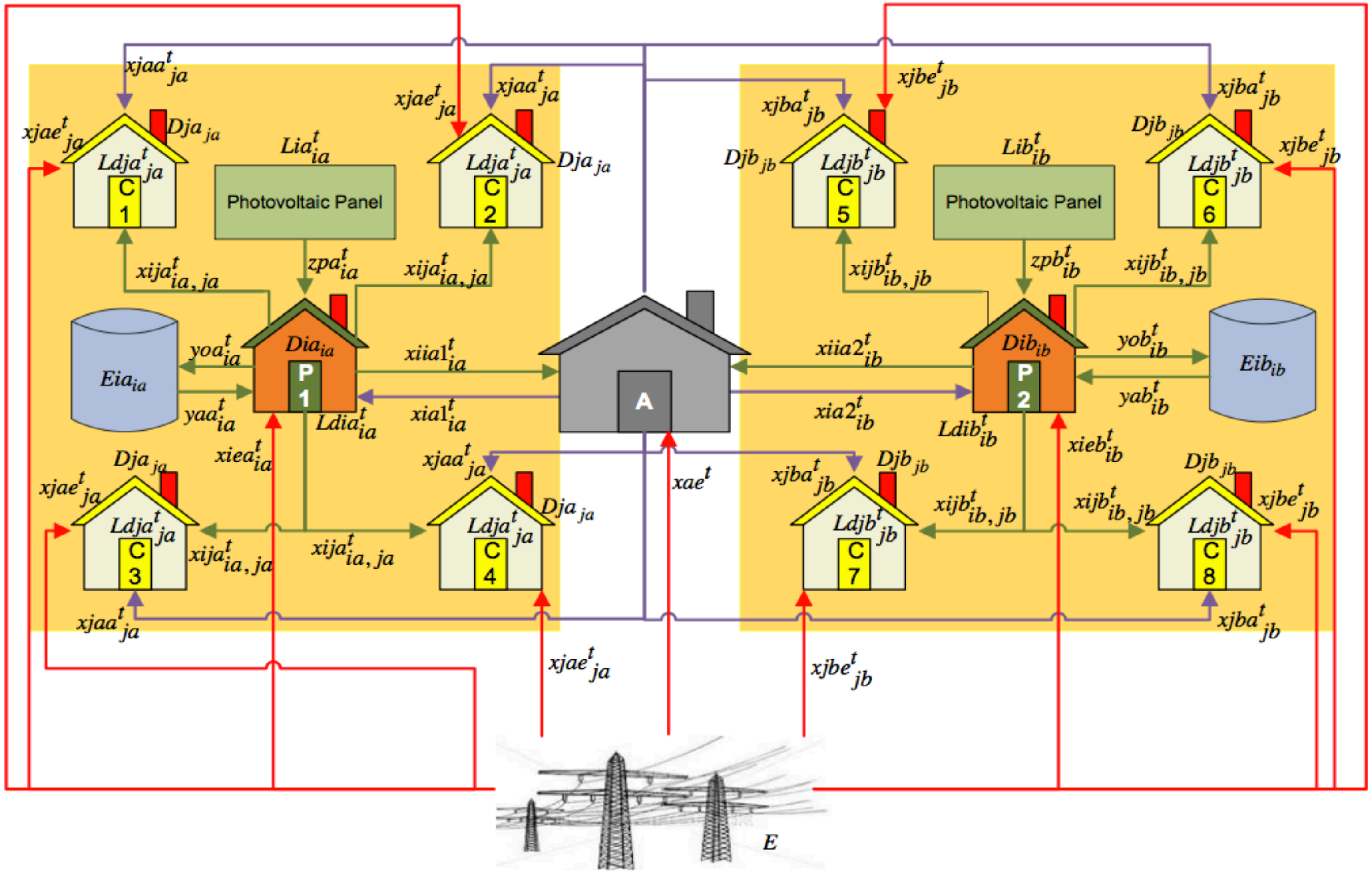


Figure 5.10: Prosumers community sharing (Case 3 - Scenario: 2.1) (Source: author)

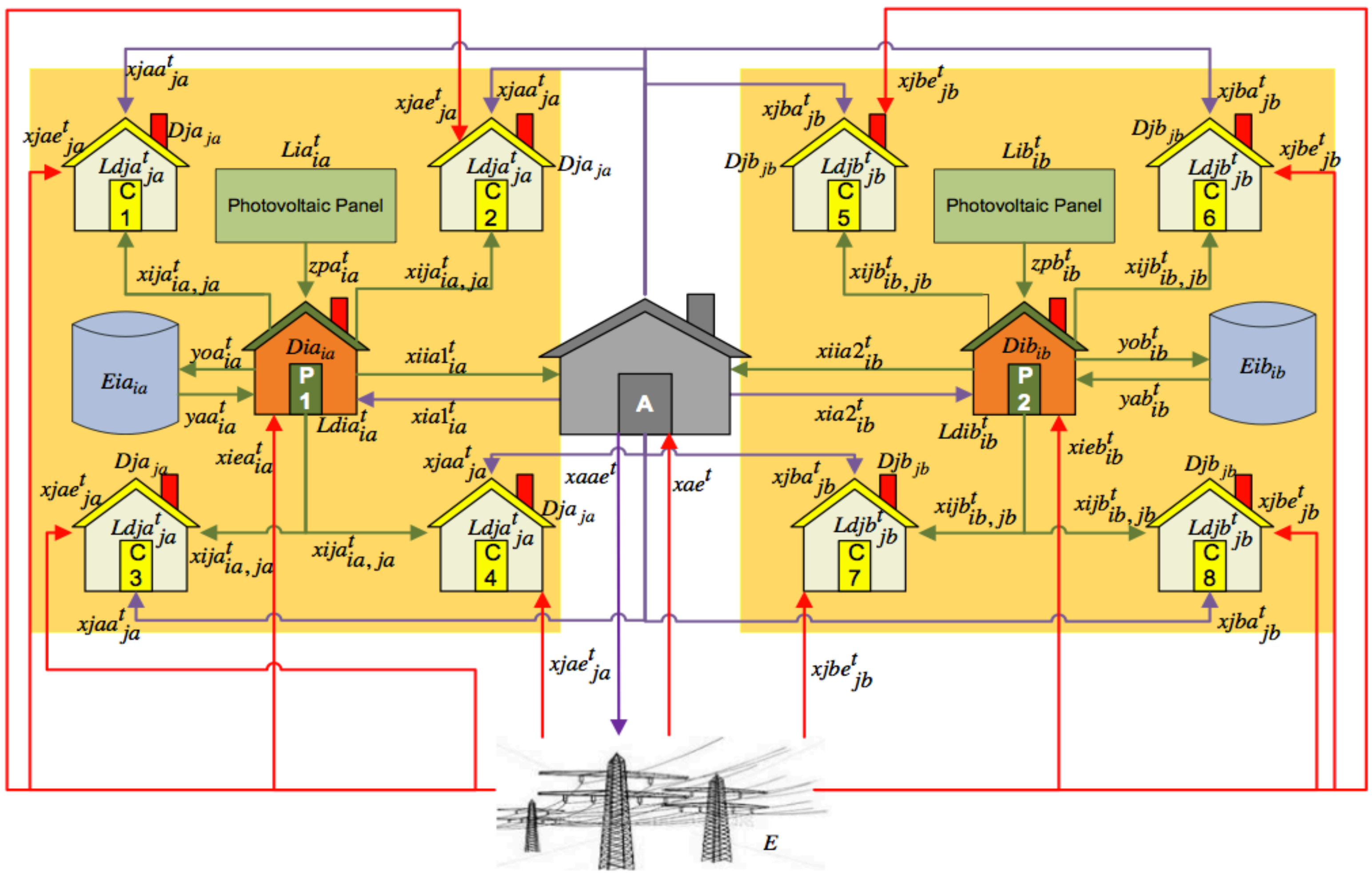


Figure 5.11: Prosumers community sharing (Case 3 - Scenario: 2.2) (Source: author)

5.6.4B: Parameters and Descriptions

Prosumers Parameters	
cia_{ia}	Unit cost of electricity storage for prosumer *ia* of community-A
cib_{ib}	Unit cost of electricity storage for prosumer *ib* of community-B
Eia_{ia}	Total storage capacity of storage device of prosumer *ia* of community-A
Eib_{ib}	Total storage capacity of storage device of prosumer *ib* of community-B
wia_{ia}	Rate of energy lost during production process for prosumer *ia* of community-A
wib_{ib}	Rate of energy lost during production process for prosumer *ib* community-B
aia_{ia}	Rate of energy lost during charging-storage process for prosumer *ia* of community-A
aib_{ib}	Rate of energy lost during charging-storage process for prosumer *ib* of community-B
hia^t_{ia}	Unit production cost of electricity in period *t* for prosumer *ia* of community-A
hib^t_{ib}	Unit production cost of electricity in period *t* for prosumer *ib* of community-B
Lia^t_{ia}	Electricity production capacity of the renewable resource in period *t* for prosumer *ia* of community-A
Lib^t_{ib}	Electricity production capacity of the renewable resource in period *t* for prosumer *ib* of community-B
Dia_{ia}	Total demand of prosumer *ia* of community-A
Dib_{ib}	Total demand of prosumer *ib* of community-B
Prosumer Selling Prices	
$pija^t_{ia,ja}$	Price of electricity kw per hour sold to consumer *ja* by its prosumer *ia* of community–A in time period *t* [*Refer Annex: A1 – No.1*]
$pijb^t_{ib,jb}$	Price of electricity kw per hour sold to consumer *jb* by its prosumer *ib* of

	community–B in time period *t* [*Refer Annex: A1 – No.2*]
$piia1_{ia}^{t}$	Price of electricity kw per hour sold to aggregator by prosumer *ia* of community-A in period *t*
$piia2_{ib}^{t}$	Price of electricity kw per hour sold to aggregator by prosumer *ib* of community-B in period *t*
Prosumers Buying Prices	
$pia1_{ia}^{t}$	Price of electricity kw per hour bought from aggregator by prosumer *ia* of community-A in period *t*
$pia2_{ib}^{t}$	Price of electricity kw per hour bought from aggregator by prosumer *ib* of community-B in period *t*
$piea_{ia}^{t}$	Price of electricity kw per hour bought from electric utility by prosumer *ia* of community-A in period *t*
$pieb_{ib}^{t}$	Price of electricity kw per hour bought from electric utility by prosumer *ib* of community-B in period *t*

Consumers Parameters	
Dja_{ja}	Total demand of consumer *ja* of community-A
Djb_{jb}	Total demand of consumer *jb* of community-B
Consumers Buying Prices	
Refer Annex: A1 – No.1	Price of electricity kw per hour bought from prosumer *ia* of Community-A by its Consumer *ja* in time period *t*
Refer Annex: A1 – No.2	Price of electricity kw per hour bought from prosumer *ib* of Community-B by its Consumer *jb* in time period *t*
$pjaa_{ja}^{t}$	Price of electricity kw per hour bought from aggregator by consumer *ja* of community-A in time period *t*
$pjba_{jb}^{t}$	Price of electricity kw per hour bought from aggregator by consumer *jb* of community-B in time period *t*
$pjae_{ja}^{t}$	Price of electricity kw per hour bought by consumer *ja* of community–A from electric utility in time period *t*

$pjbe_{jb}^{t}$	Price of electricity kw per hour bought by consumer *jb* of community–B from electric utility in time period *t*

Aggregator Parameters	
Aggregator Selling Prices	
$paae^{t}$	Price of electricity kw per hour sold by aggregator to electric utility in time period *t*
Aggregator Buying Prices	
pae^{t}	Price of electricity kw per hour bought by aggregator from electric utility in time period *t*

5.6.4C: Variables and Descriptions

Prosumers Variables	
zpa_{ia}^{t}	Quantity produced from the renewable resource by prosumer *ia* of community-A in period *t*
zpb_{ib}^{t}	Quantity produced from the renewable resource by prosumer *ib* of community-B in period *t*
zaa_{ia}^{t}	Quantity available after production loss for prosumer *ia* of community-A in period *t*
zab_{ib}^{t}	Quantity available after production loss for prosumer *ib* of community-B in period *t*
yoa_{ia}^{t}	Quantity transferred to storage device in period *t* by prosumer *ia* of community-A
yob_{ib}^{t}	Quantity transferred to storage device in period *t* by prosumer *ib* of community-B
yaa_{ia}^{t}	Quantity acquired from storage device in period *t* by prosumer *ia* of community-A
yab_{ib}^{t}	Quantity acquired from storage device in period *t* by prosumer *ib* of

	community-B
saa_{ia}^{t}	Actual storage inside the device in period *t* for prosumer *ia* of community-A
sab_{ib}^{t}	Actual storage inside the device in period *t* for prosumer *ib* of community-B
$Ldia_{ia}^{t}$	Proportion of total demand satisfied in period *t* for prosumer *ia* of community-A (load allocations)
$Ldib_{ib}^{t}$	Proportion of total demand satisfied in period *t* for prosumer *ib* of community-B (load allocations)
Prosumer Selling Quantities	
$xija_{ia,ja}^{t}$	Quantity sold by prosumer *ia* of community-A to its consumer *ja* [*Refer Annex: A1 – No.3*]
$xijb_{ib,jb}^{t}$	Quantity sold by prosumer *ib* of community-B to its consumer *jb* [*Refer Annex: A1 – No.4*]
$xiia1_{ia}^{t}$	Quantity sold by prosumer *ia* of community-A to aggregator in period *t*
$xiia2_{ib}^{t}$	Quantity sold by prosumer *ib* of community-B to aggregator in period *t*
Prosumer Buying Quantities	
$xia1_{ia}^{t}$	Quantity bought by prosumer *ia* of community-A from aggregator in period *t*
$xia2_{ib}^{t}$	Quantity bought by prosumer *ib* of community-B from aggregator in period *t*
$xiea_{ia}^{t}$	Quantity bought by prosumer *ia* of community-A from electric utility in period *t*
$xieb_{ib}^{t}$	Quantity bought by prosumer *ib* of community-B from electric utility in period *t*
Consumers Variables	
$Ldja_{ja}^{t}$	Proportion of total demand satisfied in period *t* for consumer *ja* of community-A (load allocations)
$Ldjb_{jb}^{t}$	Proportion of total demand satisfied in period *t* for consumer *jb* of

	community-B (load allocations)
Consumer Buying Quantities	
[*Refer Annex: A1 – No.3*]	Quantity bought by consumer *ja* of community-A from its prosumer *ia* in time period *t*
[*Refer Annex: A1 – No.4*]	Quantity bought by consumer *jb* of community-B from its prosumer *ib* in time period *t*
$xjaa_{ja}^{t}$	Quantity bought by consumer *ja* of community-A from aggregator in time period *t*
$xjba_{jb}^{t}$	Quantity bought by consumer *jb* of community-B from aggregator in time period *t*
$xjae_{ja}^{t}$	Quantity bought by consumer *ja* of community-A from elect-utility in time period *t*
$xjbe_{jb}^{t}$	Quantity bought by consumer *jb* of community-B from elect-utility in time period *t*
Aggregator Variables	
Aggregator Selling Quantities	
$xaae^{t}$	Quantity sold by aggregator to electric utility in time period *t*
Aggregator Buying Quantities	
xae^{t}	Quantity bought by aggregator from electric utility in time period *t*

5.6.4D: Objective Function – Scenario 2.1

Objective function is to maximize the community profits, where selling to the electric utility is not allowed.

max $\sum_{ia}^{I}\sum_{ja}^{J}\sum_{t}^{T} xija_{ia,ja}^{t}.pija_{ia,ja}^{t} + \sum_{ib}^{M}\sum_{jb}^{N}\sum_{t}^{T} xijb_{ib,jb}^{t}.pijb_{ib,jb}^{t}$	Revenues from directly selling to respective community consumers *[Refer Annex: A2 – No.1]*
$+ \sum_{ia}^{I}\sum_{t}^{T} xiia1_{ia}^{t}.piia1_{ia}^{t} + \sum_{ib}^{M}\sum_{t}^{T} xiia2_{ib}^{t}.piia2_{ib}^{t}$	Revenues from selling to aggregator
$- \sum_{ia}^{I}\sum_{t}^{T} xia1_{ia}^{t}.pia1_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} xia2_{ib}^{t}.pia2_{ib}^{t}$	Prosumers cost of buying electricity from aggregator
$-\sum_{ia}^{I}\sum_{t}^{T} xiea_{ia}^{t}\ .piea_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} xieb_{ib}^{t}\ .pieb_{ib}^{t}$	Prosumers cost of buying electricity from electric utility
$-\sum_{ja}^{J}\sum_{t}^{T} xjaa_{ja}^{t}.pjaa_{ja}^{t} - \sum_{jb}^{N}\sum_{t}^{T} xjba_{jb}^{t}.pjba_{jb}^{t}$	Consumers costs of buying electricity from aggregator
$-\sum_{ja}^{J}\sum_{t}^{T} xjae_{ja}^{t}\ .pjae_{ja}^{t} - \sum_{jb}^{N}\sum_{t}^{T} xjbe_{jb}^{t}\ .pjbe_{jb}^{t}$	Consumers cost of buying electricity from electric utility
$- \sum_{ia}^{I}\sum_{t}^{T} zpa_{ia}^{t}.hia_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} zpb_{ib}^{t}.hib_{ib}^{t}$	Production costs
$- \sum_{ia}^{I}\sum_{t}^{T} saa_{ia}^{t}.cia_{ia} - \sum_{ib}^{M}\sum_{t}^{T} sab_{ib}^{t}.cib_{ib}$	Storage costs

5.6.4E: Constraints – Scenario 2.1

1	Quantity produced in time period *t* is less than or equal to total production capacity of the renewable resource.
	$zpa_{ia}^{t} \leq Lia_{ia}^{t} \quad \forall\, ia, t \in I, T$ $zpb_{ib}^{t} \leq Lib_{ib}^{t} \quad \forall\, ib, t \in M, T$
2	Quantity available is equal to quantity produced minus loss in time period *t*.
	$zaa_{ia}^{t} = zpa_{ia}^{t} * (1 - wia_{ia}) \quad \forall\, ia, t \in I, T$ $zab_{ib}^{t} = zpb_{ib}^{t} * (1 - wib_{ib}) \quad \forall\, ib, t \in M, T$
3	Storage availability – i.e. what is available inside the storage device in time period *t*.
	$saa_{ia}^{t} = saa_{ia}^{t-1} + (yoa_{ia}^{t} * (1 - aia_{ia})) - yaa_{ia}^{t} \quad \forall\, ia, t \in I, T$ $sab_{ib}^{t} = sab_{ib}^{t-1} + (yob_{ib}^{t} * (1 - aib_{ib})) - yab_{ib}^{t} \quad \forall\, ib, t \in M, T$
4	Storage capacity in time period *t*.
	$saa_{ia}^{t} = Eia_{ia} \quad \forall\, ia, t \in I, T$ $sab_{ib}^{t} = Eib_{ib} \quad \forall\, ib, t \in M, T$
5	Sum of all load allocations for each community prosumers must be equal to their total demand.
	$\sum_{t}^{T} Ldia_{ia}^{t} = Dia_{ia} \quad \forall\, ia \in I$ $\sum_{t}^{T} Ldib_{ib}^{t} = Dib_{ib} \quad \forall\, ib \in M$
6	Sum of all load allocations for each community consumers must be equal to their total demand.
	$\sum_{t}^{T} Ldja_{ja}^{t} = Dja_{ja} \quad \forall\, ja \in J$ $\sum_{t}^{T} Ldjb_{jb}^{t} = Djb_{jb} \quad \forall\, jb \in N$
7	Maximum quantity that community consumers can get to satisfy their demand.
	$\sum_{ia}^{I} \sum_{t}^{T} (xija_{ia,ja}^{t} + xjaa_{ja}^{t} + xjae_{ja}^{t}) \leq Dja_{ja} \quad \forall\, ja \in J$

	$\sum_{ib}^{M}\sum_{t}^{T}(xijb_{ib,jb}^{t} + xjba_{jb}^{t} + xjbe_{jb}^{t}) \leq Djb_{jb} \quad \forall jb \in N$
8	Sourcing options by which communities' prosumers can satisfy their own demand and it should be less or equal to their total demand.
	$\sum_{t}^{T}(zaa_{ia}^{t} + yaa_{ia}^{t} + xia1_{ia}^{t} + xiea_{ia}^{t}) - \sum_{ja}^{J}\sum_{t}^{T} xija_{ia,ja}^{t} - \sum_{t}^{T} xiia1_{ia}^{t} \leq Dia_{ia} \quad \forall ia \in I$ $\sum_{t}^{T}(zab_{ib}^{t} + yab_{ib}^{t} + xia2_{ib}^{t} + xieb_{ib}^{t}) - \sum_{jb}^{N}\sum_{t}^{T} xijb_{ib,jb}^{t} - \sum_{t}^{T} xiia2_{ib}^{t} \leq Dib_{ib} \quad \forall ib \in M$
9	Prosumers balance constraint – all prosumer's inflows are equal to outflows in time period *t*.
	$zaa_{ia}^{t} + yaa_{ia}^{t} + xia1_{ia}^{t} + xiea_{ia}^{t} = Ldia_{ia}^{t} + \sum_{ja}^{J} xija_{ia,ja}^{t} + xiia1_{ia}^{t} + yoa_{ia}^{t} \quad \forall ia, t \in I, T$ $zab_{ib}^{t} + yab_{ib}^{t} + xia2_{ib}^{t} + xieb_{ib}^{t} = Ldib_{ib}^{t} + \sum_{jb}^{N} xijb_{ib,jb}^{t} + xiia2_{ib}^{t} + yob_{ib}^{t} \quad \forall ib, t \in M, T$
10	Consumers balance constraint – all consumer's inflows are equal to outflows in time period *t*.
	$\sum_{ia}^{I} xija_{ia,ja}^{t} + xjaa_{ja}^{t} + xjae_{ja}^{t} = Ldja_{ja}^{t} \quad \forall ja, t \in J, T$ $\sum_{ib}^{M} xijb_{ib,jb}^{t} + xjba_{jb}^{t} + xjbe_{jb}^{t} = Ldjb_{jb}^{t} \quad \forall jb, t \in N, T$
11	Aggregator balance constraint – all aggregator's inflows are equal to outflows in time period *t*.
	$\sum_{ia}^{I} xiia1_{ia}^{t} + \sum_{ib}^{M} xiia2_{ib}^{t} + xae^{t} = \sum_{ia}^{I} xia1_{ia}^{t} + \sum_{ja}^{J} xjaa_{ja}^{t} + \sum_{ib}^{M} xia2_{ib}^{t} + \sum_{jb}^{N} xjba_{jb}^{t} \quad \forall t \in T$

12	If-else conditions (If prosumers in each community have total production greater than their total demand then no external purchasing is allowed from electric utility and aggregator and else if it is lower then no selling to consumers and aggregator is allowed.)
	Prosumer-A $$\boldsymbol{If} \sum_{t}^{T}\sum_{ia}^{I} Lia_{ia}^{t} \geq \sum_{ia}^{I} Dia_{ia} \ \boldsymbol{then}\ xiea_{\boldsymbol{ia}}^{\boldsymbol{t}}, xia1_{\boldsymbol{ia}}^{\boldsymbol{t}} = 0$$ $$\boldsymbol{Else\ If} \sum_{t}^{T}\sum_{ia}^{I} Lia_{ia}^{t} \leq \sum_{ia}^{I} Dia_{ia} \ \boldsymbol{then}\ xija_{\boldsymbol{ia,ja}}^{\boldsymbol{t}}, xiia1_{\boldsymbol{ia}}^{\boldsymbol{t}} = 0$$ Prosumer-B $$\boldsymbol{If} \sum_{t}^{T}\sum_{ib}^{I} Lib_{ib}^{t} \geq \sum_{ib}^{I} Dib_{ib} \ \boldsymbol{then}\ xieb_{\boldsymbol{ib}}^{\boldsymbol{t}}, xia2_{\boldsymbol{ib}}^{\boldsymbol{t}} = 0$$ $$\boldsymbol{Else\ If} \sum_{t}^{T}\sum_{ib}^{I} Lib_{ib}^{t} \geq \sum_{ib}^{I} Dib_{ib} \ \boldsymbol{then}\ xijb_{\boldsymbol{ib,jb}}^{\boldsymbol{t}}, xiia2_{\boldsymbol{ib}}^{\boldsymbol{t}} = 0$$
13	Non-negativity
	$$zpa_{ia}^{t}, zpb_{ib}^{t}, zaa_{ia}^{t}, zab_{ib}^{t}, yoa_{ia}^{t}, yob_{ib}^{t}, yaa_{ia}^{t}, yab_{ib}^{t}, saa_{ia}^{t}, sab_{ib}^{t},$$ $$Ldia_{ia}^{t}, Ldib_{ib}^{t}, xija_{ia,ja}^{t}, xijb_{ib,jb}^{t}, xiia1_{ia}^{t}, xiia2_{ib}^{t}, xia1_{ia}^{t}, xia2_{ib}^{t}, xiea_{ia}^{t}, xieb_{ib}^{t},$$ $$Ldja_{ja}^{t}, Ldjb_{jb}^{t}, xjaa_{ja}^{t}, xjba_{jb}^{t}, xjae_{ja}^{t}, xjbe_{jb}^{t}, xae^{t} \geq 0$$

5.6.4F: Objective Function – Scenario 2.2

Objective function is to maximize the community profits, where aggregator can sell prosumers electricity to other communities as well as can also sell to the electric utility E.

max $$\sum_{ia}^{I}\sum_{ja}^{J}\sum_{t}^{T} xija_{ia,ja}^{t} . pija_{ia,ja}^{t}$$ $$+\sum_{ib}^{M}\sum_{jb}^{N}\sum_{t}^{T} xijb_{ib,jb}^{t} . pijb_{ib,jb}^{t}$$	Revenues from selling to respective community consumers *[Refer Annex: A2 – No.1]*

$+\sum_{ia}^{I}\sum_{t}^{T} xiia1_{ia}^{t}.piia1_{ia}^{t}$ $+\sum_{ib}^{M}\sum_{t}^{T} xiia2_{ib}^{t}.piia2_{ib}^{t}$	Revenues from selling to aggregator
$-\sum_{ia}^{I}\sum_{t}^{T} xia1_{ia}^{t}.pia1_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} xia2_{ib}^{t}.pia2_{ib}^{t}$	Prosumers cost of buying electricity from aggregator
$-\sum_{ia}^{I}\sum_{t}^{T} xiea_{ia}^{t}.piea_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} xieb_{ib}^{t}.pieb_{ib}^{t}$	Prosumers cost of buying electricity from electric utility
$-\sum_{ja}^{J}\sum_{t}^{T} xjaa_{ja}^{t}.pjaa_{ja}^{t} - \sum_{jb}^{N}\sum_{t}^{T} xjba_{jb}^{t}.pjba_{jb}^{t}$	Consumers costs of buying electricity from aggregator
$-\sum_{ja}^{J}\sum_{t}^{T} xjae_{ja}^{t}.pjae_{ja}^{t} - \sum_{jb}^{N}\sum_{t}^{T} xjbe_{jb}^{t}.pjbe_{jb}^{t}$	Consumers cost of buying electricity from electric utility
$-\sum_{ia}^{I}\sum_{t}^{T} zpa_{ia}^{t}.hia_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} zpb_{ib}^{t}.hib_{ib}^{t}$	Production costs
$-\sum_{ia}^{I}\sum_{t}^{T} saa_{ia}^{t}.cia_{ia} - \sum_{ib}^{M}\sum_{t}^{T} sab_{ib}^{t}.cib_{ib}$	Storage costs

5.6.4G: Constraints – Scenario 2.2

1	Quantity produced in time period *t* is less than or equal to total production capacity of the renewable resource.
	$zpa_{ia}^{t} \leq Lia_{ia}^{t} \;\; \forall\, ia, t \in I, T$ $zpb_{ib}^{t} \leq Lib_{ib}^{t} \;\; \forall\, ib, t \in M, T$
2	Quantity available is equal to quantity produced minus loss in time period *t*.
	$zaa_{ia}^{t} = zpa_{ia}^{t} * (1 - wia_{ia}) \;\; \forall\, ia, t \in I, T$ $zab_{ib}^{t} = zpb_{ib}^{t} * (1 - wib_{ib}) \;\; \forall\, ib, t \in M, T$
3	Storage availability – i.e. what is available inside the storage device in time period *t*.

	$$saa_{ia}^{t} = saa_{ia}^{t-1} + (yoa_{ia}^{t} * (1 - aia_{ia})) - yaa_{ia}^{t} \quad \forall\, ia, t \in I, T$$ $$sab_{ib}^{t} = sab_{ib}^{t-1} + (yob_{ib}^{t} * (1 - aib_{ib})) - yab_{ib}^{t} \quad \forall\, ib, t \in M, T$$
4	Storage capacity in time period *t*.
	$$saa_{ia}^{t} = Eia_{ia} \quad \forall\, ia, t \in I, T$$ $$sab_{ib}^{t} = Eib_{ib} \quad \forall\, ib, t \in M, T$$
5	Sum of all load allocations for each community prosumers must be equal to their total demand.
	$$\sum_{t}^{T} Ldia_{ia}^{t} = Dia_{ia} \quad \forall\, ia \in I$$ $$\sum_{t}^{T} Ldib_{ib}^{t} = Dib_{ib} \quad \forall\, ib \in M$$
6	Sum of all load allocations for each community consumers must be equal to their total demand.
	$$\sum_{t}^{T} Ldja_{ja}^{t} = Dja_{ja} \quad \forall\, ja \in J$$ $$\sum_{t}^{T} Ldjb_{jb}^{t} = Djb_{jb} \quad \forall\, jb \in N$$
7	Maximum quantity that community consumers can get to satisfy their demand.
	$$\sum_{ia}^{I} \sum_{t}^{T} (xija_{ia,ja}^{t} + xjaa_{ja}^{t} + xjae_{ja}^{t}) \leq Dja_{ja} \quad \forall\, ja \in J$$ $$\sum_{ib}^{M} \sum_{t}^{T} (xijb_{ib,jb}^{t} + xjba_{jb}^{t} + xjbe_{jb}^{t}) \leq Djb_{jb} \quad \forall\, jb \in N$$
8	Sourcing options by which community prosumers can satisfy their own demand and it should be less or equal to their total demand.
	$$\sum_{t}^{T} (zaa_{ia}^{t} + yaa_{ia}^{t} + xia1_{ia}^{t} + xiea_{ia}^{t}) - \sum_{ja}^{J} \sum_{t}^{T} xija_{ia,ja}^{t} - \sum_{t}^{T} xiia1_{ia}^{t} \leq Dia_{ia} \quad \forall\, ia \in I$$ $$\sum_{t}^{T} (zab_{ib}^{t} + yab_{ib}^{t} + xia2_{ib}^{t} + xieb_{ib}^{t}) - \sum_{jb}^{N} \sum_{t}^{T} xijb_{ib,jb}^{t} - \sum_{t}^{T} xiia2_{ib}^{t} \leq Dib_{ib} \quad \forall\, ib \in M$$

9	Prosumers flows balance – all inflows to prosumers are equal to outflows in time period *t*.
	$zaa_{ia}^{t} + yaa_{ia}^{t} + xia1_{ia}^{t} + xiea_{ia}^{t} = Ldia_{ia}^{t} + \sum_{ja}^{J} xija_{ia,ja}^{t} + xiia1_{ia}^{t} + yoa_{ia}^{t} \quad \forall\, ia, t \in I, T$ $zab_{ib}^{t} + yab_{ib}^{t} + xia2_{ib}^{t} + xieb_{ib}^{t} = Ldib_{ib}^{t} + \sum_{jb}^{N} xijb_{ib,jb}^{t} + xiia2_{ib}^{t} + yob_{ib}^{t} \quad \forall\, ib, t \in M, T$
10	Consumers flows balance – all inflows to consumers are equal to outflows in time period *t*.
	$\sum_{ia}^{I} xija_{ia,ja}^{t} + xjaa_{ja}^{t} + xjae_{ja}^{t} = Ldja_{ja}^{t} \quad \forall\, ja, t \in J, T$ $\sum_{ib}^{M} xijb_{ib,jb}^{t} + xjba_{jb}^{t} + xjbe_{jb}^{t} = Ldjb_{jb}^{t} \quad \forall\, jb, t \in N, T$
11	Aggregator flows balance – all inflows to aggregator are equal to outflows in time period *t*.
	$\sum_{ia}^{I} xiia1_{ia}^{t} + \sum_{ib}^{M} xiia2_{ib}^{t} + xae^{t} = \sum_{ia}^{I} xia1_{ia}^{t} + \sum_{ja}^{J} xjaa_{ja}^{t} + \sum_{ib}^{M} xia2_{ib}^{t} + \sum_{jb}^{N} xjba_{jb}^{t} + xaae^{t} \quad \forall\, t \in T$
12	If-else conditions (If prosumers in each community have total production greater than their total demand then no external purchasing is allowed from electric utility and aggregator and else if it is lower then no selling to consumers and aggregator is allowed.)
	Prosumer-A $\boldsymbol{If} \sum_{t}^{T} \sum_{ia}^{I} Lia_{ia}^{t} \geq \sum_{ia}^{I} Dia_{ia} \;\boldsymbol{then}\; xiea_{\boldsymbol{ia}}^{\boldsymbol{t}}, xia1_{\boldsymbol{ia}}^{\boldsymbol{t}} = 0$ $\boldsymbol{Else\ If} \sum_{t}^{T} \sum_{ia}^{I} Lia_{ia}^{t} \leq \sum_{ia}^{I} Dia_{ia} \;\boldsymbol{then}\; xija_{\boldsymbol{ia,ja}}^{\boldsymbol{t}}, xiia1_{\boldsymbol{ia}}^{\boldsymbol{t}} = 0$

	Prosumer-B $$\boldsymbol{If} \sum_{t}^{T}\sum_{ib}^{I} Lib_{ib}^{t} \geq \sum_{ib}^{I} Dib_{ib} \;\; \boldsymbol{then}\; xieb_{\boldsymbol{ib}}^{\boldsymbol{t}}, xia2_{\boldsymbol{ib}}^{\boldsymbol{t}} = 0$$ $$\boldsymbol{Else\ If} \sum_{t}^{T}\sum_{ib}^{I} Lib_{ib}^{t} \geq \sum_{ib}^{I} Dib_{ib} \;\; \boldsymbol{then}\; xijb_{\boldsymbol{ib,jb}}^{\boldsymbol{t}}, xiia2_{\boldsymbol{ib}}^{\boldsymbol{t}} = 0$$
13	Non-negativity
	$$zpa_{ia}^{t}, zpb_{ib}^{t}, zaa_{ia}^{t}, zab_{ib}^{t}, yoa_{ia}^{t}, yob_{ib}^{t}, yaa_{ia}^{t}, yab_{ib}^{t}, saa_{ia}^{t}, sab_{ib}^{t},$$ $$Ldia_{ia}^{t}, Ldib_{ib}^{t}, xija_{ia,ja}^{t}, xijb_{ib,jb}^{t}, xiia1_{ia}^{t}, xiia2_{ib}^{t}, xia1_{ia}^{t}, xia2_{ib}^{t}, xiea_{ia}^{t}, xieb_{ib}^{t},$$ $$Ldja_{ja}^{t}, Ldjb_{jb}^{t}, xjaa_{ja}^{t}, xjba_{jb}^{t}, xjae_{ja}^{t}, xjbe_{jb}^{t}, xae^{t}, xaae^{t} \geq 0$$

5.6.5: Case 3 – Scenario 3

Scenario 3: Sharing in two communities through aggregator by allowing market selling	Profit maximization of all communities (Network Perspective) (Refer Figure 5.12)

In this scenario, electricity is shared between two communities through the aggregator. Aggregator acts as a community agent and market buyer. This scenario evaluates the profits of all communities by including the aggregator, as highlighted in the Figure 5.12

5.6.5A: Assumptions

This scenario holds the same assumptions that are discussed in case 3 scenario 1 and 2.

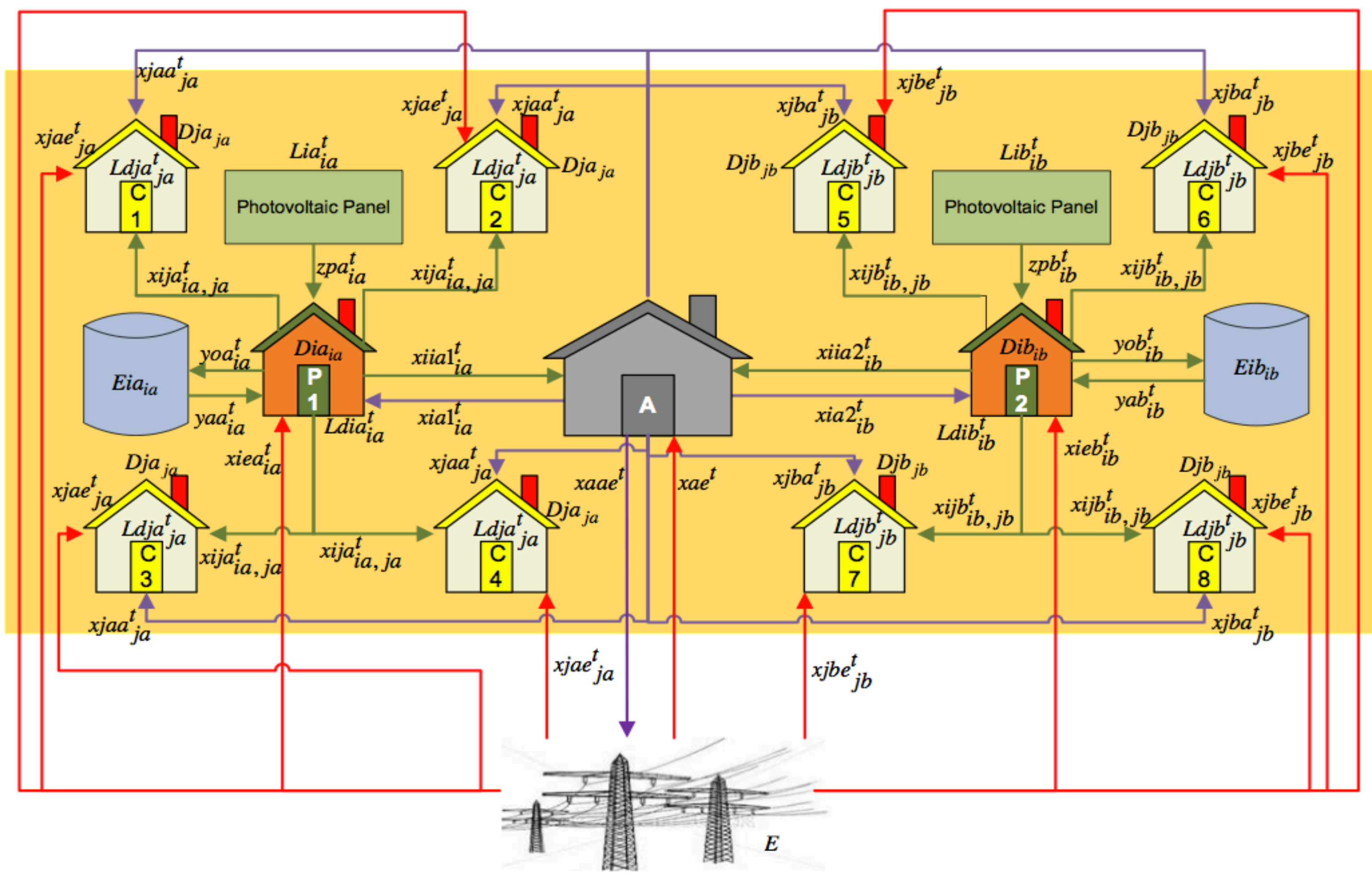


Figure 5.12: Prosumers community sharing (Scenario: 3) (Source: author)

5.6.5B: Parameters and Descriptions

Prosumers Parameters	
cia_{ia}	Unit cost of electricity storage for prosumer *ia* of community-A
cib_{ib}	Unit cost of electricity storage for prosumer *ib* of community-B
Eia_{ia}	Total storage capacity of storage device of prosumer *ia* of community-A
Eib_{ib}	Total storage capacity of storage device of prosumer *ib* of community-B
wia_{ia}	Rate of energy lost during production process for prosumer *ia* of community-A
wib_{ib}	Rate of energy lost during production process for prosumer *ib* community-B
aia_{ia}	Rate of energy lost during charging-storage process for prosumer *ia* of community-A
aib_{ib}	Rate of energy lost during charging-storage process for prosumer *ib* of community-B
hia_{ia}^{t}	Unit production cost of electricity in period *t* for prosumer *ia* of community-A
hib_{ib}^{t}	Unit production cost of electricity in period *t* for prosumer *ib* of community-B
Lia_{ia}^{t}	Electricity production capacity of the renewable resource in period *t* for prosumer *ia* of community-A
Lib_{ib}^{t}	Electricity production capacity of the renewable resource in period *t* for prosumer *ib* of community-B
Dia_{ia}	Total demand of prosumer *ia* of community-A
Dib_{ib}	Total demand of prosumer *ib* of community-B
Prosumer Selling Prices	
$pija_{ia,ja}^{t}$	Price of electricity kw per hour sold to consumer *ja* by its prosumer *ia* of community–A in time period *t* [*Refer Annex: A3 – No. 1*]

$pijb^{t}_{ib,jb}$	Price of electricity kw per hour sold to consumer *jb* by its prosumer *ib* of community–B in time period *t* [*Refer Annex: A3 – No. 2*]
$piia1^{t}_{ia}$	Price of electricity kw per hour sold to aggregator by prosumer *ia* of community-A in period *t* [*Refer Annex: A3 – No. 3*]
$piia2^{t}_{ib}$	Price of electricity kw per hour sold to aggregator by prosumer *ib* of community-B in period *t* [*Refer Annex: A3 – No. 4*]
Prosumers Buying Prices	
$pia1^{t}_{ia}$	Price of electricity kw per hour bought from aggregator by prosumer *ia* of community-A in period *t* [*Refer Annex: A3 – No. 5*]
$pia2^{t}_{ib}$	Price of electricity kw per hour bought from aggregator by prosumer *ib* of community-B in period *t* [*Refer Annex: A3 – No. 6*]
$piea^{t}_{ia}$	Price of electricity kw per hour bought from electric utility by prosumer *ia* of community-A in period *t*
$pieb^{t}_{ib}$	Price of electricity kw per hour bought from electric utility by prosumer *ib* of community-B in period *t*

Consumers Parameters	
Dja_{ja}	Total demand of consumer *ja* of community-A
Djb_{jb}	Total demand of consumer *jb* of community-B
Consumers Buying Prices	
Refer Annex: A3 – No. 1	Price of electricity kw per hour bought from prosumer *ia* of community-A by its Consumer *ja* in time period *t*
Refer Annex: A3 – No. 2	Price of electricity kw per hour bought from prosumer *ib* of community-B by its Consumer *jb* in time period *t*
$pjaa^{t}_{ja}$	Price of electricity kw per hour bought from aggregator by consumer *ja* of community-A in time period *t* [*Refer Annex: A3 – No. 7*]
$pjba^{t}_{jb}$	Price of electricity kw per hour bought from aggregator by consumer *jb* of community-B in time period *t* [*Refer Annex: A3 – No. 8*]
$pjae^{t}_{ja}$	Price of electricity kw per hour bought by consumer *ja* of community–A

	from Electric Utility in time period *t*
$pjbe_{jb}^{t}$	Price of electricity kw per hour bought by consumer *jb* of community–B from Electric Utility in time period *t*
Aggregator Parameters	
Aggregator Selling Prices	
$paae^{t}$	Price of electricity kw per hour sold by aggregator to electric utility in time period *t*
Refer Annex: A3 – No. 5	Price of electricity kw per hour sold by aggregator to prosumer *ia* of community-A in time period *t*
Refer Annex: A3 – No. 6	Price of electricity kw per hour sold by aggregator to prosumer *ib* of community-B in time period *t*
Refer Annex: A3 – No. 7	Price of electricity kw per hour sold by aggregator to consumer *ja* of community-A in time period *t* in time period *t*
Refer Annex: A3 – No. 8	Price of electricity kw per hour sold by aggregator to consumer *jb* of community-B
Aggregator Buying Prices	
pae^{t}	Price of electricity kw per hour bought by aggregator from electric utility in time period *t*
Refer Annex: A3 – No. 3	Price of electricity kw per hour bought by aggregator from prosumer *ia* of community-A in time period *t*
Refer Annex: A3 – No. 4	Price of electricity kw per hour bought by aggregator from prosumer *ib* of community-B in time period *t*

5.6.5C: Variables and Descriptions

Prosumers Variables	
zpa_{ia}^{t}	Quantity produced from the renewable resource by prosumer *ia* of community-A in period *t*
zpb_{ib}^{t}	Quantity produced from the renewable resource by prosumer *ib* of

	community-B in period *t*
zaa_{ia}^{t}	Quantity available after production loss for prosumer *ia* of community-A in period *t*
zab_{ib}^{t}	Quantity available after production loss for prosumer *ib* of community-B in period *t*
yoa_{ia}^{t}	Quantity transferred to storage device in period *t* by prosumer *ia* of community-A
yob_{ib}^{t}	Quantity transferred to storage device in period *t* by prosumer *ib* of community-B
yaa_{ia}^{t}	Quantity acquired from storage device in period *t* by prosumer *ia* of community-A
yab_{ib}^{t}	Quantity acquired from storage device in period *t* by prosumer *ib* of community-B
saa_{ia}^{t}	Actual storage inside the device in period *t* for prosumer *ia* of community-A
sab_{ib}^{t}	Actual storage inside the device in period *t* for prosumer *ib* of community-B
$Ldia_{ia}^{t}$	Proportion of total demand satisfied in period *t* for prosumer *ia* of community-A (load allocations)
$Ldib_{ib}^{t}$	Proportion of total demand satisfied in period *t* for prosumer *ib* of community-B (load allocations)
Prosumer Selling Quantities	
$xija_{ia,ja}^{t}$	Quantity sold by prosumer *ia* of community-A to its consumer *ja* in time period *t* [*Refer Annex: A3 – No. 9*]
$xijb_{ib,jb}^{t}$	Quantity sold by prosumer *ib* of community-B to its consumer *jb* in time period *t* [*Refer Annex: A3 – No. 10*]
$xiia1_{ia}^{t}$	Quantity sold by prosumer *ia* of community-A to aggregator in time period *t* [*Refer Annex: A3 – No. 11*]
$xiia2_{ib}^{t}$	Quantity sold by prosumer *ib* of community-B to aggregator in time period

	t [*Refer Annex: A3 – No. 12*]
Prosumer Buying Quantities	
$xia1_{ia}^{t}$	Quantity bought by prosumer *ia* of community-A from aggregator in time period *t* [*Refer Annex: A3 – No. 13*]
$xia2_{ib}^{t}$	Quantity bought by prosumer *ib* of community-B from aggregator in time period *t* [*Refer Annex: A3 – No. 14*]
$xiea_{ia}^{t}$	Quantity bought by prosumer *ia* of community-A from electric utility in time period *t*
$xieb_{ib}^{t}$	Quantity bought by prosumer *ib* of community-B from electric utility in time period *t*

Consumers Variables	
$Ldja_{ja}^{t}$	Proportion of total demand satisfied in period *t* for consumer *ja* of community-A (load allocations)
$Ldjb_{jb}^{t}$	Proportion of total demand satisfied in period *t* for consumer *jb* of community-B (load allocations)
Consumer Buying Quantities	
Refer Annex: A3 – No. 9	Quantity bought by consumer *ja* of community-A from its prosumer *ia* in time period *t*
Refer Annex: A3 – No. 10	Quantity bought by consumer *jb* of community-B from its prosumer *ib* in time period *t*
$xjaa_{ja}^{t}$	Quantity bought by consumer *ja* of community-A from aggregator in time period *t* [*Refer Annex: A3 – No. 15*]
$xjba_{jb}^{t}$	Quantity bought by consumer *jb* of community-B from aggregator in time period *t* [*Refer Annex: A3 – No. 16*]
$xjae_{ja}^{t}$	Quantity bought by consumer *ja* of community-A from electric utility in time period *t*
$xjbe_{jb}^{t}$	Quantity bought by consumer *jb* of community-B from electric utility in time period *t*

Aggregator Variables	
Aggregator Selling Quantities	
$xaae^t$	Quantity sold by aggregator to electric utility in time period *t*
Refer Annex: A3 – No. 13	Quantity sold by aggregator to prosumer *ia* of community-A in time period *t*
Refer Annex: A3 – No. 14	Quantity sold by aggregator to prosumer *ib* of community-B in time period *t*
Refer Annex: A3 – No. 15	Quantity sold by aggregator to consumer *ja* of community–A in time period *t*
Refer Annex: A3 – No. 16	Quantity sold by aggregator to consumer *jb* of community–B in time period *t*
	Aggregator Buying Quantities
xae^t	Quantity bought by aggregator from electric utility in time period *t*
Refer Annex: A3 – No. 11	Quantity bought by aggregator from prosumer *ia* of community-A in time period *t*
Refer Annex: A3 – No. 12	Quantity bought by aggregator from prosumer *ib* of community-B in time period *t*

5.6.5D: Objective Function

Objective function is to maximize the profits of all communities including the aggregator.

$max \sum_{ia}^{I}\sum_{ja}^{J}\sum_{t}^{T} xija_{ia,ja}^{t}.pija_{ia,ja}^{t} + \sum_{ib}^{M}\sum_{jb}^{N}\sum_{t}^{T} xijb_{ib,jb}^{t}.pijb_{ib,jb}^{t}$	Prosumers revenues from selling to respective community consumers *[Refer Annex: A4 – No. 1]*

$+ \sum_{ia}^{I} \sum_{t}^{T} xiia1_{ia}^{t} . piia1_{ia}^{t} + \sum_{ib}^{M} \sum_{t}^{T} xiia2_{ib}^{t} . piia2_{ib}^{t}$	Prosumers revenues from selling to aggregator *[Refer Annex: A4 – No. 2]* *[Refer Annex: A5 – No. 1]*
$+ \sum_{t}^{T} xaae^{t} . paae^{t}$	Aggregator revenues from selling to electric utility
$+ \sum_{ia}^{I} \sum_{t}^{T} xia1_{ia}^{t} . pia1_{ia}^{t} + \sum_{ib}^{M} \sum_{t}^{T} xia2_{ib}^{t} . pia2_{ib}^{t}$	Aggregator revenues from selling to prosumers *[Refer Annex: A4 – No. 3]* *[Refer Annex: A5 – No. 2]*
$+ \sum_{ja}^{J} \sum_{t}^{T} xjaa_{ja}^{t} . pjaa_{ja}^{t} + \sum_{jb}^{N} \sum_{t}^{T} xjba_{jb}^{t} . pjba_{jb}^{t}$	Aggregator revenues from selling to consumers *[Refer Annex: A4 – No. 4]* *[Refer Annex: A5 – No. 3]*
$- \sum_{ia}^{I} \sum_{t}^{T} xia1_{ia}^{t} . pia1_{ia}^{t} - \sum_{ib}^{M} \sum_{t}^{T} xia2_{ib}^{t} . pia2_{ib}^{t}$	Prosumers cost of buying from aggregator *[Refer Annex: A4 – No. 3]* *[Refer Annex: A5 – No. 2]*
$- \sum_{ia}^{I} \sum_{t}^{T} xiea_{ia}^{t} . piea_{ia}^{t} - \sum_{ib}^{M} \sum_{t}^{T} xieb_{ib}^{t} . pieb_{ib}^{t}$	Prosumers cost of buying from electric utility
$- \sum_{ja}^{J} \sum_{t}^{T} xjaa_{ja}^{t} . pjaa_{ja}^{t} - \sum_{jb}^{N} \sum_{t}^{T} xjba_{jb}^{t} . pjba_{jb}^{t}$	Consumers costs of buying from aggregator *[Refer Annex: A4 – No. 4]* *[Refer Annex: A5 – No. 3]*
$- \sum_{ja}^{J} \sum_{t}^{T} xjae_{ja}^{t} . pjae_{ja}^{t} - \sum_{jb}^{N} \sum_{t}^{T} xjbe_{jb}^{t} . pjbe_{jb}^{t}$	Consumers cost of buying from electric utility
$- \sum_{t}^{T} xae^{t} . pae^{t}$	Aggregator costs of buying from electric utility

$- \sum_{ia}^{I} \sum_{t}^{T} xiia1_{ia}^{t} . piia1_{ia}^{t}$ $- \sum_{ib}^{M} \sum_{t}^{T} xiia2_{ib}^{t} . piia2_{ib}^{t}$	Aggregator costs of buying from prosumers *[Refer Annex: A4 – No. 2]* *[Refer Annex: A5 – No. 1]*
$- \sum_{ia}^{I} \sum_{t}^{T} zpa_{ia}^{t} . hia_{ia}^{t} - \sum_{ib}^{M} \sum_{t}^{T} zpb_{ib}^{t} . hib_{ib}^{t}$	Production costs
$- \sum_{ia}^{I} \sum_{t}^{T} saa_{ia}^{t} . cia_{ia} - \sum_{ib}^{M} \sum_{t}^{T} sab_{ib}^{t} . cib_{ib}$	Storage costs

5.6.5E: Constraints

1	Quantity produced in time period *t* is less than or equal to total production capacity of the renewable resource.
	$zpa_{ia}^{t} \leq Lia_{ia}^{t} \quad \forall\, ia, t \in I, T$ $zpb_{ib}^{t} \leq Lib_{ib}^{t} \forall\, ib, t \in M, T$
2	Quantity available is equal to quantity produced minus loss in time period *t*.
	$zaa_{ia}^{t} = zpa_{ia}^{t} * (1 - wia_{ia}) \quad \forall\, ia, t \in I, T$ $zab_{ib}^{t} = zpb_{ib}^{t} * (1 - wib_{ib}) \quad \forall\, ib, t \in M, T$
3	Storage availability – i.e. what is available inside the storage device in time period *t*.
	$saa_{ia}^{t} = saa_{ia}^{t-1} + (yoa_{ia}^{t} * (1 - aia_{ia})) - yaa_{ia}^{t} \quad \forall\, ia, t \in I, T$ $sab_{ib}^{t} = sab_{ib}^{t-1} + (yob_{ib}^{t} * (1 - aib_{ib})) - yab_{ib}^{t} \quad \forall\, ib, t \in M, T$
4	Storage capacity in time period *t*.
	$saa_{ia}^{t} = Eia_{ia} \quad \forall\, ia, t \in I, T$ $sab_{ib}^{t} = Eib_{ib} \quad \forall\, ib, t \in M, T$
5	Sum of all load allocations for each community prosumers must be equal to their total demand.
	$\sum_{t}^{T} Ldia_{ia}^{t} = Dia_{ia} \quad \forall\, ia \in I$

	$$\sum_{t}^{T} Ldib_{ib}^{t} = Dib_{ib} \quad \forall\, ia \in M$$
6	Sum of all load allocations for each community consumers must be equal to their total demand.
	$$\sum_{t}^{T} Ldja_{ja}^{t} = Dja_{ja} \quad \forall\, ja \in J$$ $$\sum_{t}^{T} Ldjb_{jb}^{t} = Djb_{jb} \quad \forall\, jb \in N$$
7	Sourcing options by which community prosumers can satisfy their own demand and it should be less or equal to their total demand.
	$$\sum_{t}^{T} (zaa_{ia}^{t} + yaa_{ia}^{t} + xia1_{ia}^{t} + xiea_{ia}^{t}) - \sum_{ja}^{J} \sum_{t}^{T} xija_{ia,ja}^{t} - \sum_{t}^{T} xiia1_{ia}^{t} \leq Dia_{ia} \quad \forall\, ia \in I$$ $$\sum_{t}^{T} (zab_{ib}^{t} + yab_{ib}^{t} + xia2_{ib}^{t} + xieb_{ib}^{t}) - \sum_{jb}^{N} \sum_{t}^{T} xijb_{ib,jb}^{t} - \sum_{t}^{T} xiia2_{ib}^{t} \leq Dib_{ib} \quad \forall\, ib \in M$$
8	Prosumers flows balance – all inflows to prosumers are equal to outflows in time period *t*.
	$$zaa_{ia}^{t} + yaa_{ia}^{t} + xia1_{ia}^{t} + xiea_{ia}^{t} = Ldia_{ia}^{t} + \sum_{ja}^{J} xija_{ia,ja}^{t} + xiia1_{ia}^{t} + yoa_{ia}^{t} \quad \forall\, ia, t \in I, T$$ $$zab_{ib}^{t} + yab_{ib}^{t} + xia2_{ib}^{t} + xieb_{ib}^{t} = Ldib_{ib}^{t} + \sum_{jb}^{N} xijb_{ib,jb}^{t} + xiia2_{ib}^{t} + yob_{ib}^{t} \quad \forall\, ib, t \in M, T$$
9	Consumers flows balance – all inflows to consumers are equal to outflows in time period *t*.
	$$\sum_{ia}^{I} xija_{ia,ja}^{t} + xjaa_{ja}^{t} + xjae_{ja}^{t} = Ldja_{ja}^{t} \quad \forall\, ja, t \in J, T$$ $$\sum_{ib}^{M} xijb_{ib,jb}^{t} + xjba_{jb}^{t} + xjbe_{jb}^{t} = Ldjb_{jb}^{t} \quad \forall\, jb, t \in N, T$$
10	Aggregator flows balance – all inflows to aggregator are equal to outflows in time

	period *t*.
	$$\sum_{ia}^{I} xiia1_{ia}^{t} + \sum_{ib}^{M} xiia2_{ib}^{t} + xae^{t} = \sum_{ia}^{I} xia1_{ia}^{t} + \sum_{ja}^{J} xjaa_{ja}^{t} + \sum_{ib}^{M} xia2_{ib}^{t} + \sum_{jb}^{N} xjba_{jb}^{t} + xaae^{t} \quad \forall\, t\, \in T$$
11	If-else conditions (If prosumers in each community have total production greater than their total demand then no external purchasing is allowed from electric utility and aggregator and else if it is lower then no selling to consumers and aggregator is allowed.)
	Prosumer-A $$\boldsymbol{If} \sum_{t}^{T}\sum_{ia}^{I} Lia_{ia}^{t} \geq \sum_{ia}^{I} Dia_{ia} \ \boldsymbol{then}\ xiea_{\boldsymbol{ia}}^{\boldsymbol{t}}, xia1_{\boldsymbol{ia}}^{\boldsymbol{t}} = 0$$ $$\boldsymbol{Else\ If} \sum_{t}^{T}\sum_{ia}^{I} Lia_{ia}^{t} \leq \sum_{ia}^{I} Dia_{ia} \ \boldsymbol{then}\ xija_{\boldsymbol{ia,ja}}^{\boldsymbol{t}}, xiia1_{\boldsymbol{ia}}^{\boldsymbol{t}} = 0$$ Prosumer-B $$\boldsymbol{If} \sum_{t}^{T}\sum_{ib}^{M} Lib_{ib}^{t} \geq \sum_{ib}^{M} Dib_{ib} \ \boldsymbol{then}\ xieb_{\boldsymbol{ib}}^{\boldsymbol{t}}, xia2_{\boldsymbol{ib}}^{\boldsymbol{t}} = 0$$ $$\boldsymbol{Else\ If} \sum_{t}^{T}\sum_{ib}^{M} Lib_{ib}^{t} \geq \sum_{ib}^{M} Dib_{ib} \ \boldsymbol{then}\ xijb_{\boldsymbol{ib,jb}}^{\boldsymbol{t}}, xiia2_{\boldsymbol{ib}}^{\boldsymbol{t}} = 0$$
14	Non-negativity
	$$zpa_{ia}^{t}, zpb_{ib}^{t}, zaa_{ia}^{t}, zab_{ib}^{t}, yoa_{ia}^{t}, yob_{ib}^{t}, yaa_{ia}^{t}, yab_{ib}^{t}, saa_{ia}^{t}, sab_{ib}^{t}, Ldia_{ia}^{t}, Ldib_{ib}^{t}, xija_{ia,ja}^{t}, xijb_{ib,jb}^{t}, xiia1_{ia}^{t}, xiia2_{ib}^{t}, xia1_{ia}^{t}, xia2_{ib}^{t}, xiea_{ia}^{t}, xieb_{ib}^{t}, Ldja_{ja}^{t}, Ldjb_{jb}^{t}, xjaa_{ja}^{t}, xjba_{jb}^{t}, xjae_{ja}^{t}, xjbe_{jb}^{t}, xae^{t}, xaae^{t} \quad \geq 0$$

Chapter Summary

The challenges to electricity grids arise from supply side as well as from the demand side. At the supply side, increasing integration of renewable energy resources (RERs) is bringing two main challenges. It includes less stability of the RERs because of the uncontrollable fluctuation and secondly the reverse flows originating from the supply surplus. At the demand side, increasing energy demands along with new forms of electricity loads (such as electric vehicles) are putting grids infrastructure under the pressure in terms of capacity constraints and supply reliability. To effectively deal with such issues, smart grids emphasize the need of collaborative platforms that can enable the local generations. These local generations, where demand and supply can be more locally balanced, require participation of proactive consumers. The previous chapter has presented a detailed analysis, related to shifting the consumption trends to a more collaborative process, for seeking consumers' active participation towards grid reliability. This chapter has presented and discussed an analytical energy-sharing model to facilitate consumers in managing their smart energy demand. The purpose of the analytical model is to demonstrate how consumers demand flexibility (i.e. response) in the social context (community) can be beneficial towards locally balancing the supply and demand. Proactive consumers having accesses to the adequate collaboration platforms, equipped with sophisticated intelligent techniques, may increase the capability to effectively manage the demand profile. Accordingly, the energy-sharing model is categorized into three main cases depending on the proactive consumers collaboration level towards energy sustainability. These cases include Prosumer-to-Company, Prosumer-to-Consumers, and Prosumers-to-Prosumers collaboration level. Linear programming (LP) is used to formulate all the network flows in the cases. Considering the multiple attributes (related to consumption and production) in the model increases the complexity level and therefore, requires an optimal solution for the clear understanding. Different collaboration cases explain that consumers' active participation can provide them more choices and a higher flexibility towards managing their energy demand with lower costs.

CHAPTER 6: TEST AND VALIDATION

Chapter Abstract

In the previous chapter, we have presented and formulated an energy-shared network model to demonstrate consumers' active participation towards energy sustainability. Accordingly, in this chapter we tested and validated our developed model. The chapter starts with the discussion related to test and validation process, and the steps involved in each process. For testing phase, we implemented and solved the decision models through the GAMS and obtained the optimal solutions, the same is presented and discussed. We also performed the Design of Experiments that is discussed in detail. For the validation phase, we empirically tested our model by using real data of a company. The chapter concludes by presenting a detailed discussion related to experiment results.

6.1: Model Testing and Validation

The model testing and its validation are key processes for assessing the reliability of the analytical models. Model testing help us to determine whether the model implementation is correct and accurately represents the conceptual descriptions of the model. Model validation demonstrates that the model specifications are a reasonable representation of the actual system.

For the testing and the validation process of the model (which is presented in the previous chapter), we performed the following steps:

- For testing phase: All decision models are solved and generated their respective optimal solutions. Along this, different design of experiments is also performed.

- For the validation: Energy-shared network model is empirically tested by using the real input parameter values and their distribution.

6.2: Optimal Solutions

We have developed an energy-shared community network model that optimizes the energy sharing among the groups of consumers at their community level. To develop this network model, we started with the single proactive consumer collaborating with the electric utility, and then we enlarged the model according to the collaboration level in a network perspective. Each decision model (based on the collaboration level) is implemented and solved through General Algebraic Modeling System (GAMS) and the CPLEX optimization engine. GAMS provided us the optimal solutions for every decision model. Optimal solutions verified that all equations and constraints in every decision model are implemented correctly and are equally satisfied.

As an example, Figure 6.1 visualizes a decision model where electricity is shared between two communities through the aggregator. Prosumers and consumers participate in energy demand management to collectively optimize the communities' profits. In this model, the aggregator acts as an agent between these two communities, and buys the electricity from the electric utility for the community members. Excess electricity production is only sold to electric utility when the community members do not require it. Community–A members (prosumer and consumers) fulfill their demands from the internal production resource (renewable energy resource). On the other hand, to manage the unsatisfied electricity demands of community–B, the aggregator buys the electricity for its consumers from the electric utility and from the prosumer of community–A. The network flows based on the optimal solution are depicted in Figure 6.2.

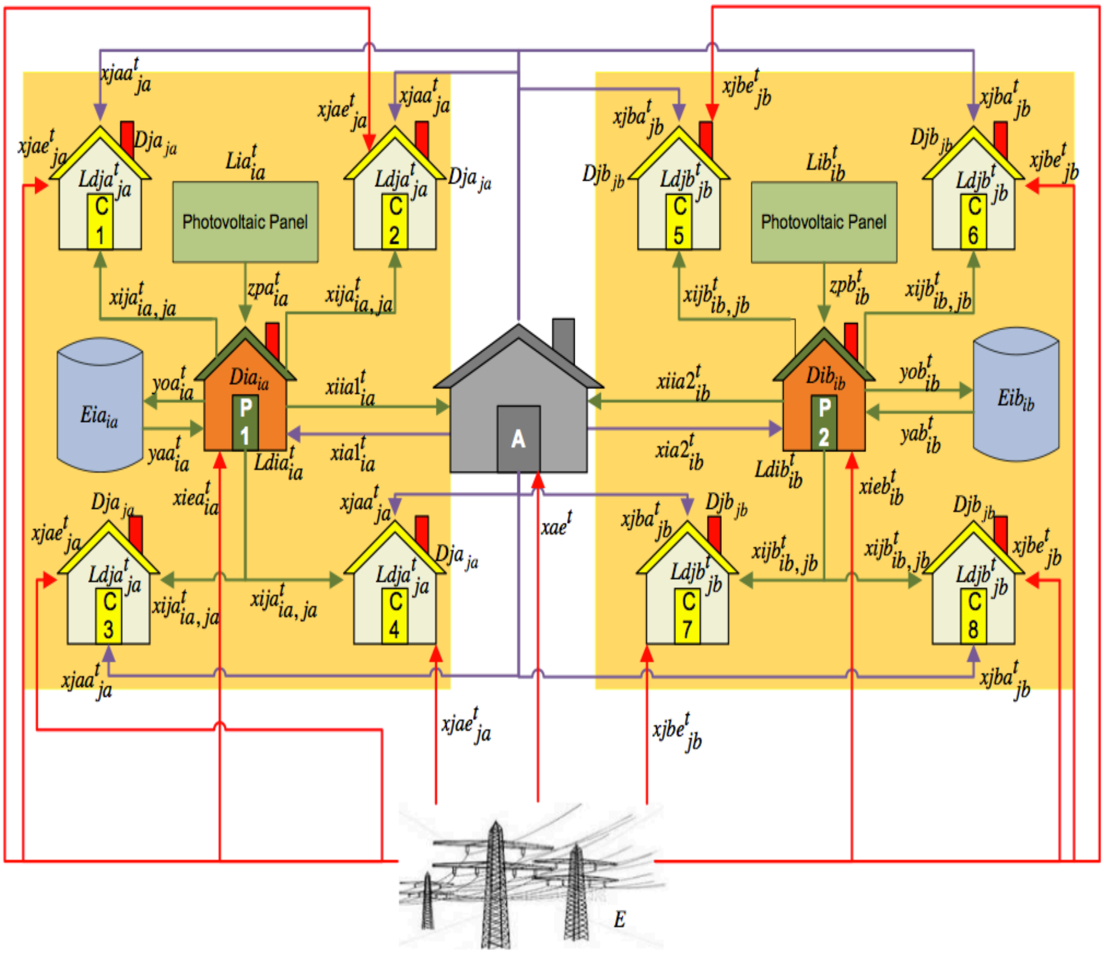


Figure 6.1: Prosumers community sharing (Source: author)

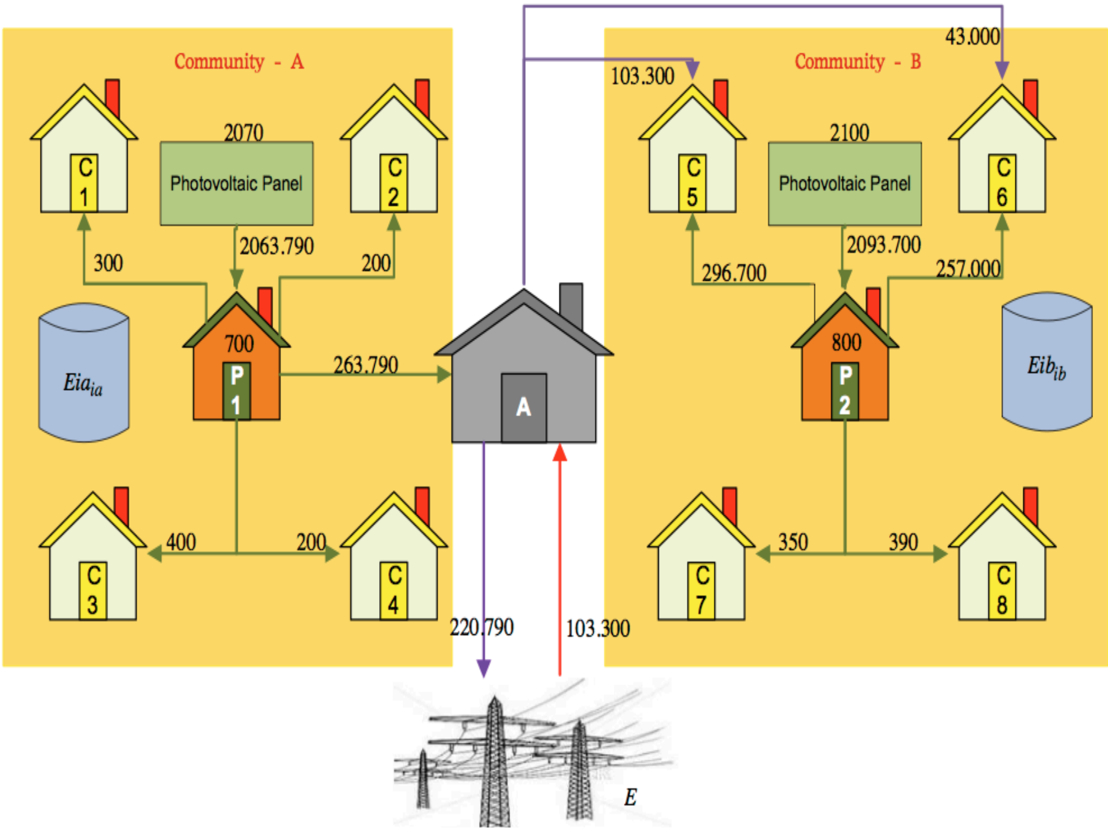


Figure 6.2: Optimal network flows in prosumers community sharing

(Source: author)

6.3: Design of Experiments

To further verify the model implementation and its associated specifications, we performed the design of experiments. These different experiments helped us to analyze how the model behaves in terms of its performance according the model size in terms of number of actors and time periods considered. For this stage, first we carried out the data automation to handle the large amount of data, and secondly we designed and performed the experiments.

Design of experiments (DoE) helped us to assure the model consistency through GAMS solution times. DoE also assisted us in validating the model, because the experiments are performed by using the real historical data obtained from the company.

6.3.1: Data Automation

For the data automation in the model, we used Python, a computer programing language, to write a script generating random problem instances according to a set of specified parameters. This script facilitated us in the model evaluation, data automation, and to perform the design of experiments.

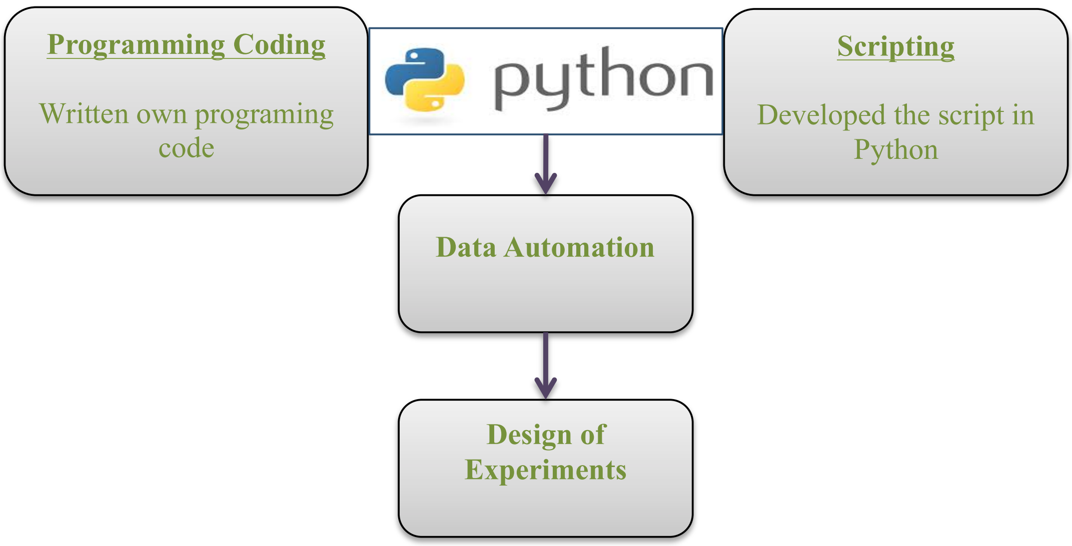


Figure 6.3: Use of Python scripting (Source: author)

6.3.2: Design of Experiment Procedure

The design of experiments (DoE) is a systematic procedure that is carried out under the controlled conditions to determine the known/unknown effects of various factors in testing the model. DoE is also termed as experimental design or designed experiments. In DoE, various model processes are analyzed by performing the experiments. DoE helps to evaluate which of the process inputs can have a significant impact on the process outputs. By performing these experiments, model developers can measure and set the target level of process inputs to achieve a desired results/outputs. There are three primary factors in the process that are analyzed in the experimental design. It includes:

- **Factors:** are considered as process inputs that are to be analyzed. It can include controlled factors and also the uncontrolled factors.
- **Levels:** are the settings of the inputs considered for each factor.
- **Outcome:** is a response of the chosen factors and their desired settings.

To perform the designed experiments, we selected 'communities' as factors to analyze the prosumers and consumers integration in a network perspective. Accordingly, levels that are the desired settings in each community include the number of proactive consumers (prosumers), the number of consumers, and the number of production time slots. The outcome includes network costs and the time required by the GAMS to provide the optimal solution in the given settings. Figure 6.4 presents the considered factors and levels for the experiments, and the studied outcomes.

The energy-shared community network model (we have already proposed in Chapter 5) aims to strike for the balance between service levels (i.e. demand satisfaction) and costs of the network, considering the alternative energy resources. In this regard, model developers should perform and validate the tests that are intending towards the energy demand management of network participants given the available renewable energy resources. Therefore, we selected the number of prosumers and consumers to analyze what impact they can have on managing the energy demands in the community. Moreover, we selected the production time slots to analyze its impact on consumers demand flexibility. The considered factors and their levels helped us to determine the significant inputs (levels) that can affect the optimal process outcome.

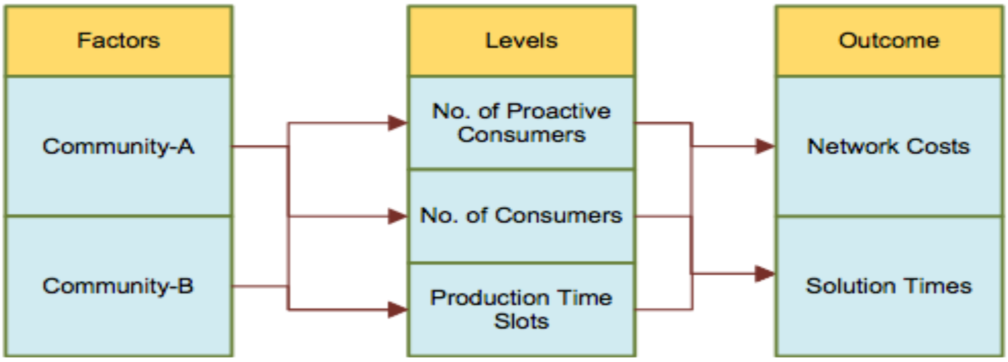


Figure 6.4: Process aspects analyzed in the experimental design (Source: author)

6.3.3: Experiments Designing Process

The experiments designing process enables the model developers to systematically carry out the various experiments. We performed the different tests by following the DoE process flow chart (Figure 6.5). The process started by stating the objective. Objective can be determined based on prosumers and consumers collaboration. It includes collaboration between prosumer-to-company, prosumer-to-consumers, and prosumers-to-prosumers.

To perform the tests we focused on the prosumers-to-prosumers collaboration as a main objective. It is selected because this collaboration stage is more complex and comprehensively covers the various perspectives (related to consumption, production, and distribution) in energy-shared community network model. Based on the defined objective, the next step defined the experiment factors and their levels. Accordingly, required data related to defined levels is entered and modified.

The data is modified with the use of data handler. In our case, the designed Python script reads and modifies the data. The file generated by the Python script is verified in terms of syntax check for the GAMS. The next step performed the experiment by solving the problem with the GAMS. If the optimal solution is found, it is subsequently recorded and interpreted. The same procedure is repeated to perform different experiments.

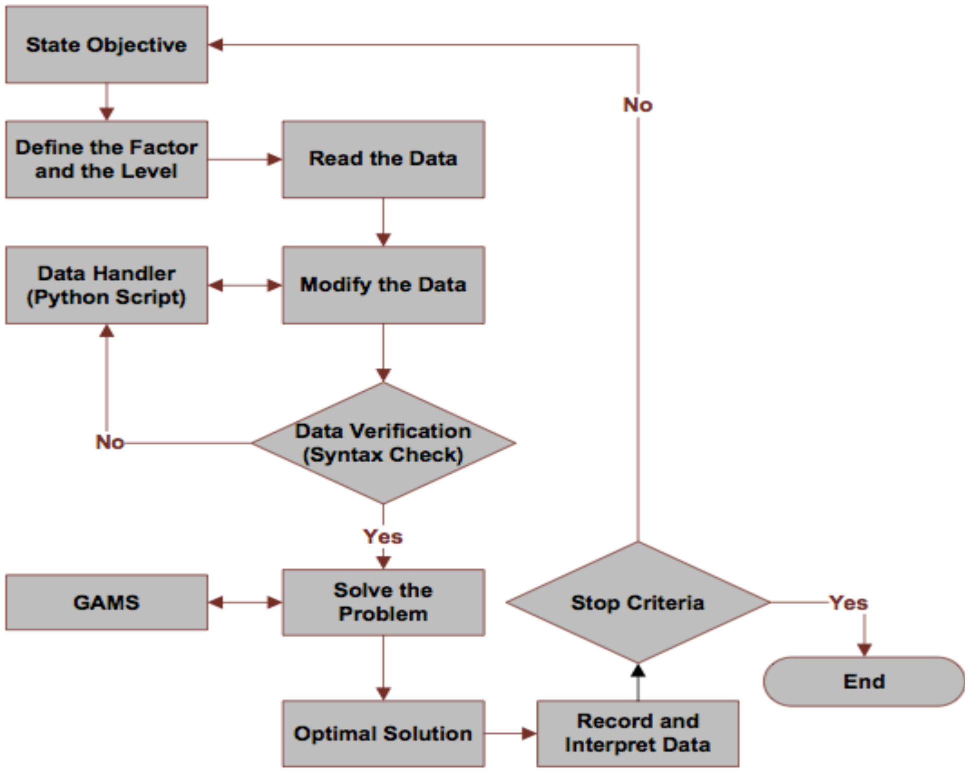


Figure 6.5: Experiment design process flow chart (Source: author)

6.3.4: GAMS Solution Times

As a process output, we calculated the GAMS solution time while performing every experiment. It helped us to check the model consistency and its performance (solving efficiency) with the increase of model size. GAMS perform two-pass process for compiling and executing its models. Upon successful formulation and execution of the energy-shared network model, GAMS presented different times for reporting as depicted in Figure 6.6. In order to evaluate the model efficiency we only considered the resource usage time (i.e. time spent for solving the model). The reason for such selection is to analyze the impact of model enlargement on its solving efficiency (i.e. adequate model size to get the optimal solution). For a common understanding, each time is defined below and is represented in seconds under Table 6.2.

PreSolve Time:

PreSolve / Compilation time is a first pass for the GAMS and is a time required by GAMS to initially compile the model. This time is governed by (and/or based on) the time required to initially read the model structure and its data files.

Generation Time:

This is the time required for GAMS second pass and is a time spent in *generating* the model. This describes the time spent since model completion (syntax check) is finished. It is dominated by various calculations on the existing data and the accomplishment of other preliminary functions such as use of long loops.

Execution Time:

It is a time required to execute all the statements to the point where the solver is called and process a solve statement. The execution time includes executing the statements, solver time, and also reporting time where necessary. Solver time is linked with the resource usage by the solver, that is a time taken by the solver against the model solution.

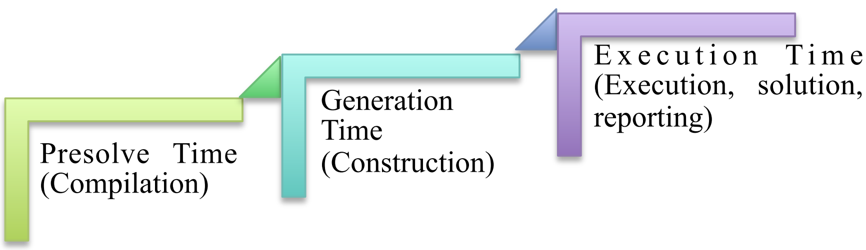


Figure 6.6: GAMS various solution times (Source: author)

6.4: Performed Experiments

For the experimentation, we performed 53 different experiments. Each experiment is conducted through experiment designing process. For the sake of simplicity in understanding the experiments results, we grouped the experiments into cases/scenarios as shown in the Table 6.1. Each case/scenario is representing either increasing/decreasing dimension (such as number of consumers, prosumers, and/or time slots). With the designed Python script, a number of experiments can be performed, since problem instances can be easily enlarged or reduced. The performed experiments results are presented in the Table 6.2 and are discussed in section 6.6.

Table 6.1: Changing parameters in the performed experiments

Cases	Scenarios	Changing Parameter
Case A	Serial No. 1 – 8	***Increase in Prosumers:*** Keeping the consumers and time slots constant, the number of prosumers are increased.
Case B	Serial No. 9 – 16	***Increase in Consumers:*** Keeping the prosumers and time slots constant, the number of consumers is increased.
Case C	Serial No. 17 – 24	***Increase in Time Slots:*** Keeping the prosumers and consumers constant, the number of time slots is increased.
Case D	Serial No. 25 – 32 Serial No. 33 – 39 Serial No. 41 – 48	***Increasing Prosumers and Consumers:*** With increased time slots (that is with reduced duration of each time slot), number of prosumers and consumers are increased.

Case E	Serial No. 49 – 53	***Increasing all:*** In each scenario, number of consumers, prosumers and times slots are simultaneously increased to verify the model solution / results.

6.5: Model Validation

To validate the model we empirically tested our model through input parameter values and their distribution. These input parameter values are obtained from a real historical data of an organization. In this regard, a private multi–specialized clinical care and research hospital (hereafter termed as Hospital) is contacted in the Italian healthcare industry. The Hospital, having 313 beds of which 16 are intensive care, covers inpatient and outpatients services. For the inpatient services hospital has 9 operation rooms and for outpatient services it has 50 clinics inside the hospital. Hospital has 5 different buildings with different energy requirements.

The hospital owns a cogeneration (COG) plant to meet the energy demand of buildings. A COG is capable of producing heat (thermal energy) and electric power (electricity) simultaneously. The Hospital uses thermal energy for the sterilization of the equipment, and for heating space purpose, whereas electric power is used for the electricity consumption. The Hospital provided us the data related to electricity production and its consumption for the year 2013. Accordingly, we used this data in our model to analyze the optimal consumption and distribution of electricity in its buildings.

The optimal solution obtained through GAMS shows that total electricity consumption of the Hospital is efficiently distributed among its buildings through their demand flexibility. Moreover, increasing the flexibility at the demand side can reduce Hospital electricity purchases from the electric utility. To further verify the results, we performed the different experiments (as per experiment designing process) by using the provided Hospital data.

Results presented in the Table 6.2 demonstrates that higher engagement of proactive consumers creates positive impact on managing the energy demand as more renewable energy resources can be shared among others.

6.6: Discussions

This discussion part explains and analyses the results that are obtained from design of experiments.

Case A – Scenarios with increasing prosumers:

The experiments performed under this case are related to analyze the impact of proactive consumers on the process outcome (network costs and solution time). Under these scenarios, the number of prosumers is increased, i.e. from 2 prosumers to 256 prosumers in each community. In each community we consider 8 consumers and 8 time slots (panning horizon of two days) for their electricity production.

As per results (Table 6.2) the more prosumers being available for sharing their distributed energy resources the more positive impact it will have on satisfying / managing the consumers energy demand. The objective function value positively increases and yields higher profits with more prosumers. On the other side, **Figure 6.7** (on page 178) shows that as resource usage time also increases, that means solver provides the optimal solution with more resource usage.

Case B – Scenarios with increasing consumers:

The experiments performed under this case are related to analyze the impact of consumers on the process outcome (network costs and solution time). Under these scenarios number of consumers are increased from 8 to 1024 consumers. Prosumers are fixed at 2 with 8 time slots (i.e. planning horizon of two days with 6 hours time slot).

The results show that increasing the number of consumers without increasing the prosumers reduces the community profits. It indicates that the absence of proactive consumers (prosumers) may lead to excessive burdens on the electric utility grids, as the grid has to satisfy the demand of all energy-seeking consumers by itself. The objective function value decreases as more energy is bought from outside the community. GAMS can efficiently solve the model for the community size of 2 prosumers and 1024 consumers. However as shown in **Figure 6.8** (on page 179), it takes more resources usage time with the increase of consumers.

Case C – Scenarios with increasing time slots:

The experiments performed under this case are related to analyze the impact of production time slots on the process outcome (network costs and solution time). In these scenarios, number of time slots is increased from 8 to 1024 without changing the number of prosumers and consumers. Planning horizon is two days where increasing the number of time slots refers to reducing the time span of each slot. To exemplify, 8 time slots consist 6 hourly slots where as 32 time slots consist 1.5-hour slots.

Changing the number of slots in the model enlargement does not have any impact on the objective function value, unless the production capacity remains fixed. However, shorter time slots may have some impact on the consumers demand flexibility, as consumers need to actively participate towards managing their energy demands. Based on the optimal solutions, we can argue that consumers passively responding to production constraints (as per time slots) may increase their costs of electricity purchases from outside the network and vice versa. As shown in **Figure 6.9** (on page 180) GAMS resource usage time gradually increases with the increase in time slots. However, solver requires higher time for providing the optimal solution under 1024 time slots to efficiently distribute the electricity production among network participants.

Case D – Scenarios with increasing prosumers and consumers:

The experiments performed under this case are related to analyze the combined impact of prosumers and consumers on the process outcomes. From scenario 25 to 48 prosumers and consumers are increased simultaneously under the time slots of 16, 32 and 48. Resource usage time significantly increases as with increasing prosumers and consumers. As exemplified in **Figure 6.10** (on page 181), by having 256 prosumers, 1024 consumers and 16 time slots for each prosumer, solver requires 627.783 seconds (10.463 minutes) to provide the optimal solution.

Compared to this, if we have the same number of prosumers and consumers but with the time slots of 32 and/or 48, GAMS resource usage time exceeds its limits (1000 seconds / 16.67 minutes). With such excess of limits, GAMS cannot provide the optimal solution. As shown in **Figure 6.11 and 6.12** (on page 182 and 183) resource usage time drops to zero which, indicates that optimal solution is not computable given the computing system parameters.

The objective function value changes in accordance to the number of prosumers and consumers. However, function value remains negative because there are more energy-seeking consumers compared to the dynamic consumers (prosumers) in the community. In order to reduce the energy sourcing from the external grid (i.e. to gain higher profits) we need to have more renewable energy resources that can assist in satisfying the consumers demands. Dissemination of renewable resources becomes possible as more consumers are pushed to enter into the domain of proactive consumers.

Case E – Scenarios with increasing prosumers and consumers:

The experiments performed under this case are related to analyze the combined response of factor levels on the process outcomes. In each scenario (from 49 to 53 in Table 6.2), prosumers, consumers and time slots are simultaneously increased. Under these scenarios, the same results are obtained as previously discussed. As analyzed above in Case C, given the same production capacity increasing number of time slots have no impact on the objective function value. Increasing prosumers has positive impact and leads to higher profits whereas increasing only the consumers has negative impact in terms of reduced profits and increases the external energy sourcing cost. As shown in **Figure 6.13** (on page 184) resource usage time sharply increases if all values are simultaneously increased.

To summarize the above discussion, model efficiency remains the same as it provides the optimal solution with negligible resource usage time. It suggests that, the structure of the model is consistent with the stated decision problem, objective function, and the time it takes to provide the optimal solution. However, as the prosumers, consumers and, time slots reached to a certain level (e.g. 256, 1024 and 32) the model solution calls for a different problem formulation that is computationally more efficient to handle the system complexity. Combining heuristics solution procedure may also increase this computational efficiency. Moreover, increasing the prosumers generates higher profits, as there are more renewable energy resources that can be shared among others. Increase in consumers diminishes the profits, as their energy requirements need to be satisfied from the external grid. Reducing the time span (i.e. from 6 hour to 0.5 hour time slot) does not have any impact on the objective function of maximizing profits. However, this time span may have some impact on improving the demand flexibility, as shorter span requires active participations of consumers.

Chapter Summary

Model testing and validation tasks are the essential part of the model development. These tasks ensure that model is designed and implemented properly, and demonstrate the close representation of the reality. Thus, we tested and validated our analytical energy – sharing model, presented and discussed in the previous chapter. Testing phase ensures that model is programmed correctly, mathematical formulations are implemented properly, and the model does not contain errors. To confirm these, we implemented and solved our decision models through GAMS and CPLEX optimization engine, and accordingly we obtained the respective optimal solutions. All the optimal solutions are thoroughly checked to ensure that model formulations (equations and constraints) are implemented correctly and are equally satisfied in each solution. To further support the testing and validation process, we performed the design of experiments. The experiments are conducted based on the experiments designing process. Number of experiments can be performed using the developed Python script; nevertheless 53 different experiments are performed. Performed experiments assisted us to analyze the impact of process inputs (proactive consumers, consumers, and production slot) on the process outputs (GAMS solution times and network costs). Validation phase ensures that model meets its requirements and its solution addresses the problem. To confirm this, we empirically validated our model using the real historical data of a company in the Italian health care industry. Our empirical validation focuses on the model testing and its solution process. Results of the performed experiments show that active participation of consumers and prosumers have positive impact on locally managing the energy supply and demand. Empirical validation (based on the optimal solution obtained through GAMS) shows that total electricity consumption of the company is efficiently distributed among its buildings through their demand flexibility. Moreover, improved flexibility of the demand side may reduce the external electricity purchases of a company.

Table 6.2: Model scenarios (Source: author)

						Solution Time (seconds)					
Sr. No.	Increase	Pros	Cons	Time Slots	Objective Value	Presolve Time (PT)	Generation Time (GT)	Execution Time	Resource Usage Time	Total Execution Time (TET)	Total Time (PT+GT+TET)
1	Increase in Prosumers -> Fixed Consumers -> Fixed Time Slots	2	8	8	-4,290.3928	0.05	0.010	0.010	0.059	0.069	0.129
2		4	8	8	6,812.8605	0.06	0.010	0.010	0.070	0.080	0.150
3		8	8	8	22,173.4221	0.05	0.010	0.010	0.070	0.080	0.140
4		16	8	8	43,900.6516	0.05	0.020	0.020	0.060	0.080	0.150
5		32	8	8	87,355.1105	0.03	0.030	0.030	0.140	0.170	0.230
6		64	8	8	174,264.0284	0.01	0.050	0.050	0.210	0.260	0.320
7		128	8	8	348,081.8642	0.02	0.080	0.080	0.260	0.340	0.440
8		256	8	8	695,717.5358	0.04	0.140	0.140	1.191	1.331	1.511
9	Increase in Consumers -> Fixed Prosumers -> Fixed Time Slots	2	8	8	-4,290.3928	0.06	0.010	0.010	0.060	0.070	0.140
10		2	16	8	-19,684.0389	0.05	0.010	0.010	0.060	0.070	0.130
11		2	32	8	-50,471.3310	0.05	0.020	0.020	0.060	0.080	0.150
12		2	64	8	-112,045.9153	0.03	0.020	0.020	0.040	0.060	0.110
13		2	128	8	-235,195.0840	0.01	0.040	0.040	0.030	0.070	0.120
14		2	256	8	-481,493.4213	0.01	0.060	0.060	0.090	0.150	0.220
15		2	512	8	-974,090.0958	0.02	0.120	0.120	0.080	0.200	0.340
16		2	1024	8	-1,959,283.4449	0.03	0.220	0.220	0.140	0.360	0.610
17	Increase in	2	8	8	-4,290.3928	0.05	0.010	0.010	0.060	0.070	0.130

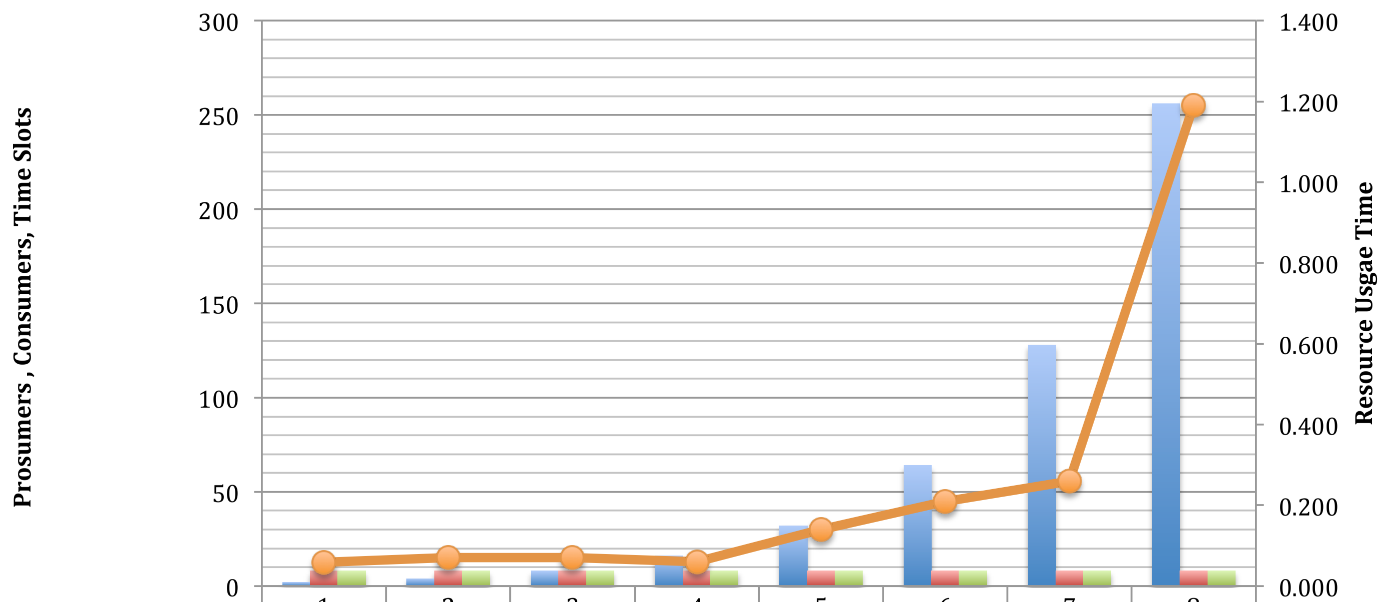
18	Time Slots ->	2	8	16	-4,290.3928	0.06	0.010	0.010	0.060	0.070	0.140
19	Fixed	2	8	32	-4,290.3928	0.05	0.020	0.020	0.060	0.080	0.150
20	Consumers ->	2	8	64	-4,290.3928	0.03	0.020	0.020	0.140	0.160	0.210
21	Fixed	2	8	128	-4,290.3928	0.01	0.040	0.050	0.120	0.170	0.220
22	Prosumers	2	8	256	-4,290.3928	0.02	0.080	0.080	0.190	0.270	0.370
23		2	8	512	-4,290.3928	0.06	0.191	0.191	0.530	0.721	0.972
24		2	8	1024	-4,290.3928	0.16	0.530	0.530	2.383	2.913	3.603
25		2	8	16	-4,290.3928	0.05	0.010	0.010	0.050	0.060	0.120
26	Increased Time	4	16	16	-8,580.7856	0.04	0.020	0.020	0.060	0.080	0.140
27	Slots ->	8	32	16	-17,161.5711	0.01	0.040	0.040	0.140	0.180	0.230
28	Increase in	16	64	16	-34,323.1423	0.02	0.100	0.100	0.130	0.230	0.350
29	Prosumers ->	32	128	16	-68,646.2845	0.06	0.291	0.291	0.600	0.891	1.242
30	Increase in	64	256	16	-137,292.5691	0.45	1.652	1.652	4.196	5.848	7.950
31	Consumers	128	512	16	-274,585.1381	0.91	5.849	5.849	31.645	37.494	44.253
32		256	1024	16	-549,170.2763	28.79	74.286	74.477	627.783	702.260	805.336
33		2	8	32	-4,290.3928	0.02	0.010	0.010	0.050	0.060	0.090
34	Increased Time	4	16	32	-8,580.7856	0.02	0.030	0.030	0.130	0.160	0.210
35	Slots ->	8	32	32	-17,161.5711	0.01	0.070	0.070	0.150	0.220	0.300
36	Increase in	16	64	32	-34,323.1423	0.03	0.191	0.191	0.270	0.461	0.682
37	Prosumers ->	32	128	32	-68,646.2845	0.22	0.611	0.611	1.792	2.403	3.234
38	Increase in	64	256	32	-137,292.5691	0.73	2.844	2.844	9.994	12.838	16.412
39	Consumers	128	512	32	-274,585.1381	27.41	11.977	11.977	173.639	185.616	225.003
40		256	1024	32	**NA*1**	602.01	1219.564	1219.734	NA	1219.734	3041.308
41	Increased Time	2	8	48	-4,290.3928	0.03	0.020	0.020	0.045	0.065	0.115

42	Slots ->	4	16	48	-8,580.7856	0.01	0.090	0.090	0.080	0.170	0.270
43	Increase in	8	32	48	-17,161.5711	0.01	0.120	0.120	0.150	0.270	0.400
44	Prosumers ->	16	64	48	-34,323.1423	0.05	0.301	0.301	0.440	0.741	1.092
45	Increase in	32	128	48	-68,646.2845	0.32	1.402	1.402	2.673	4.075	5.797
46	Consumers	64	256	48	-137,292.5691	0.74	3.986	3.986	17.244	21.230	25.956
47		128	512	48	-274,585.1381	14.67	29.011	29.041	234.707	263.748	307.429
48		256	1024	48	**NA*2**	2901.27	5798.568	5799.169	NA	5799.169	14499.007
49	Increase in	2	8	8	-4,290.3928	0.02	0.040	0.040	0.030	0.070	0.130
50	Time Slots ->	4	16	16	-8,580.7856	0.04	0.020	0.020	0.050	0.070	0.130
51	Increase in	8	32	32	-17,161.5711	0.01	0.070	0.070	0.140	0.210	0.290
52	Prosumers ->	16	64	48	-34,323.1423	0.05	0.270	0.270	0.450	0.720	1.040
53	Increase in Consumers	32	128	96	-68,646.2845	0.73	2.393	2.393	6.519	8.912	12.035

Table Notes:

1. Pros = Prosumers in both communities
2. Cons = Consumers in both communities
3. Iteration Count Limit: Iteration Count limit in each scenario for GAMS CPLEX is taken as 200,000.
4. NA = Not Accessible
5. NA*1 = "Not enough memory to build start for original LP" (dictfile = 0)
6. NA*2 = "CPLEX Error 1001: Out of memory" (dictfile = 0)
7. Dictionary file (dictfile) in GAMS is created for the solver in order to store the names of all the equations and variables. Whereas against the serial number 40 and 48 the dictionary file is not created (‘dictfile = 0’). Under the presence of high number of parameters, such procedure is carried out to avoid creating any dictionary file for the GAMS for saving the resource memory.

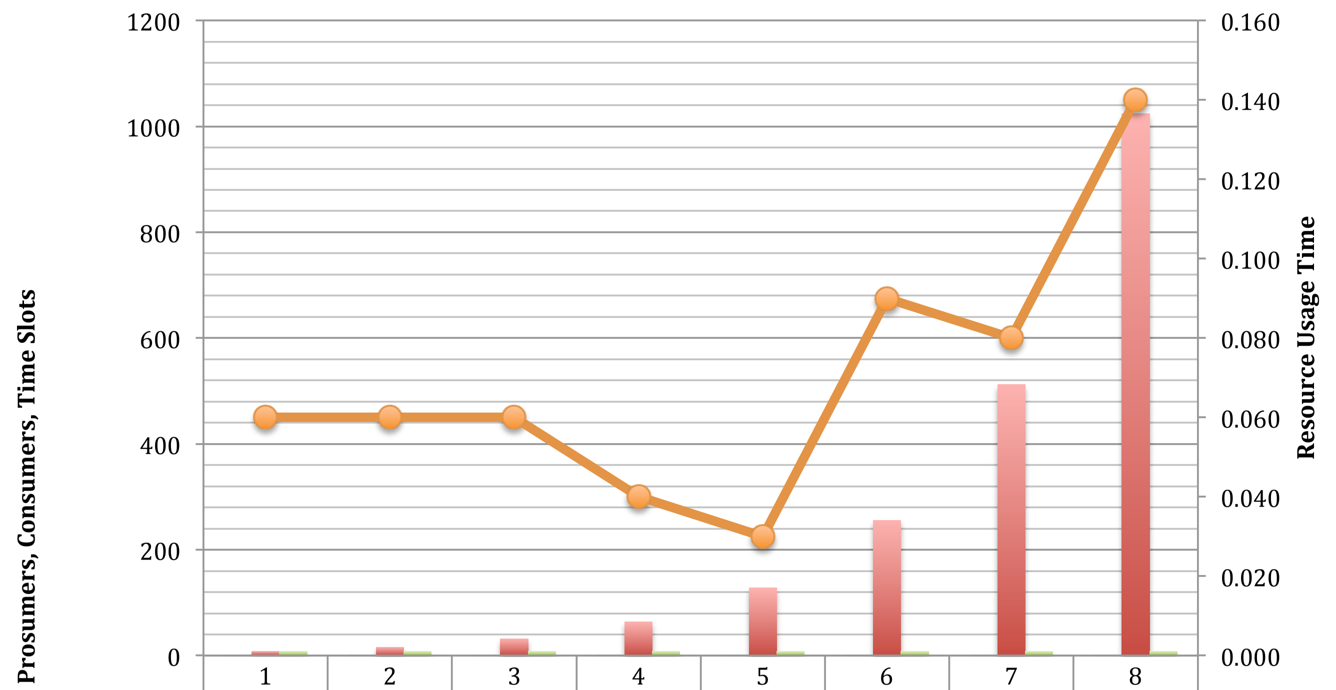
Graphs



	1	2	3	4	5	6	7	8
Pros	2	4	8	16	32	64	128	256
Cons	8	8	8	8	8	8	8	8
Time Slots	8	8	8	8	8	8	8	8
Resource Usage Time (seconds)	0.059	0.070	0.070	0.060	0.140	0.210	0.260	1.191

No. of Observations

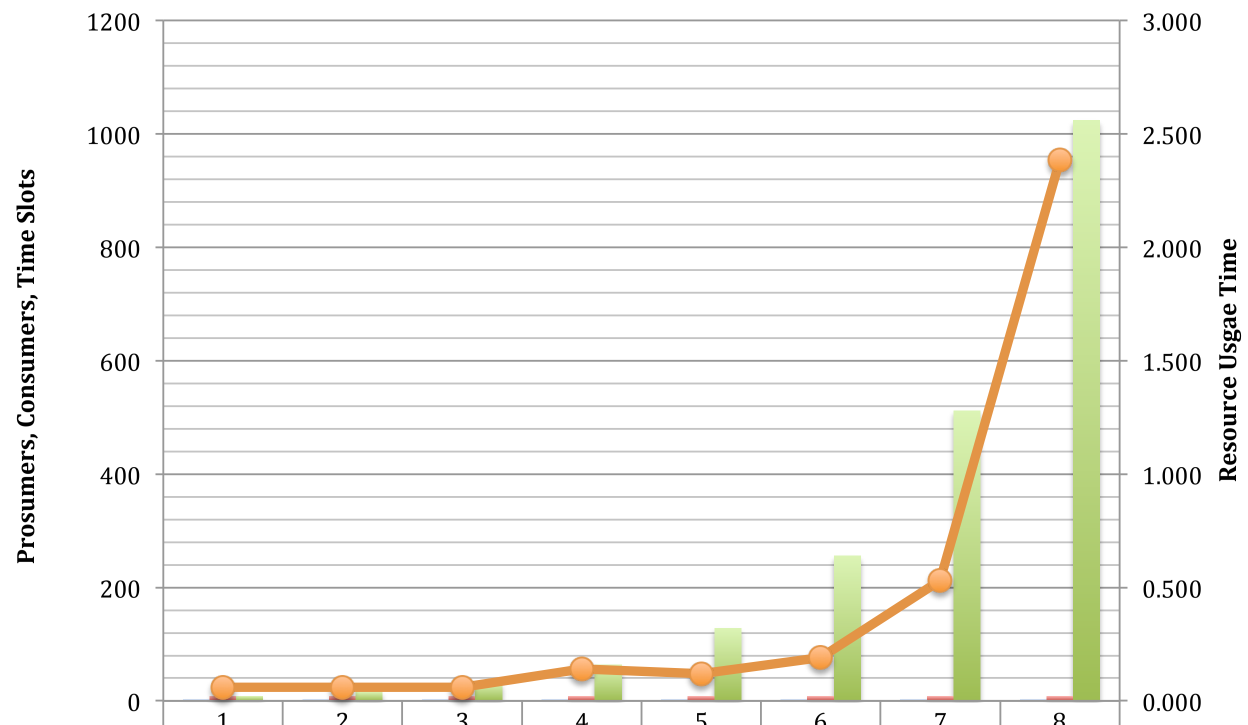
Figure 6.7: Increase in prosumers (Source: author)



	1	2	3	4	5	6	7	8
Pros	2	2	2	2	2	2	2	2
Cons	8	16	32	64	128	256	512	1024
Time Slots	8	8	8	8	8	8	8	8
Resource Usage Time (seconds)	0.060	0.060	0.060	0.040	0.030	0.090	0.080	0.140

No. of Observations

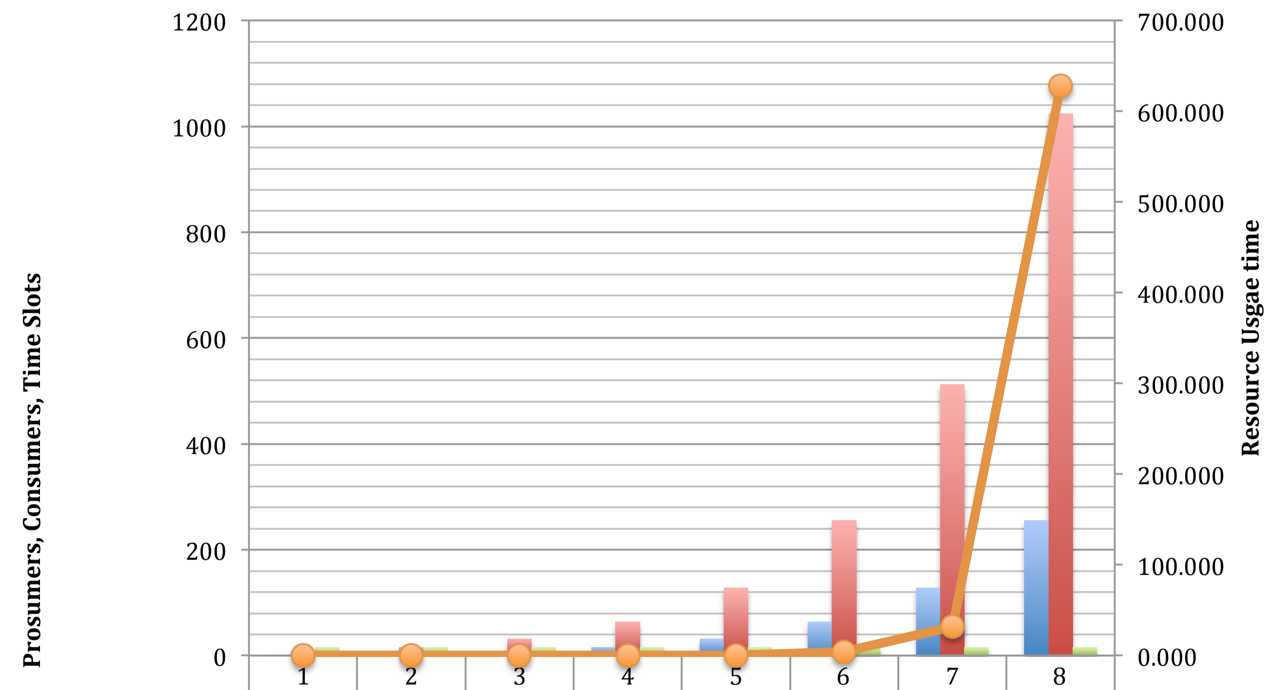
Figure 6.8: Increase in consumers (Source: author)



	1	2	3	4	5	6	7	8
Pros	2	2	2	2	2	2	2	2
Cons	8	8	8	8	8	8	8	8
Time Slots	8	16	32	64	128	256	512	1024
Resource Usage Time (seconds)	0.060	0.060	0.060	0.140	0.120	0.190	0.530	2.383

No. of Observations

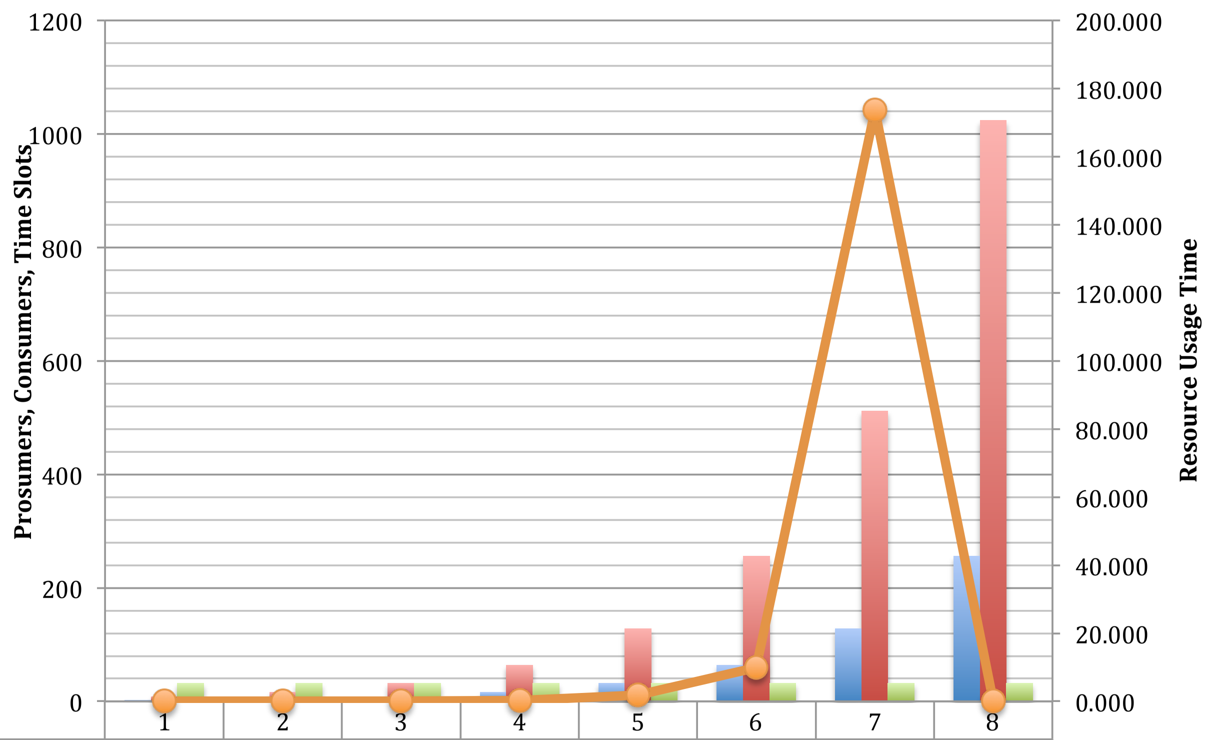
Figure 6.9: Increase in time slots (Source: author)



	1	2	3	4	5	6	7	8
Pros	2	4	8	16	32	64	128	256
Cons	8	16	32	64	128	256	512	1024
Time Slots	16	16	16	16	16	16	16	16
Resource Usage Time (seconds)	0.050	0.060	0.140	0.130	0.600	4.196	31.645	627.783

No. of Observations

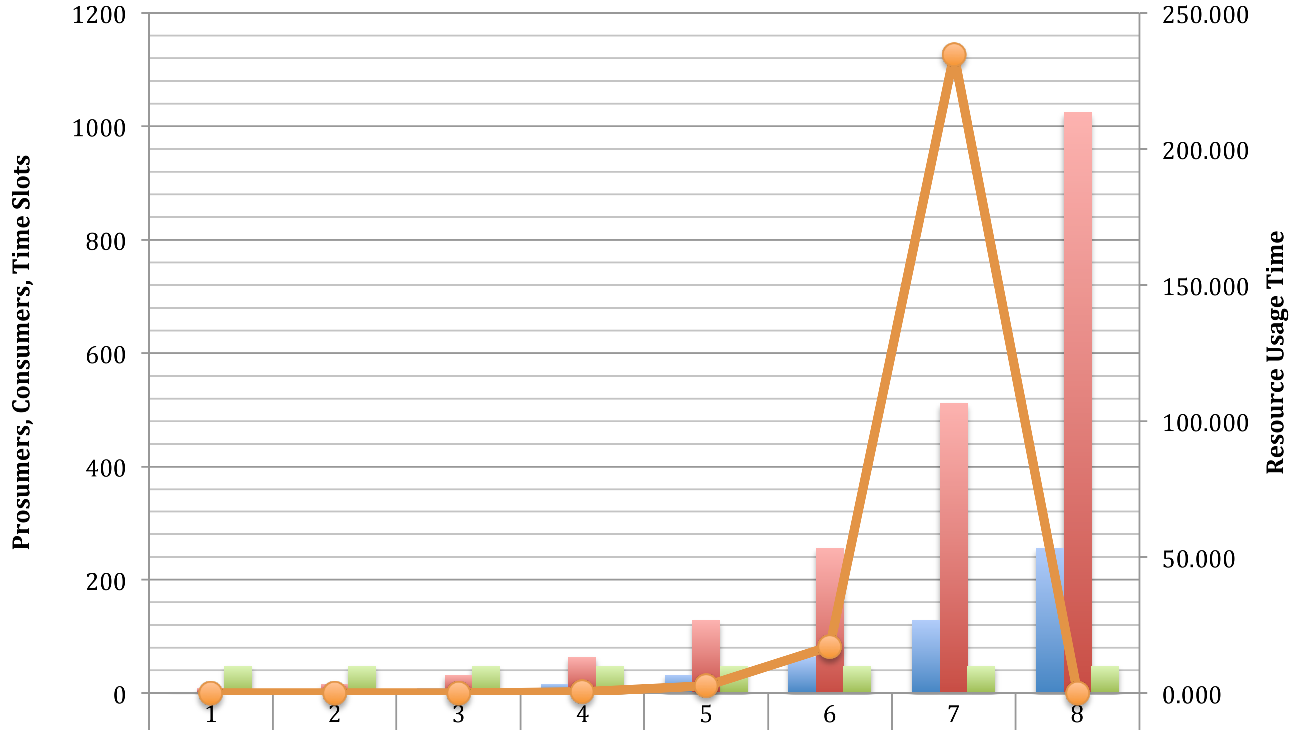
Figure 6.10: Increase in pros and cons with increased time slots (16) (Source: author)



	1	2	3	4	5	6	7	8
Pros	2	4	8	16	32	64	128	256
Cons	8	16	32	64	128	256	512	1024
Time Slots	32	32	32	32	32	32	32	32
Resource Usage Time (seconds)	0.050	0.130	0.150	0.270	1.792	9.994	173.639	0.000

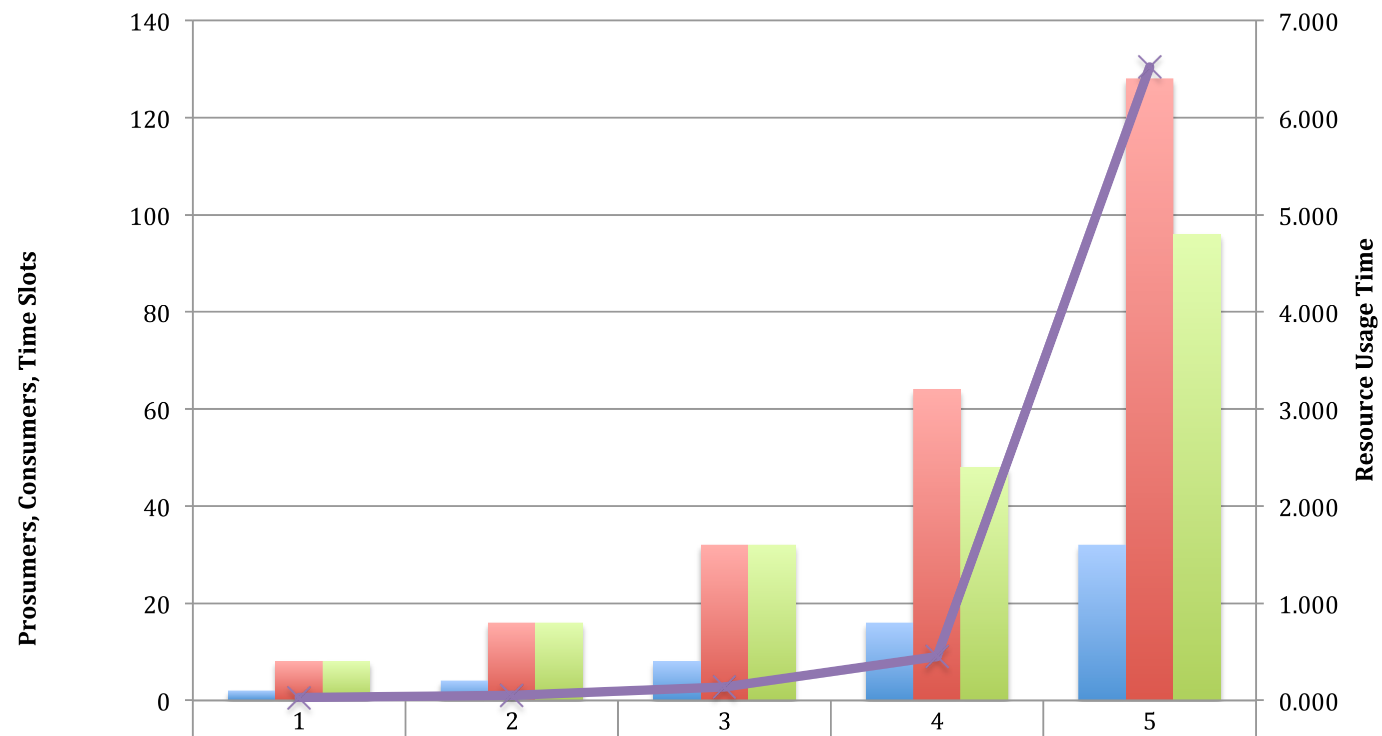
No. of Observations

Figure 6.11: Increase in pros and cons with increased time slots (32) (Source: author)



No. of Observations	1	2	3	4	5	6	7	8
Pros	2	4	8	16	32	64	128	256
Cons	8	16	32	64	128	256	512	1024
Time Slots	48	48	48	48	48	48	48	48
Resource Usage Time (seconds)	0.045	0.080	0.150	0.440	2.673	17.244	234.707	0.000

Figure 6.12: Increase in pros and cons with increased time slots (48) (Source: author)



	1	2	3	4	5
Pros	2	4	8	16	32
Cons	8	16	32	64	128
Time Slots	8	16	32	48	96
Resource Usage Time (seconds)	0.030	0.050	0.140	0.450	6.519

No. of Observations

Figure 6.13: Increasing all (Source: author)

CHAPTER 7: CONCLUSIONS AND FUTURE RESEARCH

7.1: Conclusions

Electricity production and distribution through Smart Grids can deliver efficient and low-carbon energy for the sustainable economic infrastructure. Smart Grids deployment is an important step towards diminishing the heavy reliance on fossil fuels and achieving the sustainability by reducing the carbon footprints. The smart grid infrastructure necessitates networked architectures with the ability to integrate distributed renewable energy resources, which is key requirement to alleviate sustainability impacts.

The renewable energy resources (RERs) are increasingly being integrated in the Smart Grids for the provision of sustainable energy. However, the efficient utilization of these resources requires high-level grid planning and operational scheduling, because productions from these resources are neither controllable nor accurately predictable. There are many different ways to streamline and improve the renewable resources integration into the power grids. It can include increasing system flexibility for accommodating unique behaviors of RERs, implementing sophisticated technological solutions, increasing capacity, and improving grid infrastructure.

For improving system flexibility, the high attention is being given towards distributed renewable generations along managing the demand side of the grid. Demand side management (DSM) can provide significant benefits both at economic and operation level. DSM, an essential part of smart grids: it is a cost effective tariff program for managing the electricity loads that generates benefits both for utilities and consumers. However, under DSM programs, utility companies take most of the decisions and actions, while consumers have little or no control. On the other side, consumer engagements (as active participations) for managing demands with the distributed renewable generation can provide more flexibility and stability to the power systems.

In this regard, consumers and the households' engagement represent a significant opportunity. Their engagements can provide meaningful contributions towards energy savings efforts, particularly by adopting the distributed renewable generations. However, providing the sustainable energy in the future will also require a change of perception that is how consumers should perceive the energy and how they should use it. Under the current circumstances, consumers and their communities expect unconstrained and reliable energy supply for satisfying their needs and this approach is also an essence of current electrical grid systems. With the increasing penetration of renewable resources, it will be much difficult to follow such approach and, if unmanaged, the same level of service cannot be provided.

Seeking proactive participation of consumers through collaboration can assist utilities in shifting the consumption trends where demand will follow the supply side instead of supply following the demand. In view of this, consumers' engagement as proactive participants in collaborative environment is mostly overlooked in the literature and hence it should be addressed to generate most value from demand side participation.

Responding to the sustainability challenges from the above-mentioned perspective necessitates a properly designed collaboration platforms. These platforms will assist in shifting the mindset towards more efficient consumption patterns; alongside it will empower a strong collaboration to seek equilibrium between supply and demand sides. Therefore, by considering the consumer-centric approach, this research work was focused towards exploring the demand side flexibility with the support of proactive consumers in managing the energy demands under the collaborative environment.

However, persuading the active participation of consumers necessitates changing the consumption trends and having a different nature of demand. From this perspective the first research question mentioned below, addresses how nature itself of the demand is changing under a collaboration environment and how consumers should be induced towards this environment.

Research Question 1: How can we define smart demand and what are the key determinants?

We considered the term Smart Demand as a term expressing the main characteristics of the demand signals expressed in the collaboration environment. Under this environment, consumer demand can be shifted in time and/or compensated through other participatory efforts of the community. The smartness of the demand is linked to the actions undertaken to reduce/shift/redistribute the demand profile under the collaborative systems considering the shared benefits. Accordingly, three main dimensions are envisioned to contextualize the smart demand, which includes sustainability, collaboration, and intelligence.

In view of these dimensions, Smart demand consideration towards energy demand management explains that demand of energy is becoming a sustainable collaborative process. This process involves different players having distinct requirements, where all the connected members should collaborate to get the mutual benefits in terms of their sustainable energy consumptions. Accordingly, consumers should be encouraged for their active participation. Their participation would assist achieving the *sustainability* targets (with mutual gains comprising economic, social, and environmental benefits) through *collaboration* (by creating flexibility in demand) with the help of *intelligence* (instrumentations, products, systems).

The extent to which consumers are engaged and are encouraged to be active player would have a considerable impact on the smart grids success. As more and more consumers enter into the domain of proactive consumers, the more significant impact they can have on the grid infrastructure. However, different factors can impede and motivate consumers for their proactive participations. With this consideration, first research question analyzed the key determinants related to proactive participations.

Based on the extensive literature review analysis, the key issues and challenges are identified that can potentially obstruct consumers' proactive participation in the collaborative arrangements. The challenges identified encompass the consumers' internal parameters (such as behavioral, contextual factors) and also the external parameters (such as exogenous conditions like infrastructure, government interventions). Inclusive consideration of such factors can induce prosumers and consumers active participations towards their sustainable prosumption and consumption respectively.

The key *results obtained from the first research question* highlights that consumers should be induced to change their consumption patterns in conjunction with the dimensions of smart energy demand, rather than merely highlighting the environmental perspective/benefits. Moreover, consumers should be provided with properly designed collaboration platform that can yield mutual benefits (financial, personal, behavioral), and provision of such platforms would assist them to create higher demand flexibility.

The second research question mentioned below demonstrates the contributions of proactive consumers towards managing the smart energy demands under the provision of collaborative platforms.

Research Question 2: How can growing smart energy demand be met efficiently trough consumers active participation?

With the widespread implementation of smart grids, some of the renewable energy resources will be directly installed at the customer premises to increase their participations. This participation will transform the passive role of consumers to more active contributors. Smart grids technologies would allow prosumers to integrate their renewable energy resources into local energy networks. Accordingly, in this research question we developed an analytical model aiming to facilitate consumers' active participations towards energy consumption and generation in local energy networks.

Our analytical model demonstrated the integration of proactive consumers (prosumers) and consumers into a network perspective. For this, we envisioned the energy sharing among the groups of consumers at their community level. This energy-shared community network model optimizes the energy sharing among network participants through smart energy demand management. The model proposed three cases, each representing the proactive consumers participation towards energy demand management. The cases are based on the proactive consumers collaboration level that includes prosumer-to-company, prosumer-to-consumers, and prosumers-to-prosumers collaboration. The purpose of the analytical model and its proposed cases was to demonstrate how consumers demand flexibility in the community perspective could be beneficial in locally balancing the energy supply and demand.

In this regard, all the different decision models are formulated through Linear Programming and implemented into the General Algebraic Modeling System (GAMS). For the model testing and validation we performed the design of experiments and empirically validated our model through real historical data obtained from a company in the Italian health care industry. Performed design of experiments helped us to test the model performance according to its different sizes. Results shown that model efficiency remains same and requires negligible solution time to solve the model.

However, after a certain level, model solution calls for a different and more efficient problem formulation to handle the system complexity. Empirical model validation ensured that model meets its requirements and addresses the main problem. Optimal solution of the model validation shows that company total electricity consumption is efficiently distributed among its building through their demand flexibility.

The key *results obtained from the second research question* highlights that active participation of prosumers and consumers creates a positive impact on locally managing the energy supply and demand. Moreover, consumers can benefit from their demand flexibility assuming they actively participate in the collaborative arrangements. This active participation of prosumers and consumer would also allow them to exchange or sell their demand flexibility among the connected members in the energy networks.

7.2: Main Contributions

The literature review suggested that consumer engagements and their collaboration under smart grids are mainly focused towards controlling and/or reducing the energy consumptions through demand response programs. Importantly, utilization of proactive consumers in utility-consumer collaboration is mostly overlooked. Accordingly, our main goal was to analyze the contributions of proactive consumers along with the integration impact of various renewable energy resources in a collaborative network. In our work, we deeply focused on consumers' collaboration as their proactive participation towards energy demand management. We considered the organization, interactions, and the management of prosumers and consumers integration in a residential/domestic environment. Along this, we envisioned their integration into a network perspective for locally balancing the energy supply and demand under the presence of renewable energy resources.

From the above perspective, research study contributes to theory by highlighting the importance and determining the key requirements of consumers' proactive participations and their collaboration towards energy demand management. This collaboration at the demand side is primarily targeted to induce consumers as to actively participate towards energy sustainability, and resultantly we elucidated the concept of ***smart energy demand*** that differs according to the literature. The work intends to fill the research gap in understanding how various renewable energy resources can be integrated for the composition of electricity supply in the ***residential/domestic environment*** and highlights the role of an aggregator in the residential environment, which is currently limited to the industrial perspective. Moreover towards the practical contribution, our presented analytical model can be used to develop a strong relationship between ***consumer and their community*** according to different collaborative arrangements, as model highlights the key determinants and the contributions of consumers along with their community for the sustainable integration of renewable energy resources.

7.3: Future Research Work

In our work, we proposed and developed an energy-shared community network model with the objective to seek an appropriate balance between service levels (i.e. demand satisfaction) and the costs of the network. The model provides the optimal solution where the cost is minimized given the demand satisfaction. In the developed model demand signals are expressed in a collaborative environment. This environment allows the individual demand to be shifted in time and/or compensated through other participatory members in the network. All the community-network participants have a single objective that is to minimize their cost function.

Such objective can justify that participants are willing to collaborate in terms of creating demand flexibility for the achievement of common objective. However, this collaboration may not be able to accommodate consumer's required comfort level and satisfaction simultaneously. Accordingly, our future research work objective is to consider a multi-objective optimization problem. By adopting this multi-objective programming, we would investigate the combined effect of cost, comfort and satisfaction on individuals' energy demand management subject to aggregator resource allocation. It may help to design better control strategies that can provide a suitable trade-off for an individual in terms of cost factor, comfort level and his satisfaction level.

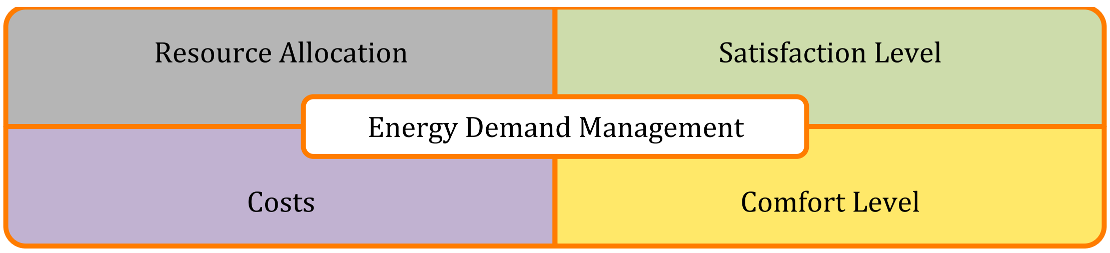


Figure 7.1: Multi-objective energy demand management (Source: author)

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ANNEXURES

Presentations and Publications

The results of this research work have been presented and discussed in several doctoral workshops, research seminars, summer schools, and international scientific conferences. The details are as below:

	Doctoral Workshops, Research Seminars, Summer Schools
2013	PhD Doctoral Workshop, APMS 2013, Pennsylvania, USA. September 2013.
2012	PhD Doctoral Workshop, APMS 2012, Rhodes, Greece. September 2012.
2012	PhD Summer School (XVII Summer School "Francesco Turco" Ed), Venice, Italy. September 2012.
2012	CELS Research Seminar, Faculty of Engineering, University of Bergamo, July 2012.
2012	EIASM Doctoral Research Seminar, Brussels, Belgium. February 2012.
2011	PhD Summer Academy, Zaragoza Logistics Centre, Zaragoza, Spain. June – July 2011.

	International Scientific Conferences
2013	IEEE International Conference on Industrial Engineering and Engineering Management, Bangkok, Thailand. December 2013.
2013	International Conference on Advances in Production Management Systems. Sustainable Production and Service Supply Chains. Pennsylvania, USA. September 2013.
2012	International Conference on Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services. Rhodes,

	Greece. September 2012.
2012	EcoMobility 2012 – Conference on sustainable transportation. Oresund EcoMobility Knowledge & Innovation Centre, Copenhagen, Denmark. January 2012.

Progress in this research work has also been supported by the international exchange research period,

July 2011 – January 2012	MIT – Zaragoza Logistics Centre, Zaragoza, Spain.

Following research papers are published during the PhD program:

Tariq, Z., Cavalieri, S., and Pinto, R. (2013). "Determinants of Smart Energy Demand Management: An Exploratory Analysis". *In Advances in Production Management Systems. Sustainable Production and Service Supply Chains,* Vol. 415, pp. 548-555. Springer.

Tariq, Z., (2013). "Smart energy demand management – A collaborative framework for consumers' active participation". Paper presented at the at the 6th PhD Doctoral Workshop, APMS 2013, State College, Pennsylvania State University, USA.

Jaenglom, K. and **Tariq, Z.** (2013). "The Role of Purchasing Management Towards Sustainable Supply Chain: A Life cycle perspective", In Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management, Thailand. IEEE.

Case Formulations Annexure

Annexures: Case 3 – Scenario 2

Annex: A1

Since there is only One Prosumer in each community therefore following parameters and variables are equivalent to each other.

A1	Parameters	
No.1	Price of electricity kw per hour sold to consumer *ja* by its prosumer *ia* of community-A in time period *t*	Price of electricity kw per hour bought from Prosumer *ia* of Community-A by its Consumer *ja* in time period *t*
	$pija^{t}_{ia,ja}$	$pjai^{t}_{ja,ia}$
No.2	Price of electricity kw per hour sold to consumer *jb* by its prosumer *ib* of community-B in time period *t*	Price of electricity kw per hour bought from Prosumer *ib* of Community-A by its Consumer *jb* in time period *t*
	$pijb^{t}_{ib,jb}$	$pjbi^{t}_{jb,ib}$

A1	Variables	
No.3	Quantity sold by Prosumer *ia* of Community-A to its Consumer *ja*	Quantity bought by consumer *ja* of community-A from its prosumer *ia* in time period *t*
	$xija^{t}_{ia,ja}$	$xjai^{t}_{ja,ia}$
No.4	Quantity sold by Prosumer *ib* of Community-B to its Consumer *jb*	Quantity bought by consumer *jb* of community-B from its prosumer *ib* in time period *t*
	$xijb^{t}_{ib,jb}$	$xjbi^{t}_{jb,ib}$

Annex: A2

Following variables are considered equivalent to each other in the Objective Function therefore, only one of each (i.e. left column) is considered.

A2	Objective Function	
No.1	Prosumers revenues from directly selling to respective Community Consumers	Consumers Costs of buying from their respective Community Prosumers
	$\sum_{ia}^{I}\sum_{ja}^{J}\sum_{t}^{T} xija_{ia,ja}^{t}.\, pija_{ia,ja}^{t} + \sum_{ib}^{M}\sum_{jb}^{N}\sum_{t}^{T} xijb_{ib,jb}^{t}.\, pijb_{ib,jb}^{t}$	$\sum_{ja}^{J}\sum_{ia}^{I}\sum_{t}^{T} xjai_{ja,ia}^{t}.\, pjai_{ja,ia}^{t} - \sum_{jb}^{N}\sum_{ib}^{M}\sum_{t}^{T} xjbi_{jb,ib}^{t}.\, pjbi_{jb,ib}^{t}$

Annexures: Case 3 – Scenario 3

Annex: A3

Since there is only One Prosumer / Aggregator in each community therefore following **Parameters and Variables** are equivalent to each other.

A3	Parameters	
No.1	Price of electricity kw per hour sold to consumer *ja* by its prosumer *ia* of community–A in time period *t*	Price of electricity kw per hour bought from Prosumer *ia* of Community-A by its Consumer *ja* in time period *t*
	$pija^{t}_{ia,ja}$	$pjai^{t}_{ja,ia}$
No.2	Price of electricity kw per hour sold to consumer *jb* by its prosumer *ib* of community–B in time period *t*	Price of electricity kw per hour bought from Prosumer *ib* of Community-B by its Consumer *jb* in time period *t*
	$pijb^{t}_{ib,jb}$	$pjbi^{t}_{jb,ib}$
No.3	Price of electricity kw per hour sold to Aggregator by Prosumer *ia* of community-A in period *t*	Price of electricity kw per hour bought by Aggregator from prosumer *ia* of community-A in time period *t*
	$piia1^{t}_{ia}$	$pai1^{t}_{ia}$
No.4	Price of electricity kw per hour sold to Aggregator by Prosumer *ib* of community-B in period *t*	Price of electricity kw per hour bought by Aggregator from prosumer *ib* of community-B in time period *t*
	$piia2^{t}_{ib}$	$pai2^{t}_{ib}$
No.5	Price of electricity kw per hour bought from Aggregator by prosumer *ia* of community-A in period *t*	Price of electricity kw per hour sold by Aggregator to prosumer *ia* of community-A in time period *t*
	$pia1^{t}_{ia}$	$paai1^{t}_{ia}$

No.6	Price of electricity kw per hour bought from Aggregator by prosumer *ib* of community-B in period *t*	Price of electricity kw per hour sold by Aggregator to prosumer *ib* of community-B in time period *t*
	$pia2_{ib}^{t}$	$paai2_{ib}^{t}$
No.7	Price of electricity kw per hour bought from Aggregator by consumer *ja* of community-A in time period *t*	Price of electricity kw per hour sold by Aggregator to consumer *ja* of community-A in time period *t*
	$pjaa_{ja}^{t}$	$paja_{ja}^{t}$
No.8	Price of electricity kw per hour bought from Aggregator by consumer *jb* of community-B in time period *t*	Price of electricity kw per hour sold by Aggregator to consumer *jb* of community-B in time period *t*
	$pjba_{jb}^{t}$	$pajb_{jb}^{t}$

A3	Variables	
No.9	Quantity sold by Prosumer *ia* of Community-A to its Consumer *ja* in time period *t*	Quantity bought by consumer *ja* of community-A from its prosumer *ia* in time period *t*
	$xija_{ia,ja}^{t}$	$xjai_{ja,ia}^{t}$
No.10	Quantity sold by Prosumer *ib* of Community-B to its Consumer *jb* in time period *t*	Quantity bought by consumer *jb* of community-B from its prosumer *ib* in time period *t*
	$xijb_{ib,jb}^{t}$	$xjbi_{jb,ib}^{t}$
No.11	Quantity sold by Prosumer *ia* of Community-A to Aggregator in time period *t*	Quantity bought by Aggregator from prosumer *ia* of community-A in time period *t*
	$xiia1_{ia}^{t}$	$xai1_{ia}^{t}$
No.12	Quantity sold by Prosumer *ib* of Community-B to Aggregator in time period *t*	Quantity bought by Aggregator from prosumer *ib* of community-B in time period *t*

	$xiia2_{ib}^{t}$	$xai2_{ib}^{t}$
No.13	Quantity bought by Prosumer *ia* of community-A from Aggregator in time period *t*	Quantity sold by Aggregator to prosumer *ia* of community-A in time period *t*
	$xia1_{ia}^{t}$	$xaai1_{ia}^{t}$
No.14	Quantity bought by Prosumer *ib* of community-B from Aggregator in time period *t*	Quantity sold by Aggregator to prosumer *ib* of community-B in time period *t*
	$xia2_{ib}^{t}$	$xaai2_{ib}^{t}$
No.15	Quantity bought by consumer *ja* of community-A from Aggregator in time period *t*	Quantity sold by Aggregator to consumer *ja* of community–A in time period *t*
	$xjaa_{ja}^{t}$	$xaja_{ja}^{t}$
No.16	Quantity bought by consumer *jb* of community-B from Aggregator in time period *t*	Quantity sold by Aggregator to consumer *jb* of community–A in time period *t*
	$xjba_{jb}^{t}$	$xajb_{jb}^{t}$

Annex: A4

Following variables are considered equivalent to each other in the **Objective Function** therefore, only one of each (i.e. left column) is considered.

A4	Objective Function	
No.1	Prosumers revenues from selling to respective community consumers	Consumers costs of buying from their community prosumers
	$\sum_{ia}^{I}\sum_{ja}^{J}\sum_{t}^{T} xija_{ia,ja}^{t}.pija_{ia,ja}^{t} + \sum_{ib}^{M}\sum_{jb}^{N}\sum_{t}^{T} xijb_{ib,jb}^{t}.pijb_{ib,jb}^{t}$	$\sum_{ja}^{J}\sum_{ia}^{I}\sum_{t}^{T} xjai_{ja,ia}^{t}.pjai_{ja,ia}^{t} - \sum_{jb}^{N}\sum_{ib}^{M}\sum_{t}^{T} xjbi_{jb,ib}^{t}.pjbi_{jb,ib}^{t}$
No.2	Prosumers revenues from selling to aggregator	Aggregator costs of buying from community prosumers
	$\sum_{ia}^{I}\sum_{t}^{T} xiia1_{ia}^{t}.piia1_{ia}^{t} + \sum_{ib}^{M}\sum_{t}^{T} xiia2_{ib}^{t}.piia2_{ib}^{t}$	$\sum_{ia}^{I}\sum_{t}^{T} xai1_{ia}^{t}.pai1_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} xai2_{ib}^{t}.pai2_{ib}^{t}$
No.3	Prosumers cost of buying electricity from aggregator	Aggregator revenues from selling to prosumers
	$\sum_{ia}^{I}\sum_{t}^{T} xia1_{ia}^{t}.pia1_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} xia2_{ib}^{t}.pia2_{ib}^{t}$	$\sum_{ia}^{I}\sum_{t}^{T} xaai1_{ia}^{t}.paai1_{ia}^{t} + \sum_{ib}^{M}\sum_{t}^{T} xaai2_{ib}^{t}.paai2_{ib}^{t}$
No.4	Consumers costs of buying electricity from aggregator	Aggregator revenues from selling to consumers
	$\sum_{ja}^{J}\sum_{t}^{T} xjaa_{ja}^{t}.pjaa_{ja}^{t} - \sum_{jb}^{N}\sum_{t}^{T} xjba_{jb}^{t}.pjba_{jb}^{t}$	$\sum_{ja}^{J}\sum_{t}^{T} xaja_{ja}^{t}.paja_{ja}^{t} + \sum_{jb}^{N}\sum_{t}^{T} xajb_{jb}^{t}.pajb_{jb}^{t}$

Annex: A5

Since Objective Function of the Case 3 – Scenario 3 is to maximize the profits of the whole Network (i.e. by including Prosumers, Consumers, and Aggregator) therefore, following are considered twice in order to compute the profits / costs of each entity in the network.

A5	Objective Function		
No.1	Prosumers revenues from selling to aggregator	Aggregator costs of buying from community prosumers	
	$\sum_{ia}^{I}\sum_{t}^{T} xiia1_{ia}^{t}.piia1_{ia}^{t} + \sum_{ib}^{M}\sum_{t}^{T} xiia2_{ib}^{t}.piia2_{ib}^{t}$	$-\sum_{ia}^{I}\sum_{t}^{T} xiia1_{ia}^{t}.piia1_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} xiia2_{ib}^{t}.piia2_{ib}^{t}$	It is included to compute aggregator costs.
No.2	Prosumers cost of buying electricity from aggregator	Aggregator revenues from selling to prosumers	
	$-\sum_{ia}^{I}\sum_{t}^{T} xia1_{ia}^{t}.pia1_{ia}^{t} - \sum_{ib}^{M}\sum_{t}^{T} xia2_{ib}^{t}.pia2_{ib}^{t}$	$\sum_{ia}^{I}\sum_{t}^{T} xia1_{ia}^{t}.pia1_{ia}^{t} + \sum_{ib}^{M}\sum_{t}^{T} xia2_{ib}^{t}.pia2_{ib}^{t}$	It is included to compute aggregator revenues.
No.3	Consumers costs of buying electricity from aggregator	Aggregator revenues from selling to consumers	
	$-\sum_{ja}^{J}\sum_{t}^{T} xjaa_{ja}^{t}.pjaa_{ja}^{t} - \sum_{jb}^{N}\sum_{t}^{T} xjba_{jb}^{t}.pjba_{jb}^{t}$	$\sum_{ja}^{J}\sum_{t}^{T} xjaa_{ja}^{t}.pjaa_{ja}^{t} + \sum_{jb}^{N}\sum_{t}^{T} xjba_{jb}^{t}.pjba_{jb}^{t}$	It is included to compute aggregator revenues.