Dynamic Demand Response in Residential Prosumer Collectives

Salma Bakr

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Abstract

This research aims at exploring how smart grid opportunities can be leveraged to ameliorate demand response practices for residential prosumer collectives, while meeting the needs of end-users and power grids.

Electricity has traditionally been generated in centralized plants then transmitted and distributed to end-users, but the increasing cost-effectiveness of micro-generation (e.g. solar photovoltaics) is resulting in the growth of more decentralized generation. The term “prosumers” is commonly used to refer to energy users (usually households) who engage in small-scale energy production. Of particular interest is the relatively new phenomenon of prosumer collectives, which typically involve interactions between small-scale decentralized generators to optimize their collective energy production and use through sharing, storing and/or trading energy. Drivers of collective prosumerism include sustaining community identity, optimizing energy demand and supply across multiple households, and gaining market power from collective action.

Managing power flows in grids integrating intermittent micro-generation (e.g. from solar photovoltaics and micro-wind turbines) presents a challenge for prosumer collectives as well as power grid operators. Smart grid technologies and capabilities provide opportunities for dynamic demand response, where flexible demand can be better matched with variable supply. Ideally, smart grid opportunities should incentivize prosumers to maximize their energy self-consumption from local supply while fairly sharing any income from trading surplus energy, or any loss of utility associated with altering energy demand patterns.

New businesses are emerging and developing various products and services around smart grid opportunities to cater for the socio-technical needs of residential prosumer collectives, where technical energy systems overlap with social interactions. This research studies how emerging businesses are using smart grid capabilities to create dynamic demand response solutions for residential prosumer collectives, and how fairness can be adopted in solutions targeting those collectives.

This research interweaves social and technical knowledge from literature to interpret the interactions and objectives of prosumer collectives in new ways, and create new socio-technical knowledge around those interpretations.

Conducting this research involved using mixed research methods to draw on social science, computer science, and power systems. In the social stream of the research, semi-structured interviews were conducted with executives in businesses providing current or potential smart grid solutions enabling dynamic demand response in residential prosumer collectives. In the technical stream, optimization, computation and game theory concepts were used to develop software algorithms for integrating fairness in allocating shared benefits and loss of utility in collective settings.

Interview findings show that new business models and prosumer-oriented solutions are being developed to support the growth of prosumer collectives. Solutions are becoming more software-based, and enabling more socially-conscious user choice. Challenges include dealing with power quality rather than capacity, developing scalable business models and adequate regulatory frameworks, and managing social risks. Automated flexibility management is anticipated to dominate dynamic demand response practices, while the grid is forecast to become one big prosumer community rather than pockets of closed communities. Additionally, the research has developed two software algorithms for residential collectives, to fairly distribute revenue and loss of utility among households. The algorithms used game theory, optimization and approximation algorithms to estimate fair shares with high accuracy using less computation time and memory resources than exact methods.

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Chapter 1

Introduction

1.1 Overview

This thesis aims at investigating how smart power grid opportunities can be leveraged to improve energy demand response activities for residential prosumer collectives, while meeting the needs of end-users and the power grid.

Price drops, improved efficiencies, and the desire to live green are driving households to increasingly uptake distributed energy generation (e.g. solar photovoltaics (PV) and wind turbines) and storage systems (e.g. batteries). Consumers are thus transforming to prosumers, who can produce their own electricity, which they can then consume, store, sell or trade [1–6].

Evidence suggests that collectives of prosumers exist around the world, ranging from organically emerging communities integrating rooftop solar PV, to third-party supported wind farm collectives [7–9]. A prosumer collective is a group of prosumers on the same power distribution network, who often share values, identity and place. A prosumer collective may include a group of households within a neighbourhood, a district, or a municipality [10–13].

A collective of prosumer households can provide increased benefits, including strengthening prosumers' market power (e.g. to sell electricity to the grid) [14, 15], and creating flexible demand across households to maximize energy self-consumption from the collective's micro-generation [10, 16].

While energy demand in households is generally highly variable, a collective of prosumer households adds to that complexity by dominantly integrating intermittent micro-generation. Demand-side energy management is thus required to create flexible demand that matches with sporadic supply.

Current demand-side energy management activities are often categorized into energy efficiency (EE) and demand response (DR). Energy efficiency is a static resource for managing demand, where the same service is provided using less energy [17]. Energy efficiency can neither be dispatched (i.e. turned on or off, or adjusted) nor controlled, and is often limited to the technical constraints of certain technologies (e.g. efficient light bulbs) [18]. Demand response is a controllable activity, and is defined as:

> *the changes in electric usage by end-user customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized [19, p. 6].*

Demand response has characteristics that can enable flexible demand in residential prosumer collectives. Nevertheless, existing demand response activities lack the capabilities required for accommodating prosumer collectives. The next section explores the motivation behind investigating how to improve demand response practices in order to cater for the needs of prosumer collectives.

1.2 Motivation

Today's demand response practices mostly target consumers, and even though a few of those practices highly correlate with renewables, they are either scarcely implemented or are used with consumers rather than prosumers (more details in Section 2.4.3. Additionally, demand response practices in general lack features for enabling communication among households in a collective, or between a collective and the grid or the electricity market, and are thus inadequate for maintaining the complex interactions arising in and around prosumer collectives.

The various changes occurring in the energy terrain today, and notably the emergence of residential prosumer collectives, necessitate the evolution of demand response practices to become more dynamic and accommodative of new end-users and their complex interactions.

The growing technology advancements in metering, communication, and control, and the increasing economic feasibility of distributed energy generation and storage technologies are supporting the transition to a “smart grid” [20–25], which should ideally enable grid stakeholders (households, electricity retailers, grid operators, etc.) to interact in a reliable, efficient and sustainable way [26].

The smart grid offers various opportunities for creating dynamic demand response in residential prosumer collectives, including scheduling energy usage among appliances and batteries across multiple households, selling the collective's electricity to the grid, and storing energy supply from micro-generation in batteries and electric vehicles for later use during peak demand periods [18, 20, 21, 27].

Most power grids worldwide are not yet smart. Nevertheless, the smart grid concept has the potential to transform such grids in a similar way to how the internet transformed two-way digital network communication. The smart grid can be viewed as an idealised integration of the electricity grid and the internet. In its fully developed form, the smart grid can be seen as a transformation from centralized to distributed control, and from a generation-oriented model to one that focuses on end-users [28].

For a socio-technical system like a prosumer collective, where technical energy systems overlap with human objectives and practices, opportunities enabled by the smart grid should ideally take social concepts (e.g. fairness) into consideration. Such concepts help in better understanding and assessing the processes and the outcomes of prosumer collectives and support them in being socially accepted [29–32]. The context governing a prosumer collective and its maturity may play a role in shaping who decides which social concepts are important (e.g. regulatory bodies, prosumers, research entities).

With regards to who is using smart grid opportunities to improve demand response practices, most top actors in power grids (grid operators, distribution companies, etc.) are unfortunately slow in offering dynamic demand response to rapidly emerging prosumer collectives (i.e. bottom actors). This difference in pace has stirred the rise of "middle actors", which can help link top and bottom actors, and enable innovative smart grid offerings. Ideally, middle actors should help prosumer collectives efficiently manage their complex power, data and money flows, while providing support to top actors to notably maintain grid reliability.

Investigating this complex socio-technical problem needs to leverage both quantitative data (e.g. from smart meters and solar PV inverters) and qualitative data (e.g. prosumers' energy aspirations and collective-oriented objectives). To tackle such a challenging piece of interdisciplinary research and create reasoned discussions from both qualitative and quantitative data, using mixed methods presents a suitable research pathway. The core benefit of using mixed methods lies in their integrated results, which combine words and narratives with numerical data [33].

1.3 Thesis Roadmap

This thesis aims to explore how smart grid capabilities can be used to improve demand response practices in residential prosumer collectives, by posing four research questions, as presented below. To tackle this aim, it is important to first review the current status of energy demand management in general, and explore what new opportunities are emerging, as presented in the first research question below.

Research Question 1 – What is the current status of energy demand management and what new opportunities exist?

To address the first research question, I first outline how power grids and electricity markets work. Then, I introduce the concepts of demand-side energy management, energy efficiency and demand response, and discuss why demand response is the energy management approach that is more suited to prosumer collectives. I then highlight the inadequacy of existing demand response practices to cater for the needs of residential prosumer collectives, and identify the emerging opportunities, made possible by the smart grid, for developing more dynamic demand response practices.

Research Question 2 – How do new opportunities offered by the smart grid support the emergence of residential prosumer collectives?

The second research question investigates how the emergence of prosumer collectives is being enabled by smart grid technologies, such as distributed energy resources, and smart metering and controls. I first introduce the concept of energy prosumerism, for individuals as well as collectives, and discuss the drivers, barriers and enablers of individual and collective prosumerism. I also review and analyze four residential prosumer collectives from around the world to inform the research herein.

Based on literature review and example collectives, I identify key aspects to be considered in prosumer collectives (e.g. fairness), and a lack of enabling solutions for dynamic demand response by top actors in the electricity system (grid operators, distribution companies, etc.). This is followed by reasoning on the emergence of new actors, namely middle actors, and an outline of their role in leveraging smart grid opportunities to develop dynamic demand response practices for residential prosumer collectives.

Research Question 3 – How are middle actors shaping smart grid offerings, and what are the implications for dynamic demand response in residential prosumer collectives?

The third question investigates middle actors and their offerings in more details, where I report on semi-structured interviews that I undertook with executives from businesses specializing in offerings enabling dynamic demand response. I assess how middle actors and their offerings can enable residential prosumer collectives to create flexible demand and optimally manage their multi-directional interactions, and learn about what future trends and challenges middle actors are forecasting for residential prosumer collectives and energy demand management.

Research Question 4 – How can fairness be fostered in dynamic demand response for residential collectives?

Literature and interview findings revealed that fairness is a key concept to be considered in dynamic demand response for residential collectives. Using optimization, computation and game theory concepts, I develop two software algorithms, where one fairly distributes a collective's revenue from selling electricity among its prosumers, and the other fairly allocates loss of utility associated with dynamic demand response among a collective of consumers.

1.4 Thesis Chapters

Chapter 2 outlines how power grids and electricity markets work, and discusses the various objectives and mechanisms of demand-side energy management. The chapter then focuses on demand response, its current approaches, and the inadequacy of such approaches in meeting the needs of residential prosumer collectives. This is followed by a discussion about the various opportunities evolving for demand response in light of smart grids.

Chapter 3 presents a literature review on the emergence of energy prosumers, both individuals and collectives, then discusses their drivers, barriers and enablers. Furthermore, the initiating entities, physical configurations, and organizational structures of prosumer collectives are presented. Four example prosumer collectives from around the world are then reviewed and analyzed to inform the work herein.

In addition, Chapter 3 underpins the lack of enabling solutions offered by top actors (e.g. grid operators) for dynamic demand response in prosumer collectives, and highlights the role of emerging middle actors in bridging this gap by leveraging smart grid opportunities to innovate dynamic demand response offerings.

In Chapter 4, the methodology used to address the third and fourth research questions of this thesis is presented, with an elaboration on the socio-technical nature of this research. The chapter also presents why mixed methods are used to address the third and fourth research questions, and sets the scene for Chapters 5 and 6.

Chapter 5 presents the findings of the interviews conducted with emerging businesses acting as middle actors in offering dynamic demand response solutions to residential prosumer collectives. The chapter illustrates how the slow response from some of the top actors in the electricity industry to address the needs of rapidly emerging prosumer collectives is opening up the doors to a wave of new businesses. The chapter focuses on the characteristics of such new businesses and the smart grid products and services they develop to cater for the needs of prosumer collectives. In addition, the chapter discusses the main challenges and future trends expected to arise in residential prosumer collectives and energy demand management.

In Chapter 6, I investigate new ways to adopt fairness in software solutions for dynamic demand response targeting collectives of households, where I develop two software algorithms for collective settings. The first algorithm fairly distributes a collective's revenue, from selling its electricity, among its prosumers, and the second fairly distributes a collective's loss of utility, associated with a demand response event, among its households.

Lastly, Chapter 7 concludes this thesis by interweaving the literature review with the social-technical findings of this research, to underpin linkages, highlight novelty, and make recommendations for future research on this topic.

1.5 My Perspectives

My interest in demand-side energy management for households started during my interdisciplinary master's degree studies, which mainly included technical, socio-economic and cultural courses on renewable energy and smart grids. Coming from an engineering background – where my bachelor's studies covered topics in electronics, communications and power engineering – I was particularly interested in smart power grids which lie at the intersection of those three engineering disciplines. In my master's thesis, I investigated the status and potential of demand-side management in the Middle East and North Africa (MENA) Region, and recommended communication and control technologies for setting up a regional smart grid environment. Additionally, I developed a load management algorithm, which reduces peak electricity demand in a household, and proposed modifications to existing electricity billing schemes to incentivize rational electricity demand.

During my master's studies, I was fascinated with renewable energy resources and their huge potential, especially as renewable micro-generation can help power grids become more decentralized, and enable consumers to produce their own electricity. However, the costs of renewable micro-generation (e.g. solar PV) during my studies in 2012 were still very high, which made renewable energy projects infeasible in some cases. Therefore, work conducted in my thesis focused on demand-side management for consumers rather than prosumers, as the concept of energy prosumerism was still in its infancy. Nevertheless, as the prices of micro-generation and battery systems dropped during the past few years, the uptake of distributed energy resources among households has risen and thus energy prosumers have emerged. This transformation triggered my curiosity to explore different perspectives of residential demand-side energy management – for prosumers rather than consumers; for collectives of households rather than individual ones; and from a socio-technical lens rather than a purely technical one.

During my PhD journey, I have attended an energy summer school in 2014 at the University of Groningen in the Netherlands. That year, the school had an interdisciplinary theme – "Smart Grids from a Global Perspective: Bridging Old and New Energy Systems". During this 2-week summer school, PhD students researching across various disciplines had the chance to attend presentations given by specialists in the field, present their research work, and take part in active discussions and workshops. I learned from experts, networked and exchanged experiences with fellow PhD students, and went on informative "new energy excursions" (one of them I discuss in Chapter 3 as an example prosumer collective).

Participating in this summer school was a very interesting and beneficial experience, which greatly motivated my research and highlighted the significance of interdisciplinary research covering emerging energy transitions in light of smart grids. More details about my presentation at the summer school, and the other presentations and publications of my PhD journey, to date, are available in Appendix D.

At the moment, I am experiencing the essence of this research firsthand, as I take up a software product management role at a new company (i.e. a middle actor) developing smart grid solutions (both software and hardware) for electric utilities to deal with the challenges of integrating distributed energy resources in power grids.

Chapter 2

Literature Review

Research Question 1 – What is the current status of energy demand management and what new opportunities exist?

2.1 Introduction

Demand-side energy management is a cost-effective way to balance electricity supply and demand while maintaining grid reliability and reducing price volatility [19, 22, 34–36]. By building on the supply-following concept rather than load-following, demand-side energy management can cost-effectively mitigate risks (e.g. asset valuation risks) that come with building new large-scale capital-intensive generation facilities [34, 37, 38]. In case of power grid contingencies (generation shortage, power line faults, etc.), managing energy demand efficiently can also help maintain power system reliability [22, 38, 39]. By encouraging consumers to reduce demand during peak periods in return for incentives, demand-side management can also help reduce electricity price volatility [19, 40–42].

Current demand-side energy management approaches broadly include energy efficiency and demand response. While energy efficiency focuses on technologies that use energy efficiently (e.g. efficient light bulbs such as LEDs) [14, 18], demand response focuses on changing demand patterns in response to incentives, electricity prices, or control signals [18, 19, 43, 44]. The responsiveness of demand response and its availability upon request make it suitable for managing energy in households, and potentially among households, where demand patterns are highly variable.

Demand response today is often implemented in the form of programs, which target various consumers (industrial, commercial, residential, etc.). Basically, program administrators (e.g. grid operators) request specific changes to demand loads, and consumers make those changes to their demand in return for compensation (lower tariffs, rebates, etc.).

While evidence indicates that prosumers and prosumer collectives are emerging [8, 9, 13, 45, 46], existing demand response practices fall short of addressing their needs, especially around managing the non-consuming attributes of prosumers (production, storage, etc.), and the interactions among prosumers in a collective, or between a collective and external stakeholders. As collective prosumerism especially grows, demand response practices need to evolve to address the changing characteristics of end-users, and how they interact together in new settings (e.g. prosumer collectives).

Smart grid capabilities (advanced metering, controls, etc.) can play an essential role in enabling the new wave of demand response practices, where energy demand in prosumer households can be flexibly matched with their intermittent micro-generation, and where such households interact together and with the grid in new ways (e.g. collaborate to achieve energy self-sufficiency from micro-generation).

This chapter presents the literature review conducted on the current approaches of managing energy demand in power grids, and highlights the drawbacks of current practices in meeting the needs of the changing energy landscape, and specifically prosumer collectives. The chapter also provides an overview of smart grids opportunities enabling new options for managing energy in residential prosumer collectives, which sets the scene for investigating how to leverage such opportunities to evolve demand response to cater for such collectives, which is the aim of this thesis.

Section 2.2 outlines how power grids and electricity markets operate, then explains how energy supply and demand are balanced in power grids, and what drives demand-side energy management practices.

Section 2.3 presents the definitions of demand-side management, broadly introduces its two approaches, energy efficiency and demand response, and explains why the rest of the thesis focuses on demand response as the suitable approach for managing energy demand in prosumer collectives.

In Section 2.4, current demand response mechanisms are discussed in details, and their inadequacy for residential prosumer collectives is underpinned. The new opportunities made available by the smart grid are presented in Section 2.5, and Section 2.6 summarizes literature review findings and highlights implications for this work.

2.2 The Electric Power Grid

This section provides an overview of power grid components, namely generation, transmission and distribution, outlines how electricity markets work, and briefly explains how power grids balance electricity supply and demand.

2.2.1 Generation, Transmission and Distribution

The first power grids were built more than 140 years ago [47]. Figure 2.1, adopted from [48], illustrates power grid components used for generation, transmission, and distribution in the case of consumer loads.

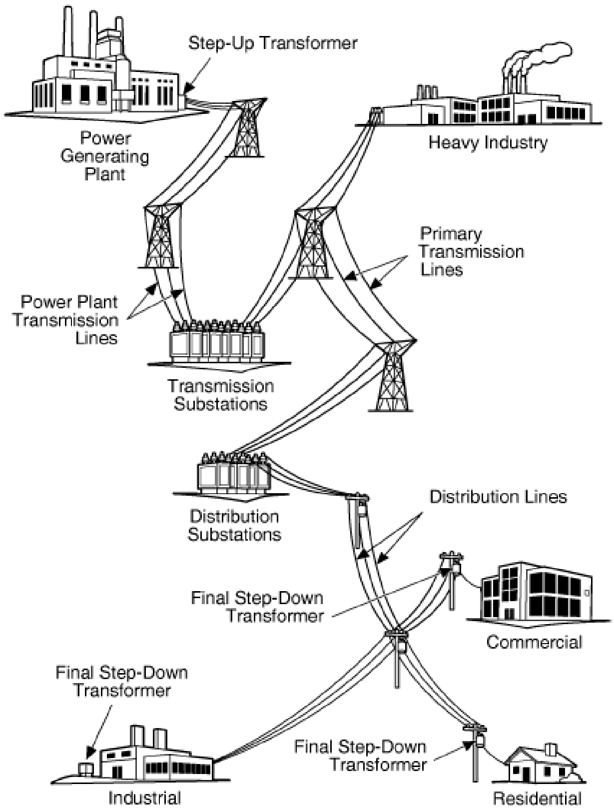

Figure 2.1: Generation, transmission and distribution in a power grid

Firstly, generators produce electricity from various sources (e.g. coal-fired power plants, hydropower plants), which are commonly centrally located in distant areas, away from consumers. Secondly, to transfer generated electricity with specific power P to end-users, it is first passed through step-up transformers which increase its voltage V (thus decreasing its current I, because $P = V * I$) to reduce transmission power losses (whose value is equal to $I^2 * R$, where R is the resistance of the transmission lines).

Thirdly, electricity is transmitted via a network of transmission lines, typically over long distances, to be distributed to consumers. Then, in the case of small-scale consumers (e.g. residential buildings), step-down transformers are used to reduce the voltage before distributing electricity to consumers via low-voltage distribution networks. For large-scale industrial consumers requiring high voltage levels, voltage may not need to be stepped down.

In most power networks, electricity is generated using a mix of different types of power plants covering electricity demand at three scales: base, intermediate, and peak. Baseload power plants, typically coal-fired and nuclear power plants, cover the minimum level of demand in a power grid by running at maximum output all the time [35, 49]. Hydropower is also used in countries like Norway and Canada to cover baseload, as it is flexible, reliable, clean, cheap and safe [50].

To cover intermediate electricity loads, which is the range of demand between base and peak loads, intermediate power plants are used; such plants do not run all the time, but can quickly ramp up and down to meet the rise and decline in demand (e.g. during morning and evening hours in households) [35]. Gas turbine power plants as well as combined cycle power plants (those comprising gas and steam turbines) are commonly used to cover intermediate loads [35, 49]. Hydropower plants are also used in some countries [51]. In the case of peak loads comprising spikes in demand, often during heat waves or winter storms, electricity is typically generated by gas turbine power plants which are expensive to operate but very fast to dispatch [34, 35, 49].

Electricity can be generated from a number of sources, and one way of categorizing those sources is to group them into renewable and non-renewable sources. Non-renewable sources for generating electricity include fossil fuels (e.g. petroleum, coal, natural gas), while renewable sources include solar rays, wind movement, ocean waves and tides, and biomass [35].

A key difference between renewable and non-renewable sources is the intermittency of some forms of renewable energies (e.g. solar and wind) which generate variable amounts of electricity depending on weather conditions and site location [35]. This variability can be on the scale of seconds or minutes (e.g. a cloud passing over the sun reducing the solar rays reaching a solar panel); days or weeks (e.g. weather conditions affecting solar and wind resources); seasons (e.g. less sunshine in winter than in summer); or multi-year (e.g. dry years affecting hydro reservoirs).

Intermittent renewable sources do not provide stable electricity production and thus cannot be used as baseload power plants. Additionally, such sources are not dispatchable like non-renewable sources, and thus cannot be made available on demand [35, 52].

2.2.2 Electricity Markets

Electric utilities have been traditionally vertically integrated, meaning that a single organisation or company owns and operates the entire supply chain of delivering electricity to end-users (i.e. generation, transmission and distribution) [53, 54]. In the US, the government believed that having a regulated wholesale electricity market where electric utilities have full control of power industry operations is essential, as it cannot be guaranteed that external enterprises will act in the public interest and ensure power supply security [54]. Nevertheless, regulated markets form monopolies, where utilities may be less concerned about efficient operations and costs. This is less likely to happen in competitive deregulated markets [53].

The deregulation of electricity wholesale markets received initial attention in the 1970s, when electricity started being perceived as a commodity that can be easily measured and thus traded [55, 56]. The objective of deregulation is to let market forces (i.e. commercial participants) establish market segments based on price, technology, quality, or scale and scope economies[1] [57]. Deregulated (i.e. liberalized) electricity markets function as auctions, where generators propose prices for supplying electricity for fixed time intervals (e.g. half-hourly), while the grid operator ranks those proposals and determines the cheapest mix of generation sources that satisfy demand [58].

Electricity markets around the world vary in their degrees of liberalization, meaning that market structures can range from being fully competitive to being totally or partially managed by vertically integrated utilities. In some cases, generation may be liberalized while transmission and distribution may be monopolized. In the US, some of the states have regulated markets (e.g. Colorado, Florida and Kentucky), while Texas and most of the states in the Northeast and Mid-Atlantic are deregulated. California, on the other hand, is partially deregulated, while other states have started deregulation in some capacity which then got suspended [59].

The competitiveness in deregulated markets allows pricing programs and offerings of service quality to grow into tools for competitive advantage [55], which encourages businesses to adopt innovative programs and services to gain and retain customers.

[1] Scale and scope economies are those where average costs are reduced by increasing the scale or scope of production, respectively [57].

2.2.3 Balancing Supply and Demand

Electricity is one of the key bases of a developed society, as adequate electricity supply facilitates technological advancement and stimulates a healthy economy [35]. Electricity is also an ephemeral commodity – meaning that it needs to be consumed directly after being generated [35]; and although electricity can be stored, large-scale storage is currently costly [60]. Thus, balancing electricity supply and demand is essential to maintaining the stability of power grids [35, 61], and such balance is the responsibility of the grid operator [35], e.g. Transpower in New Zealand, and Independent Electricity System Operator (IESO) in Ontario, Canada.

Traditionally, grid operators would ensure electricity demand is met by requesting more electricity supply from generators. Nevertheless, in the 1980s, power grids started a major transition by moving away from load-following operations towards supply-following practices, where energy demand can be tailored to the available supply capacities [61]. Demand-side energy management is especially useful during seasonal demand spikes (e.g. during heat waves and cold snaps), and in the case of intermittent supply from utility-scale renewable energy generators (e.g. on-shore and off-shore wind turbines, concentrated solar power plants), when demand flexibility (i.e. changing electricity demand) is required to balance supply and demand [62].

Demand-side energy management can postpone or cancel infrastructure expansions, reduce the use of expensive peak power plants [63], reduce spikes in electricity prices [56], and reduce losses in transmission and distribution systems [64]. The need to include demand-side energy management into power systems planning has become critical [18, 65, 66]. The next section explores demand-side management in more details.

2.3 Demand-Side Management in Power Grids

In 1984, the term "demand-side management" (DSM) was coined in the US by the Electric Power Research Institute as follows:

> *DSM activities are those which involve actions on the demand (i.e. customer) side of the electric meter, either directly or indirectly stimulated by the utility. These activities include those commonly called load management, strategic conservation, electrification, strategic growth or deliberately increased market share [66].*

Although these definitions focus on managing electricity use, DSM can encompass other forms of energy use which may not necessarily be electricity-based [18], such as co-generation of heat and power, micro-generation of heat, and district heating and cooling [67]. The following is a more inclusive and recent definition of DSM [67]:

> *DSM comprises the technologies, actions, and programs on the demand-side of energy meters that seek to manage or decrease energy consumption, in order to reduce total energy system expenditures or contribute to the achievement of policy objectives such as emissions reduction or balancing supply and demand [67, p. 943].*

The next section explains the drivers of demand-side energy management in details.

2.3.1 Drivers of Demand-Side Management

Various motivations, spanning economic, technical, and environmental issues, stimulate the planning and implementation of demand-side management (DSM) activities in power grids. The following three sections discuss the main drivers motivating the use of DSM to balance electricity supply and demand.

Cost-effectiveness

Building new generation facilities to cover mounting demand comes with operational, financial and asset valuation risks [68], while turning on peaking plants is expensive [34, 35, 49]. Demand-side energy management can mitigate such risks [22, 34, 36, 37, 69, 70], by providing a cost-effective way to create flexible demand, e.g. by reducing or shifting demand [19, 37, 38, 40, 71].

Implementing DSM measures can help grid stakeholders (e.g. grid operators, distribution companies) avoid costs needed to provide capacity, energy, ancillary services, and transmission and distribution [19, 37, 38, 72, 73], and can help customers save on electricity bills [74–77]. Additionally, DSM resources provide modularity and flexibility, as they can be added in batches as required [78], in contrast to power plants which are often large-scale, capital-intensive and long-term projects.

By participating in DSM activities, end-users help move electricity usage from expensive on-peak periods to cheaper off-peak periods [79–82]. For example, by agreeing to have air conditioners or heat pumps regularly cycled on and off during grid contingencies, end-users can receive incentives; and responding to variable electricity prices throughout the day by reducing or shifting demand can help end-users save on electricity bills [44, 83].

In addition, implementing DSM by using efficient technologies (e.g. replacing incandescent lamps with light emitting diodes (LEDs)), or new systems and appliances (e.g. adding a thermal energy storage system to a commercial or residential building) can help conserve electricity, and save money [38, 82, 84].

Reliability Concerns

The main purpose of electricity grids is to reliably supply end-users with electricity as economically as possible [85]. To guarantee reliable supply (e.g. absence of voltage spikes, which may cause appliances to malfunction, or power outages, causing inconvenience to end-users), the power grid should ideally maintain stable operation within a set of constraints relating to supply quality either directly (e.g. power frequency and voltage variations) or indirectly (e.g. system faults and equipment ratings) [85].

If the reliability of power systems is in jeopardy (e.g. generation shortage, power line faults), DSM can provide demand flexibility (i.e. changing electricity demand from normal consumption patterns) and fast reaction at a low cost [22] which can help maintain power system reliability [38, 39]. The role DSM plays in maintaining such reliability is further underpinned by the increase in intermittent supply from renewable resources (e.g. solar PV, wind turbines). Intermittent electricity supply causes fluctuations in network frequency and voltage, which can cause equipment damage [86, 87]; however, DSM can help mitigate such effects by creating flexible demand [22, 88].

Furthermore, studies have shown that deploying DSM leads to higher system reliability because DSM resources are often distributed, unlike centralized generation units which often have single points of failure [89, 90].

Price Volatility

In deregulated markets, wholesale electricity prices – often referred to as spot prices – are volatile [58, 91], and volatility can occasionally reach a risky level [92, 93] where prices spike with little or no warning, or continue spiking over a long period (e.g. during a drought) [58]. Spot prices are a function of many parameters, including location, time (e.g. day, season), weather, temperature, demand variability, and system and market conditions [91]. For example, electricity spot prices are higher during morning and evening demand peaks, and lower at night when electricity use is low.

Some customers, such as medium and large industrial and commercial facilities, can choose to accept the risks associated with volatile spot prices, or mitigate those risks (e.g. implementing DSM by shifting consumption or relying on back-up generation rather than electricity from the grid) [58]. Other customers (e.g. households and small businesses) transfer price volatility risks to electricity retailers by buying electricity through fixed price contracts [58, 94]. By encouraging end-users to curb their demand during periods of peak prices and rewarding them in return, DSM can help reduce price volatility [19, 40–42].

Demand-side management is often broadly categorized into energy efficiency (EE) and demand response (DR) [19]. The following two sections describe energy efficiency, respectively, in more details.

2.3.2 Energy Efficiency

Energy efficiency is a well-established activity of DSM [18, 19, 78], where the same service is provided using less energy [14]. Inspite of being a static resource that does not respond to power system signals, e.g. price and control signals [22], energy efficiency is regarded as a capacity resource which reduces demand loads [22].

Because energy efficiency is a static resource that cannot be dispatched or controlled, its significance as a DSM resource is often limited to certain technologies and bounded by their constraints. For such reasons, demand response is more suitable for matching electricity consumption with production in residential prosumer households, as briefly explained in the next section and further discussed in the following sections.

2.3.3 Demand Response

Demand response is defined as “the changes in electric usage by end-user customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized” [19, p. 6].

Demand response is a controllable resource that responds to price and control signals [22], and can be implemented at different end-user scales and at different levels of the power grid (e.g. system operation, distribution, retailing).

Demand response is dynamic and event-driven, and commonly includes dynamic electricity pricing, contractually obligated or voluntary curtailment, and equipment cycling [44]. It is important to note that demand response can be manual (e.g. by behaviourally reacting to a request from the grid operator to reduce demand during specific hours of the day), or automatic (e.g. by having devices that react to signals received from the grid, such as smart thermostats).

The following section reviews existing demand response mechanisms, and highlights their inadequacies for managing energy in residential prosumer collectives.

2.4 Current Demand Response Mechanisms

Demand response is often implemented through programs. The US Energy Information Administration defines DSM programs as follows:

> *DSM programs consist of the planning, implementing and monitoring activities of electric utilities which are designed to encourage consumers to modify their level and pattern of electricity usage [95].*

From a physical and a transactional point of view, a demand response program involves interactions between the program administrator (e.g. grid operator (GO), transmission system operator (TSO), distribution system operator (DSO)), program participants (i.e. consumers), and sometimes an aggregator (an entity that bundles demand response resources, especially those of small-scale consumers).

Current demand response programs are either enabled by direct communication between the program administrator and consumers, or indirectly through an aggregator. Figure 2.2, adopted from reference [96], illustrates the connections between consumers and different program administrators, and the flows of power, communication and money. As shown, in case of consumers, power flows from the direction of program administrators to consumers, while communication flows from administrators where they request consumers to change their demand (often through reduction). As a result of participating in demand response, money flows from administrators to consumers; however, money also flows from consumers to administrators when paying for electricity bills, thus making money flow bi-directional.

An example illustrating a DR program enabled by direct communication between a grid operator and a consumer is that of Alcoa Inc. – a world leading producer of aluminium. Alcoa Inc. participates in a demand response program directly with Midwest Independent System Operator (a GO and TSO serving parts of the US and Canada) to optimize the electricity demand of its aluminium smelters [97].

An example program enabled by an aggregator is that of REstore, a leading demand response aggregator in Belgium and the UK. In December 2014, REstore successfully bid a demand response portfolio totalling 22 MW of sheddable load drawn from the 50 largest industrial energy users in the UK [98].

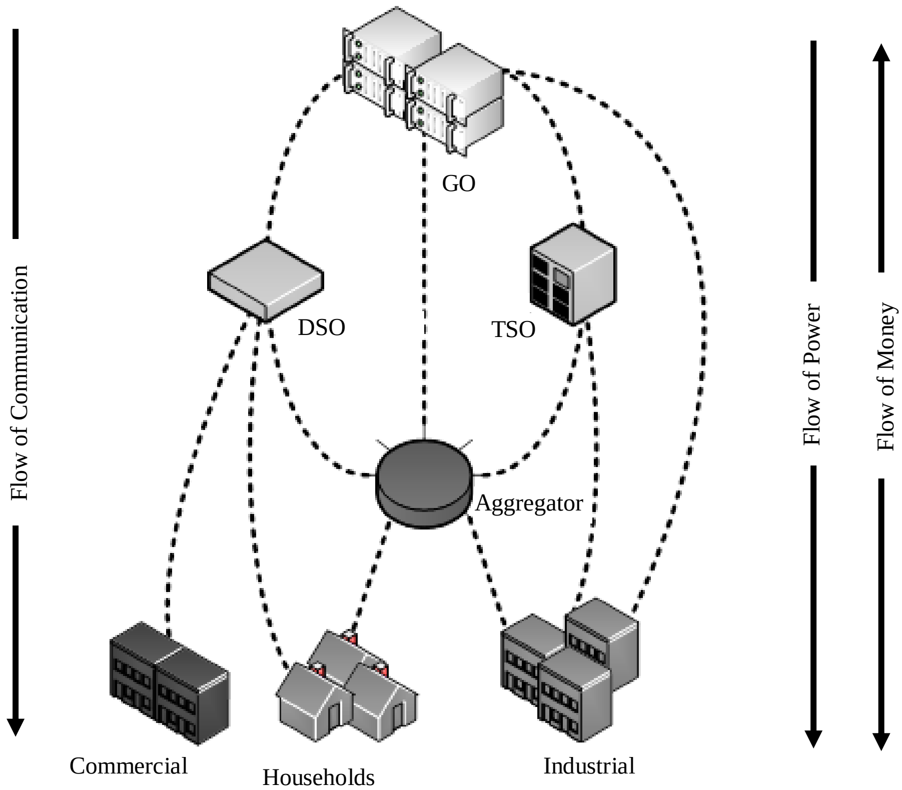

Figure 2.2: Participation of consumers in demand response programs directly or through an aggregator

Demand response programs can be categorized based on their economic or market triggers (e.g. high spot prices) and physical emergency triggers (i.e. grid status and reliability signals) [99]; or based on the services offered (e.g. energy, capacity or ancillary services [71]). Demand response programs can also be categorized based on the objectives they achieve for program administrators (e.g. load shaping and congestion management) or based on the compensation they offer to program participants (e.g. rebates, cheaper tariffs).

The following two sections investigates the details of demand response programs based on administrators' objectives at different levels of the power grid, and on compensations offered participants, respectively. This investigation helps identify the gaps in current demand response programs, which shape the improvements needed to adequately accommodate prosumer collectives and their growth, and hence feed into the overall aim of this thesis.

2.4.1 For Program Administrator

The design and implementation of a demand response program are typically managed by a program administrator, either directly or through contracting external parties (e.g. consulting firms). A program administrator is often a GO, a TSO, a DSO, or an electricity retailer. In this section, demand response mechanisms are presented based on their objectives at three power grid levels [22]: (1) system operation, (2) generation, transmission, and distribution, and (3) retail. Figure 2.3 illustrates these mechanisms for industrial, commercial and residential end-users. Mechanisms with bold dashed borders indicate that an aggregator is required for residential end-users to participate.

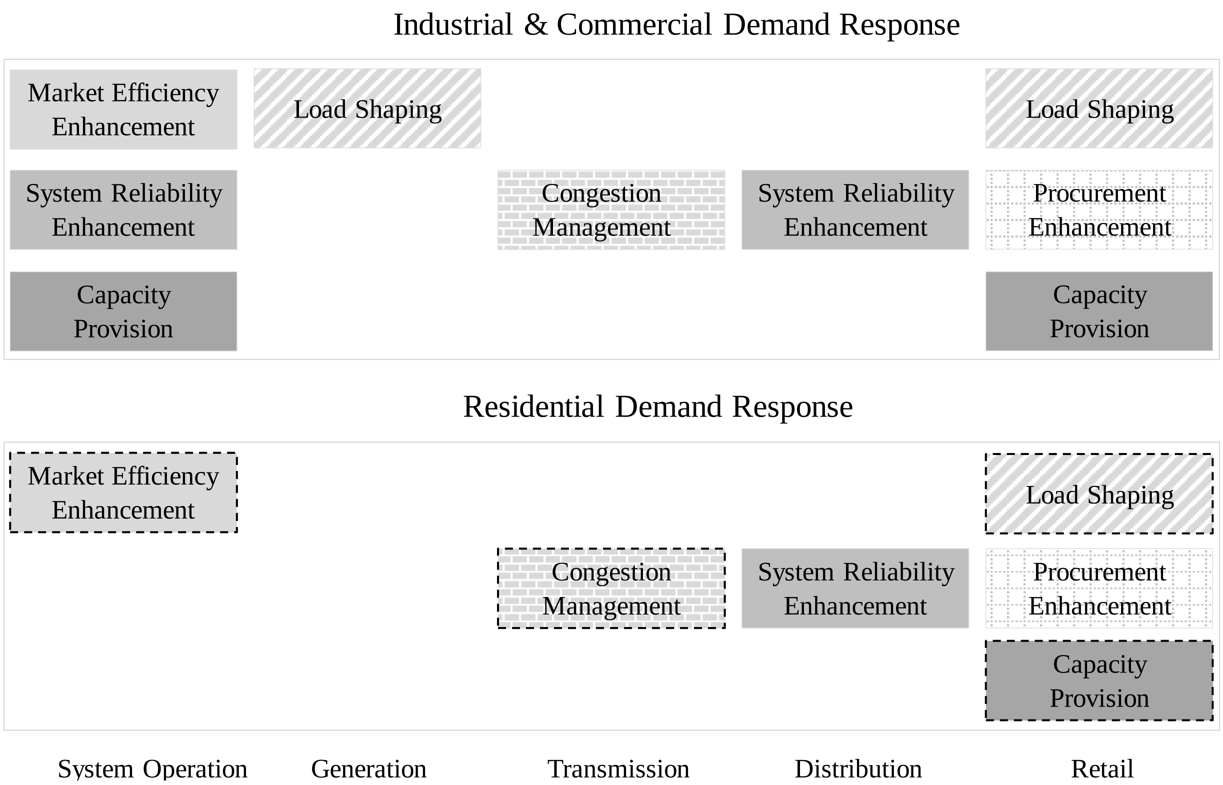

Figure 2.3: Demand response mechanisms for industrial, commercial and residential end-users at the different power grid levels based on the objectives of program administrators

Although this overview gathers currently common trends in DR mechanisms and programs around the world, there may be exceptions in some countries. More details on the objective of each mechanism and example programs are included in Appendix A.

System Operation

Demand response mechanisms implemented at the system operation level [22, 37, 38, 92, 100, 101], by the grid operator or in the wholesale market, can achieve several objectives for program administrators including enhancing power system reliability, providing capacity, and improving electricity market efficiency for industrial and commercial consumers. For residential consumers, demand response at the system operation level mainly focuses on enhancing market efficiency, and as DR programs at this level commonly require large amounts of DR resources, an aggregator is needed to collect such resources from households. Tables A.1–A.3 in Appendix A present the objectives of DR at the system operation level, and example mechanisms and programs in more details.

Generation, transmission and distribution

The implementation of demand response follows electricity from generation plants, through transmission networks, to be distributed to consumers via low-voltage networks. Currently, load shaping is available at the generation level only for industrial and commercial consumers, as it is uncommon for generators to directly deal with small-scale consumers [22, 35, 102–104]. If this mechanism becomes available to households, it would most likely require aggregating DR resources.

At the transmission level, congestion management is available for industrial, commercial, and residential consumers; however, in the case of residential consumers an aggregator is required to collect DR resources [22, 105–107]. At the distribution level, system reliability enhancement is commonly available to the three types of consumers [22, 101, 108, 109]. For residential consumers, reliability enhancement programs mainly include contractually obliged and voluntary curtailment. Such programs mostly use frequency changes to control relays in specific household devices (e.g. hot water cylinder, night storage heater), or involve behavioural response (e.g. by shifting or shedding load) to DR events requesting demand reduction. Tables A.4–A.6 in Appendix A detail the objectives of DR at the generation, transmission and distribution levels, and provide example mechanisms and programs.

Retail

Demand response is used by retailers to enhance electricity procurement, shape demand loads and manage power capacity. Programs aiming to provide capacity are available directly to industrial and commercial consumers, but require aggregators for residential consumers [110–112]. In the case of procurement enhancement, which is available to the three types of consumers, programs largely target controlling space and water heating devices (e.g. frequency-controlled hot water cylinder) or voluntary participation especially by households [113–115]. Load shaping at the retail level remains scarce, as the ability of DR to maintain load increases is limited [22]. In Tables A.7–A.9 in Appendix A, the objectives and mechanisms of DR at the retail level are presented in more details, in addition to example programs.

This overview highlights the inadequacy of current DR mechanisms, based on program administrator's objectives at different levels of the power grid. The next section presents current demand response mechanisms from the perspective of program participants, and highlights untapped potentials. The overall inadequacy of current DR mechanisms is recapped in Section 2.4.3.

2.4.2 For Program Participant

From the perspective of a program participant, DR programs can be price-based or incentive-based when compensating program participants for inconvenience or loss of utility (i.e. service) as a result of changing their electricity demand [18, 19, 21].

Price-based DR

Mechanisms triggering program participants to make demand changes based on variable prices over time are referred to as price-based DR, where both static and dynamic pricing are used to bill participants [18, 19, 21, 38]. A time-of-use (TOU) scheme is an example of static pricing, where different fixed prices are used during different times of the day [18, 19, 21]. Example dynamic pricing schemes include real-time prices (RTP) and critical peak prices (CPP) which depend on electricity spot prices [116, 117].

Many studies and pilot projects have been conducted over the past 40 years to explore the impact of TOU pricing on consumer demand, with varying results. During the 1970s and 80s, a study was conducted to test the impact of TOU pricing on peak demand in households in two locations in Germany. The TOU tariffs had three prices on weekdays and two prices on weekends, with a ratio of 2.5:1.5:1 between peak, shoulder, and off-peak prices, respectively. The study involving 1500 households in Saarland and 450 households in Freiburg found a 10% and a 3% reduction in peak demand as a result of using TOU prices, respectively [118].

The Visible Energy Trial conducted between 2008 and 2010 across eastern England, which recruited 275 households to try three smart energy monitors with different levels of complexity for at least 12 months, concluded that manually responding to TOU declines with time [116]. When residential consumers receive real-time feedback via energy monitors, although they do respond to differential prices by making changes to their demand, there is a limit to making further changes. Explanations for this limitation include an unwillingness to change certain domestic activities and appliance usage, a difficulty in negotiating demand changes among household members, and a lack of policy and market support for change [116].

As for dynamic pricing, a review examining evidence from 15 experiments in the US and Canada concluded that using CPP reduces household electricity demand by 13-20%, which rises to 27-44% when enabling technologies (e.g. programmable thermostats) are used [119].

Incentive-based DR

Rewarding program participants with incentives for changing their demand is referred to as incentive-based DR, which includes direct load control and interruptible load programs [18, 19, 21, 38].

A study evaluating the impacts of DR programs offered by US grid operators showed that more than 90% of load reductions were induced by incentive-based programs, whereas price-based programs accounted for less than 10% [120]. This can be attributed to the dispatchable and proactive features of incentive-based events, where a participant (or their device) is requested by the program administrator to reduce demand (sometimes by specific amounts) at specific times, and is compensated accordingly. In price-based programs, a participant (or their device) reacts to varying electricity prices throughout the day and week, which in turn requires a more proactive role compared to incentive-based programs.

Although incentive-based programs are more common, they seem more static than price-based programs especially in terms of required capacity and offered compensation. Such programs are more suitable for consumers with large and predictable electricity demand, such as production factories. Conversely, the variable prices offered by price-based programs are more suitable for the dynamic electricity demand of residential consumers. However, to get the most benefits out of price-based DR, especially if distributed generation and storage is available in households, more dynamic management of household electricity demand is required.

The next section recaps how current demand response practices fall short of addressing the needs of prosumer collectives.

2.4.3 Inadequate Demand Response for Prosumer Collectives

At the moment, DR practices fall short of accommodating prosumers and prosumer collectives for several reasons. Current DR mechanisms are designed for consumers, and especially tend to focus on large-scale consumers because most programs require large demand reduction quotas which in most cases can be easily achievable by large consumers. For residential consumers, such programs are mostly done at scale, where participation is through an aggregator whose role is to guarantee aggregating the minimum quota of demand reduction requested by the program administrator. This highlights the importance of having an aggregator to assemble DR resources in households in general, in order to achieve the objectives of DR mechanisms and associated programs. Additionally, it underpins the need to expand aggregation practices beyond changing the energy demand of consumers, in order to serve the energy production aspects of prosumers.

Some residential DR mechanisms are done at scale and do not require aggregators; these are mainly focused on enhancing system reliability at the distribution level or enhancing electricity procurement at the retail level. Some programs implementing such mechanisms target devices used for space or water heating (e.g. thermostats, hot water cylinders), which are triggered to cycle during peak demand periods or use cheaper electricity during night hours. With the rise in electrification and appliance ownership, such programs need to support a broader range of appliances and energy equipment (e.g. EVs and EV chargers).

Demand response programs based on voluntary participation often require consumers to manually change their demand in response to DR events, which may create difficulties for consumers to strategically choose which loads to reduce or curtail, and for program administrators to forecast the level of consumer participation. Therefore, it is important to develop new DR practices which leverage smart grid capabilities to help both consumers and prosumers make more strategic decisions with minimal manual intervention and inconvenience to energy activities in households.

Investigating the correlation of each DR mechanism with renewable energy generation (available in Tables A.1–A.9 in Appendix A) indicates that current residential DR mechanisms mostly have low to medium correlation with renewables, with the exception of those for enhancing system reliability and load shaping which tend to have high to very high correlation with renewables. Reliability enhancement programs are currently implemented for residential consumers, but lack support for prosumers, whereas retail-level load shaping for households is still in its infancy, even for consumers, because of its limited ability to maintain load increases (e.g. when the retailer serves new consumers). Thus, to accommodate the rise of prosumers, mechanisms having high correlation with renewables need to leverage new strategies and technologies to serve prosumers, and be scaled based on the growth of prosumers and prosumer collectives. Mechanisms having low correlation with renewables should ideally be redesigned to accommodate prosumers; otherwise, new mechanisms should be developed.

Price-based DR remains limited although its dynamic pricing components, which match with the highly dynamic demand patterns in households, may play a potential role in creating various financial benefits for prosumers, especially around optimizing decision-making in consuming, storing, selling and trading electricity generation from distributed generation technologies.

Demand response programs now tend to focus on communicating with individual consumers, and lack features for communicating with a collective of households, and managing interactions among such households.

The aforementioned shortcomings of current DR approaches necessitate innovating new ways for managing variable demand and intermittent supply in collective settings integrating distributed generation and storage, and various household energy practices and preferences. Smart grids can play a significant role in enabling more dynamic demand response practices which are more encompassing of prosumers and prosumer collectives.

The next sections introduce the smart grid concept, present the key features of smart grids, and discuss how smart grids can enable more active management of complex power flows and prosumer interactions in prosumer collectives.

2.5 New Opportunities in the Smart Grid

More recently, power grids have been undergoing various changes to revitalize their operations, technologies and offerings. The power grid is becoming smarter and more decentralized, by integrating new information and communication technologies (e.g. advanced metering infrastructure) and internet-like concepts (e.g. networking, distributed controls) especially at the distribution level.

The core quality of a smart grid lies in its advanced metering infrastructure, which records real-time electricity use and provides bi-directional communication for sending information and control signals between end-users and the grid [21, 121]. Rolling out smart meters and integrating distributed energy resources are opening the doors for designing and implementing new DR practices for prosumers and prosumer collectives in many countries [18, 19, 27, 122, 123].

The next two sections respectively present the key features of a smart grid, and how it can enable advanced options for managing energy in prosumer collectives.

2.5.1 Smart Grid Features

Smart grids should ideally accommodate all generation and storage options, enable new markets, products and services, and actively engage customers while providing them with more choices [124]. Studies indicate that ubiquitous technologies (e.g. smartphones), coupled with personalization [125–127], and financial, social and environmentally-driven incentives can encourage end-users to be more engaged and flexible in managing their household electricity activities [128–131].

A smart grid connects elements of the electricity grid in an analogous way to how the internet connects information and processing resources. Smart grids are a transition away from centralized power grids to a more distributed infrastructure [28].

An integral part of the smart grid is the concept of the Internet of Things (IoT) [123, 132, 133], where interconnected physical and virtual "things" (e.g. sensors, actuators, wireless technologies, cloud computers, solar panels, EVs, batteries) use and exchange data to enable advanced services [134]. Therefore, the smart grid can be perceived as a cyber-physical system which is described as follows,

> *A cyber-physical system is an integration of computation with physical processes whose behaviour is defined by both cyber and physical parts of the system. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa [135, p. 1].*

Smart grid architectures typically include three layers: hardware, communication and software [136]. The hardware layer comprises traditional transmission and distribution components (e.g. lines and poles) and smart sensors (e.g. in distribution transformers) that collect data about grid operations and status (e.g. fault locations, power quality). The communication layer enables data gathering and transfer (e.g. by smart meters which monitor power consumption and production at regular intervals and communicate such data to retailers for billing purposes). The software layer allows collected data to be aggregated and analyzed. Those three layers need to be integrated to ensure the power grid system works seamlessly [136].

When developing a smart grid implementation plan, various solutions are generally considered, including advanced metering infrastructure, distributed energy resources, customer-side systems (e.g. smart appliances), demand response, distribution management and automation, transmission enhancement, and asset optimization [124].

According to the National Energy Technology Laboratory in the US, the following characteristics ideally differentiate smart grids from conventional power grids [124].

- A smart grid ideally accommodates all generation and storage options, including new opportunities for more efficient and cleaner energy generation,
- Enables new markets, products and services, by driving inefficiencies and waste out of the market, reducing transmission congestion, and offering more green products to end-users,
- Optimizes asset utilization and operation, by minimizing costs for desired functionalities and efficiently maintaining grid equipment and operations,
- Enables active participation of customers, by increasing their interactions with grid stakeholders and offering them more choices,
- Provides high power quality for the digital economy, to avoid losses in production and productivity,
- Detects and responds to system disturbances, by performing self-assessment and healing to restore grid components and operations, and
- Operates resiliently in the event of cyber or physical attacks.

While some of those characteristics have already been incorporated in various power grids around the world (e.g. installing smart meters, using home energy management systems, and integrating wireless sensors in transmission and distribution components), the deployment of certain characteristics is still limited and largely in the research and development phase (e.g. self-healing and attack-resilient grids, which are implemented at the level of the transmission network operator).

The deployment of smart grid solutions that achieve such characteristics is expected to create benefits in six key areas, namely reliability, efficiency, economics, environmental, safety and security [124].

Reliability benefits in the smart grid include improved levels of service, by having fewer outages and power quality issues. Efficiency benefits focus on reducing the costs paid to generate, transmit, distribute and consume electricity, while benefits in economics include downward pressure on electricity prices and customer bills, opportunities to sell electricity from distributed energy resources to neighbours and the grid, and job creation.

The increasing integration of renewable micro-generation and higher efficiency in consuming energy create environmental benefits in smart grids by reducing carbon emissions and supporting the shift to a green economy. Additionally, the smart grid creates security and safety benefits in terms of mitigating the effects of hazards (e.g. natural disasters, cyber attacks), and reducing associated losses and injuries [124].

The smart grid concept has been under discussion for many years [137]. Since 2001, a number of developed countries started establishing dedicated entities to drive the change to a smart power grid [138]. The transition from a conventional electricity grid to a smart one faces many challenges (e.g. technical integration, regulatory reforms, economic returns, and social acceptance) which may take between 20 to 40 years to address [139].

In spite of the challenges, smart grids bring various opportunities. The next section explores the new options for dynamically managing energy in prosumer collectives.

2.5.2 Demand Response in the Smart Grid

The advanced technologies and characteristics of smart grids can help expand demand response to include prosumers and prosumer collectives [140, 141]. With the rise in residential prosumerism, the definition of demand response presented in Section 2.3.3 becomes narrow as this definition lacks incorporating prosumers. Demand response for prosumers is not merely about changing electricity demand in response to monetary incentives to induce lower electricity use at times of high electricity prices or system instabilities. The definition of demand response in general should ideally go beyond currently available mechanisms targeting consumers, by describing a more holistic perspective on balancing highly variable demand with intermittent supply in light of battery storage and innovative products and offerings.

The smart grid can help create new practices for active demand response in prosumer collectives, including optimizing electricity use among appliances and storage devices in multiple households, trading electricity among prosumers in the collective or selling it to the grid, and storing electricity in batteries or EVs for later use [18, 20, 21, 27]. Such opportunities may involve managing dynamic and multi-directional flows of electricity, data, and money within households, among households in a collective, between collectives, or between a collective and grid stakeholders or market players involved in energy management or aggregation.

2.6 Summary

Literature findings presented in this chapter have indicated that current demand response practices are not suitable for accommodating residential prosumer collectives. Current demand response mechanisms and programs focus on individual consumers rather than prosumers or collectives of prosumers, and often require an external party (i.e. aggregator) to collect the required quota of demand response resources from consumers.

Demand response mechanisms that highly correlate with renewables are either set up to be used with consumers rather than prosumers, which is quite inefficient, or are scarcely implemented due to limitations around supplying load increases while lacking energy storage. In addition, demand response programs lack features enabling communication among households (whether consumers or prosumers), or between grid stakeholders and a collective of households.

With the changes occurring in the energy terrain, and the rise of residential prosumer collectives, limitations of current demand response practices call for the development of new and dynamic demand response approaches, to efficiently manage the complex power flows and interactions in and around prosumer collectives. As presented in this chapter, smart grids offer various possibilities (technologies, features, etc.) to capacitate new practices for innovative demand response aimed at serving prosumer collectives.

Identifying the current practices of demand response and what new opportunities are enabled by smart grids informs the overall research aim of this thesis, which is how smart grid opportunities can be leveraged to evolve demand response approaches for residential prosumer collectives.

The next chapter investigates how smart grid opportunities support the emergence of residential prosumer collectives, and can potentially help create dynamic demand response for those collectives.

Chapter 3

Emergence of Residential Prosumer Collectives

Research Question 2 – How do new opportunities offered by the smart grid support the emergence of residential prosumer collectives?

3.1 Introduction

Evidence indicates that a range of prosumer collectives are either in proven operation or pilot phase [8, 9, 13, 45, 46]. Nevertheless, prosumer collectives bring challenges, notably around efficiently managing power flows between units of electricity production, consumption and storage, and optimizing stakeholder interactions relating to selling and trading electricity.

As presented in Chapter 2, smart grids enable a range of new technologies and features, which can help improve demand response practices (e.g. create flexible demand to match with intermittent micro-generation) in prosumer collectives [18, 20, 21, 27, 140, 141]. This chapter discusses how those smart grid opportunities are generally supporting the rise of prosumer collectives, and potentially creating dynamic demand response for those collectives, which informs the overarching research aim of this thesis.

In Section 3.2, I discuss the transition of an energy consumer to a prosumer, explain distributed energy resources in detail, and introduce the types of prosumers. This is followed by a brief discussion on the drivers, barriers and enablers of individual prosumers. Reviewing the underlying technologies and concepts of individual prosumers helps inform later investigations on prosumer collectives, and especially supports the drivers and benefits of the prosumerism component of prosumer collectives.

Section 3.3 introduces the concept of a prosumer collective and explains its purpose, and provides an overview of the drivers, barriers and enablers of prosumer collectives. The initiating entities, physical configurations and organizational structures of prosumer collectives are then investigated, and four residential prosumer collectives from around the world are reviewed and analyzed to inform the work herein.

By reviewing the emergence of prosumer collectives and example collectives, the role played by the smart grid in their emergence is generally highlighted, and specific issues to consider are underpinned.

In Section 3.5, I briefly introduce the emergence of middle actors, which play a catalyzing role between top actors and prosumer collectives, and outline their potential role in leveraging smart grid capabilities to develop dynamic demand response solutions for prosumer collectives.

Novelty in this chapter includes: (1) proposing a definition for a prosumer collective; and (2) proposing a new definition for an energy prosumer; where both definitions focus on value rather than specific physical configurations or goals.

3.2 The Energy Prosumer

The "prosumer" concept dates back to the 1980s, when it was first defined by Toffler; a prosumer is someone creating services, goods or experiences for their own satisfaction and use [142]. This concept has evolved over time, and in 2008, Tapscott and Williams argued that prosumers are creating value for everyone, not merely for themselves [143].

Applying the prosumer concept to energy is relatively new. Residential energy consumers are becoming prosumers, who are changing the way they use and value energy. A number of definitions exist for an energy prosumer, both generic and specific.

Several authors generically define an energy prosumer as a consumer who produces electricity and sells its excess to the power grid [1–4]. Another definition describes an energy prosumer as "a consumer who also produces energy to provide for their needs, and who in the instance of their production exceeding their requirements, will sell, store or trade the surplus energy" [5].

A more specific definition describes an energy prosumer as "an economically motivated entity that (1) consumes, produces and stores electricity, (2) operates or owns a small or large power grid, and hence transports electricity, and (3) optimizes the economic decisions regarding its energy utilization" [6, p. 2].

Most definitions in the literature describe an energy prosumer as a consumer who primarily produces energy to meet their own needs, and merely sells surplus energy. In line with the evolved definition of a prosumer around creating value for everyone, as described by Tapscott and Williams [143], I argue that individual prosumerism can be more encompassing than the definitions available in the literature.

An energy prosumer may choose to sell or trade all the energy they produce, or to partially consume (i.e. by using or storing) this energy and sell or trade the remainder. The decision of whether to consume, sell, trade, or store energy with the objective of maximizing value for involved stakeholders can often be based on objectives set by prosumers and/or relevant stakeholders, and bound by constraints dictated by the surroundings. Such decision-making can be enabled by the advanced products and services made possible by the smart grid.

In this thesis, I propose the following definition for an energy prosumer, as it accommodates a broader sense of value creation beyond individualistic behaviour,

> *An energy prosumer produces energy and can totally or partially consume, sell, store or trade this energy.*

Prosumers are consumers producing their own energy. Having prosumers meet their own energy needs from distributed generation creates an increased sense of autonomy for those prosumers, as they do not need to solely rely on the grid for power supply. A prosumer can alternatively choose to sell their (surplus) energy to the power grid or trade it with other households in return for incentives (e.g. money, discounts, benefits), which in turn can help create value for the prosumer and involved stakeholders. A prosumer can also use storage technologies, e.g. lithium-ion batteries, to store their energy for later use during periods of high electricity tariffs or supply shortage.

Prosumers can exist individually or collectively. Figure 3.1 illustrates a grid-connected residential prosumer with solar PV and an EV (symbolized by an EV charging station), at the bottom left, and a prosumer collective, comprising a group of households, a wind turbine and battery storage, at the bottom right. Section 3.3 investigates prosumer collectives in more details.

To better understand the emergence of prosumers, it is important to first learn about distributed energy resources, which comprise the main differentiator between consumers and prosumers. The next section explains distributed generation and storage in more detail.

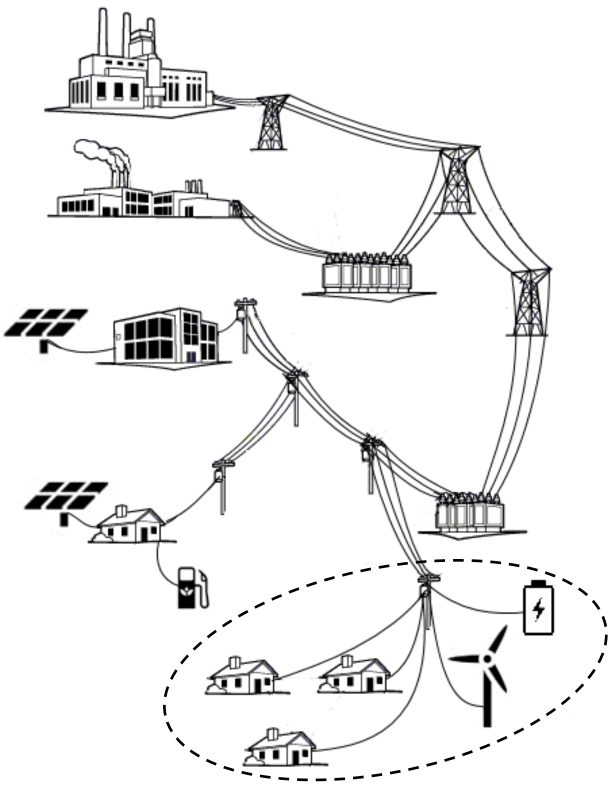

Figure 3.1: Generation, transmission and distribution in a power grid hosting prosumers and consumers

3.2.1 Distributed Energy Resources

The term "distributed energy resources" (DER) has no uniform definition, although it is commonly used in the energy industry [144]. The Electric Power Research Institute (EPRI) defines distributed energy resources (DER) as "smaller power sources that can be aggregated to provide power necessary to meet regular demand" [145].

Broader definitions are proposed by the North American Electric Reliability Corporation (NERC) [146] and the Federal Energy Regulatory Commission (FERC) [144], where distributed energy resources are defined to include distributed generation, battery storage, electric vehicles, demand response, energy efficiency, and co-generation of electricity and power.

On the one hand, the definition by EPRI describes DER as power sources but does not explicitly mention whether such sources come from generation or storage, and whether they are on- or off-grid. On the other hand, the definitions by NERC and FERC are too broad for the purpose of this research. Thus, I propose the following working definition to describe distributed energy resources, *Distributed energy resources are small-scale modular systems which produce or store electrical or thermal energy, and which are geographically close to end-users in an on-grid connection, or an off-grid stand-alone setting.*

As such, distributed energy resources comprise distributed generation and storage. Distributed generation commonly provides less than 10 MW of power, is sized based on the purpose of generation, and may either be connected to the grid or remote in an off-grid location [147–149]. Distributed storage, such as lithium-ion batteries, commonly complements distributed generation especially intermittent renewable generation which is highly weather-dependent (e.g. solar PV, micro-wind turbines). The following two sections explain distributed generation and storage, respectively, in more details.

Distributed Generation

Distributed generation is defined as "a generating plant serving a customer on-site or providing support to a distribution network connected to the grid at distribution-level voltages" [150, p. 19]. Distributed generation has been largely associated with renewable generation, due to the small size, modularity and sustainability of distributed renewables [151]. Examples of distributed generation include rooftop solar PV, community solar PV, micro-wind turbines, micro-combined heat and power (micro-CHP), and backup generators [27, 35, 147–149, 151–156].

The interest in distributed generation, notably distributed renewables, has grown in recent years, mainly due to a mixture of technological advancement, price drops, and regulatory support for renewables [157–161]. Solar photovoltaics have become dominant in harnessing solar energy to produce electricity, with the highest growth rate in renewable energy technologies [162]. Over the past decade, the global uptake of solar PV has annually grown by more than 40% [163], and over the last 40 years, PV module prices have dropped by 22.8% for each doubling in cumulative production capacity [164].

Distributed generation from solar PV can be categorized into rooftop solar and community solar [156]. While rooftop solar comprises PV panels installed on the roofs of buildings, community solar comprises PV systems installed in a focal site [165]. Advocates of community solar are motivated by the better options a community installation provides to houses with limited rooftop areas or shaded roofs, as only 22-27% of residential rooftops can be used to install solar PV [165]. In 2017, in the large metropolitan areas of the US, the price of electric energy generated from community solar, at $113/MWh, was almost half that generated from rooftop solar, at $253/MWh [156].

The global trend indicates that doubling the total installed PV capacity can result in a 23% reduction in price [166]. By 2040, Bloomberg New Energy Finance expects rooftop PV to account for 24% of electricity generation in Australia, 20% in Brazil, 15% in Germany, 12% in Japan, and 5% in the US and India [167]. Although cost discrepancies exist due to differences in locations, market conditions, resource availability, and regulations, there is generally a clear trend of cost declines especially in solar PV [157, 161].

Distributed Storage

Solar energy and wind energy are intermittent, and their electricity production may not necessarily overlap with household energy demands. Distributed storage makes it possible for residential prosumers to store energy for later use (e.g. during power outages or periods with high electricity prices) [168–172]. With advances in technologies, materials science, and economies of scale, small-scale batteries are becoming cheaper and more efficient [173].

Electric energy storage involves converting electrical energy to a form of storable energy (e.g. mechanical, potential, thermal, electrochemical), then converting it back to electrical energy when needed [168, 169, 172]. Battery technologies like lead-acid, nickel-metal hybrid, nickel-cadmium and lithium-ion are examples of distributed storage [174]. Electric vehicles can also be considered distributed storage, as they use batteries [39, 175–177].

The next two sections provide an overview of prosumers' technology adoption, and highlight the drivers, barriers and enablers of individual prosumerism, respectively.

3.2.2 Prosumers and Technology Adoption

The bell-shaped technology adoption curve, referred to as Roger's diffusion of innovation curve, is a good approach to describe the adoption process of new disruptive technologies [178]. As shown in Figure 3.2, adopted from [178], when a new technology enters the market, the first 2.5% to adopt the technology are the innovators, while the next 13.5% are the early adopters. Those referred to as majorities, both early and late, are the next 34% of adopters each, whereas the last 16% trailing behind others in adopting a new innovative technology are the laggards [178].

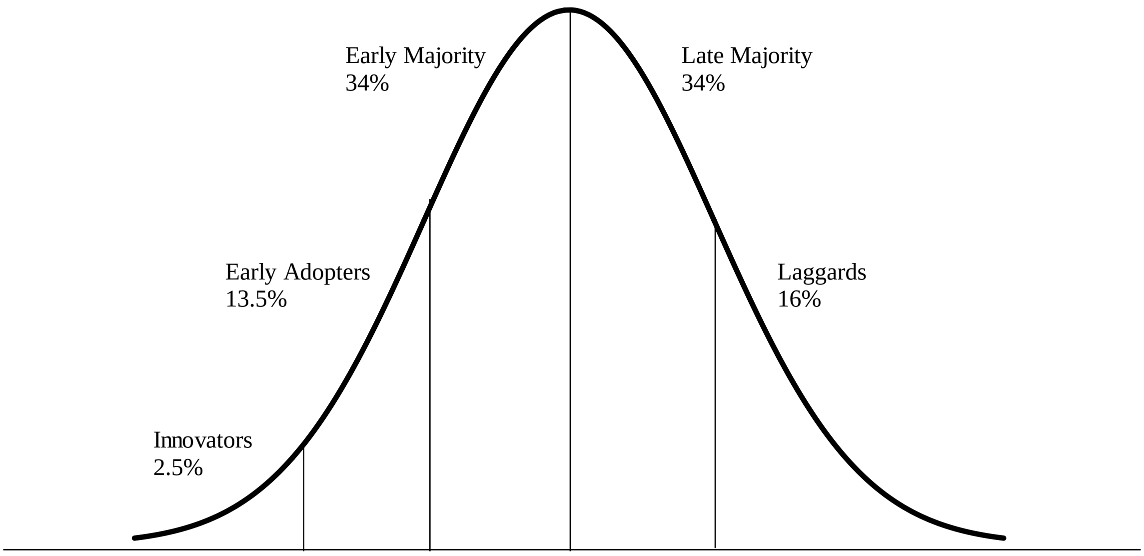

Figure 3.2: The diffusion of innovation curve

Early prosumers are typically well-informed innovators and early technology adopters with a passion for trying new technologies and taking risks in trialling new products [178–180], such as installing rooftop PV, driving electric vehicles, or using home energy management systems. Early prosumers are commonly aware of energy efficient practices, are advocates of sustainability, and do not wait for incentives to take up new technologies [10, 181]. Peer pressure from such prosumers can help boost the adoption of new technologies by their less energy-savvy circles of family, friends, acquaintances and neighbours [45].

Early and late majority prosumers are more careful, tend to avoid risks, and commonly become prosumers based on recommendations from early prosumers or due to external influence (e.g. incentives) [16, 157]. Laggards tend to resist change and may not adopt new technologies until traditional counterparts cease to exist [178].

To understand more about prosumers, it is essential to identify the motivations driving individuals to take action, the barriers that hinder this action, and the factors enabling prosumers to overcome such barriers. The next section introduces the drivers, barriers and enablers of individual prosumerism.

3.2.3 Drivers, Barriers and Enablers of Individual Prosumerism

Various drivers motivate individuals to become prosumers. A key driver is the aspiration to live a green lifestyle and have a lower carbon footprint, by generating energy from low-carbon and renewable energy sources (e.g. solar, wind, biogas) [182–185].

Another driver of prosumerism is autonomy, where a prosumer can use distributed generation to meet his energy needs [88, 185]. In this way, a prosumer can become partially or totally independent of the power grid, and can thus avoid issues like increments in electricity tariffs. There is a financial driver behind prosumerism, because self-generation is becoming more affordable as distributed generation costs drop and energy costs from retailers rise [5].

Despite the drivers of prosumerism, a number of barriers exist. The lack of supply flexibility, from intermittent generation from solar and wind energy, presents a barrier to prosumerism [151]. The non-dispatchability of intermittent generation raises concerns over its availability and reliability in meeting prosumers' demand for electricity.

The lack of finding appropriate information about prosumerism is also a barrier to adoption, e.g. trying to find neutral information on solar micro-generation from an entity that is not selling solar modules [186–188]. Finding information about companies willing to purchase electricity from prosumers, and at what price, is also an obstacle to households wanting to become prosumers [188].

Despite the barriers facing prosumerism, various enablers are becoming available to help households overcome those barriers. Smart grids are enabling new products and services for actively managing energy in prosumer households especially in light of intermittent supply from distributed renewables [62, 189, 190]. Financial incentives (e.g. feed-in tariffs) [191–193] and innovative business models (see Section 5.5.2) are also emerging to support the growth of prosumers.

In general, the emergence of prosumers creates new prospects around using and benefiting from energy which significantly differ from those of consumers. Those prospects are further extended when looking at collectives of prosumers, whose attributes, objectives, and benefits differ from individual prosumers. The next section investigates the emergence of residential prosumer collectives.

3.3 Prosumer Collectives

Thousands of prosumer collectives exist around the world [7–9], from community-owned wind farms in Scotland and Denmark, to rooftop solar panels in residential complexes in Germany and Australia. Prosumer collectives use a range of technologies, operate in different policy and regulatory contexts, involve several stakeholders and have a diversity of physical configurations and initiating entities. Such heterogeneity, in turn, may help prosumer collectives be resilient and adaptable to local conditions [8, 9, 194].

3.3.1 What is a Prosumer Collective?

Several terms are used to refer to a collection of loads (mainly households), distributed energy resources, and smart grid technologies. Boundaries are often indistinct and varying for different contexts as to what an energy project in a residential community is, and what community energy means [7]. The term "community renewable energy", for example, is described in some literature as vague and elastic [194–196].

Table 3.1 lists some of the terms used to describe a group of houses integrating distributed energy and smart grid technologies. Example terms include prosumer community group, community energy system, integrated community energy system, community micro-grid and virtual power plant.

Although those definitions have differences, they predominatly overlap. I prefer to use the term prosumer collective as I see it more inclusive of heterogeneity. To the knowledge of the author, no definition currently exists for the term "prosumer collective". Therefore, I propose the following definition, which revolves around value creation, to describe a prosumer collective,

> *A prosumer collective comprises a group of consumers producing and/or storing electricity through multi- or focal-site distributed energy resources, and leveraging information and communication technologies to create value for the collective and its external stakeholders.*

A prosumer collective is often a geographic entity with a sense of identity and shared aspirations at the neighbourhood, district or city level [10–13]. A prosumer collective can be initiated by local community efforts or by a third-party; it can be multi-site, where its distributed energy resources are installed on multiple sites, or focal-site with shared resources [5].

It is important to note that under this working definition, "prosumer" is used to refer to each member belonging to a prosumer collective, irrespective of whether the member individually installs DER or not. For example, in a focal-site collective where members share ownership and operation of a wind turbine, members are referred to as prosumers although their households are not individually producing electricity.

Table 3.1: Definitions of terms used to describe entities comprising loads, distributed energy resources, and smart grid technologies

Entity	Description
Prosumer Community Group	A network of prosumers that share energy behaviour, pursue a mutual goal (e.g. achieve energy self-sufficiency), and cooperatively compete in the energy market[180, 197].
Community Energy System	A local and small-scale electricity and/or heat production system that provides members of a local community with direct benefits including economic returns from selling energy to the grid, carbon mitigation from using clean renewable sources, and greater community cohesion [10, 198].
Integrated Community Energy System	A system comprising local generation (e.g. from combined heat and power or renewable energy resources), energy storage, and demand-side management, to help increase energy self-consumption, and match supply and demand, while cutting costs and reducing environmental impact [199, 200].
Community Micro-grid	A group of distributed energy resources and demand response technologies that are locally controlled, seen as a single demand or supply entity from a technical or a market perspective, and used to improve distribution system efficiency. In case of grid emergencies (e.g. generation shortage, scheduled maintenance), the micro-grid may disconnect from the grid and go into island-mode to maintain its reliability [10, 201].
Virtual Power Plant	A group of distributed generating units, flexible loads, and possibly storage systems, aggregated to form flexible capacity – similar to that of a power plant – which can be used to provide grid support, and access to energy markets [10, 202].

In the context of this working definition, the "value" created by the collective may take various forms, often creating win-win scenarios for the collective's prosumers and external stakeholders. A prosumer collective may create value for its members by (1) generating income from selling its locally generated electricity on the wholesale electricity market, and (2) producing clean and cheap electricity for its households. The corresponding value to external stakeholders (e.g. grid operator, electricity market) in this case may include (1) reducing generation capacity needs from conventional centrally-located power plants and thus lowering generation, transmission and distribution costs; and (2) buying clean electricity from collectives at potentially cheaper prices than electricity produced in conventional generation plants. By reviewing the terms and definitions of the entities listed in Table 3.1, which can be considered prosumer collectives, a number of similar values can be identified. The following example prosumer collectives provide more clarification.

The Findhorn Ecovillage in Scotland is a prosumer collective comprising 500 permanent residents and four wind turbines with a total capacity of 750 kW. On windy days, electricity production from the turbines covers the collective's electricity demand, thus achieving self-sufficiency for the collective, and surplus electricity is sold to the grid, thus reducing generation capacity needs and costs for the grid operator. When local production is not enough, the collective partially meets its electricity demand from its wind turbines, and buys electricity from the grid to meet the remaining demand, thus creating revenue for the respective retailer [203].

Brooklyn Micro-grid, located in New York, is a prosumer collective enabling prosumers to trade their electricity production with consumers in their community through a mobile application, thus creating income for prosumers and allowing consumers to have the option to buy clean and locally generated electricity from neighbouring prosumers [204]. Other example prosumer collectives are presented in detail in Section 3.3.6.

This thesis focuses on grid-connected prosumers and collectives, and how smart grid technologies and middle actors are supporting the emergence of those collectives and their associated dynamic demand response activities. Off-grid prosumers have different problems, which are not addressed in the scope of this thesis. Nevertheless, there may be potential overlaps between grid-connected and off-grid prosumer collectives, especially in issues relating to energy self-sufficiency and initiating entities.

3.3.2 Purpose of Prosumer Collectives

For prosumers, the main objectives of collectives include [7, 13, 205–207]: (1) meeting prosumers' total electricity demand (i.e. be a self-sufficient collective) or a part of their demand, to be less vulnerable to electricity price increases; (2) exporting electricity, to increase and diversify the collective's income; (3) using sustainable energy, to reduce their carbon footprint; (4) promoting community development and cohesion; (5) creating local jobs; (6) and helping achieve wider societal change towards sustainability.

Because prosumer collectives operate in various contexts, and can be physically configured in a number of ways, they can achieve their objectives in multiple manners. In one collective, prosumers can trade electricity amongst themselves to generate income based on their individual goals. Alternatively, a collective can sell energy regionally at the main-grid level, and optimize its profits based on the collective's goals [207]. In countries like the US and Germany, prosumer collectives contribute to regional economies, and to fossil fuel-free development [208, 209].

For grid stakeholders (grid operator, distribution system operator, electricity retailer, etc.) and third-parties (renewable energy project developers, research institutes, etc.), the primary objectives of prosumer collectives include: (1) reducing transmission and distribution losses and associated costs [19, 64, 72, 73]; (2) reducing uncertainty in the collective's power flows and improving demand forecast [210, 211]; (3) creating local grids with lower capacity demand than grids without collectives [212]; (4) developing the renewable energy industry [7]; and (5) testing scale and local siting of distributed energy and storage technologies [7].

More objectives for collectives and stakeholders involved in collectives can be found in Section 5.5.1. The next section presents the main drivers, barriers and enablers of prosumer collectives.

3.3.3 Drivers, Barriers and Enablers of Collective Prosumerism

Prosumerism has a number of drivers, barriers and enablers of action that exist whether at an individual level or a collective level. The aggregation of prosumers adds a new set of features that can sometimes stimulate and support collective action, but other times can obstruct efforts. This section reviews the factors motivating, hindering, and facilitating collective prosumerism.

Drivers

Prosumer collectives, especially community-initiated ones, are driven by a desire to be autonomous and sometimes self-empowered by securing local electricity supply independent of the grid [10, 16]. In the first independent survey on community energy projects across the UK, which investigated the objectives and development of community energy groups and their activities, Seyfang et al.[8] found that 60% of the respondents indicated that improving local energy independence was one of their motivations for partaking action. According to several community energy groups in Scotland, which have been interviewed as part of case studies conducted by Bomberg et al.[16] to explain why and how community energy groups mobilize, community wind farm development is seen as a visible and powerful sign of "community taking power".

Creating resiliency and relevant actors in a future that is potentially full of renewable energy is another motivator for prosumer collectives. In a study by Hicks and Ison [7], which involved analyzing interviews and documents for 25 prosumer collectives in the UK, US, Canada, Denmark, Austria, Germany, and Australia, future proofing and creating relevant actors in a renewable energy-powered world was identified as a motivator for prosumer collectives, as well as a benefit in some cases.

Another driver for collective action, for prosumers and consumers alike, is demand variability, which basically stems from the diversity of end-users' household appliances and energy activities (e.g. space and water heating, lighting, cooking) [70, 213]. In general, managing energy demand at the aggregate level attenuates the impacts of demand variability, by reducing uncertainty in power flows and making demand forecasts easier [210, 211].

Additionally, the declining costs of certain clean energy technologies, notably solar PV and wind turbines, are driving the uptake of distributed generation [35, 157, 158, 161, 214–216]. This may be especially beneficial for grassroots communities to develop prosumer collectives, where community members (i.e. prosumers) share investment and ownership of the collective's distributed energy resources.

Another strong driver of prosumerism in collectives is the desire to create financial gains from locally producing electricity. In contrast with individual prosumers, a prosumer collective has enhanced potential and stronger market power to create financial benefits by aggregating resources for market participation (provide collective demand response, sell the collective's energy to the grid, etc.) [46].

Sustaining community identity is another motivator for collective prosumer action [10, 16]. The "identity" notion is a profound and rich concept encompassing various context-based interpretations and definitions [217]. Community identity can arise from shared geographic location, history, facilities, or sense of belonging [45], and can be reflected by the coherence and stability presented to external entities [218, 219].

In community-initiated prosumer collectives, identity can also arise from a shared history of grassroots efforts to develop the community. The village of Fintry, Scotland, which encompasses the Smart Fintry prosumer collective, is a good example of a grassroots community with a strong identity. Prior to launching the collective, the Fintry Development Trust was awarded a number of grants which were, and still are, used to develop Fintry into a low-carbon community with sustainable energy and transport resources [220]. The Trust believes the 10 years of engagement experience, gained through building community trust, relationships, and sustainability projects in Fintry, have played a significant role in strengthening the community's sense of identity and pride, which served as an asset in developing the Smart Fintry prosumer collective [220, 221]. A strong community identity can thus help a prosumer collective build its public image as a sustainable and green entity, and trigger the support of external stakeholders [16].

The social cohesion created by prosumer collectives is another motivator of collective prosumerism. The local proximity of electricity generation in prosumer collectives plays a role in driving community involvement, as the spatially distant generation in centralized power grids create a psychological barrier where end-users do not necessarily see or directly interact with electricity production [222].

Barriers

Although many drivers motivate the development of prosumer collectives, a number of barriers hinder the collective action of prosumers. As with individual prosumers, the intermittency of solar and wind energy presents a barrier to the uptake of their distributed technologies harnessing this energy. Such intermittency creates a disruptive and frequent temporal mismatching between supply and demand [88], and thus reduces the reliability and flexibility of supply [151].

Another barrier to the growth of prosumer collectives is the limited (or lack of) representation of community energy advocates and representatives in policy-making networks. In the UK, for example, it is difficult for advocates and representatives of community energy to influence policy-making networks relating to energy investment, transmission, and access, as such networks are dominated and greatly influenced by a few large energy companies with close ties to decision makers [16].

Prosumer collectives that own and self-manage their distributed energy resources can sometimes be difficult to maintain if the prosumers' levels of commitment to drive the collective forward do not align, or if prosumers lack certain skills (negotiation, planning, etc.). This is underpinned by a survey conducted by Seyfang et al.[8] on energy communities in the UK, where 48% of survey respondents thought that group qualities, such as group characteristics and prosumer skills, are critical strengths for the success of communities.

Maintaining continuity, attracting new prosumers, retaining existing ones, and having effective leadership all present challenges to collective prosumerism [13]. Additionally, a lack of a proper legal structure for prosumer collectives may be a barrier in some cases, especially those seeking funding, where accountability is required [205].

In some countries, prosumer collectives may face market barriers – due to scale or regulatory contexts – to sell electricity to the grid, including high costs of trading, lack of incentives for grid operators to regulate integrating micro-generation, and complexity of obtaining green energy certification [223]. In prosumer collectives already selling electricity, a barrier may arise if the operational and maintenance costs of the collective's distributed resources present a burden [46].

Another barrier that may affect the social acceptance for prosumer collectives is the lack of fairness and equity [31, 32], e.g. in distributing the collective's shared income among prosumers. This highlights the need to address social notions, such as fairness, in prosumer collectives.

Despite the aforementioned barriers, various enablers drive the development of prosumer collectives, as presented in the next section.

Enablers

It is challenging to manage the various interactions within a prosumer collective and between collectives and external stakeholders (power grid, electricity market, etc.). Nevertheless, the smart grid is playing a core role in supporting those interactions by smart controls and enhanced engagement tools, and enabling new products and market models [224].

The smart grid offers prosumers a variety of robust and secure platforms for accessing and visualizing energy data (energy consumption and production, electricity buy and sell prices, etc.) [26, 28]. The Smart Fintry prosumer collective provides its prosumers, and the public, with an energy dashboard detailing the collective's wind and solar energy production, and the amount of electricity imported and exported by the collective [225].

In prosumer collectives where distributed energy resources are locally owned by prosumers (not third-parties), local ownership can act as an enabler to collective prosumerism [13, 226, 227]. Locally-owned energy projects have shown a greater impact in terms of economic value and job creation when compared with absentee-owned projects (i.e. owned by third party) [226, 228].

3.3.4 Initiating Entity versus Physical Configuration

A prosumer collective is commonly initiated either by a local community or a third-party (private company, government body, etc.), and can be developed either on multiple sites or a single focal site [5]. Figure 3.3, adopted from [5], illustrates four models of prosumer collectives, based on initiating entity and configuration.

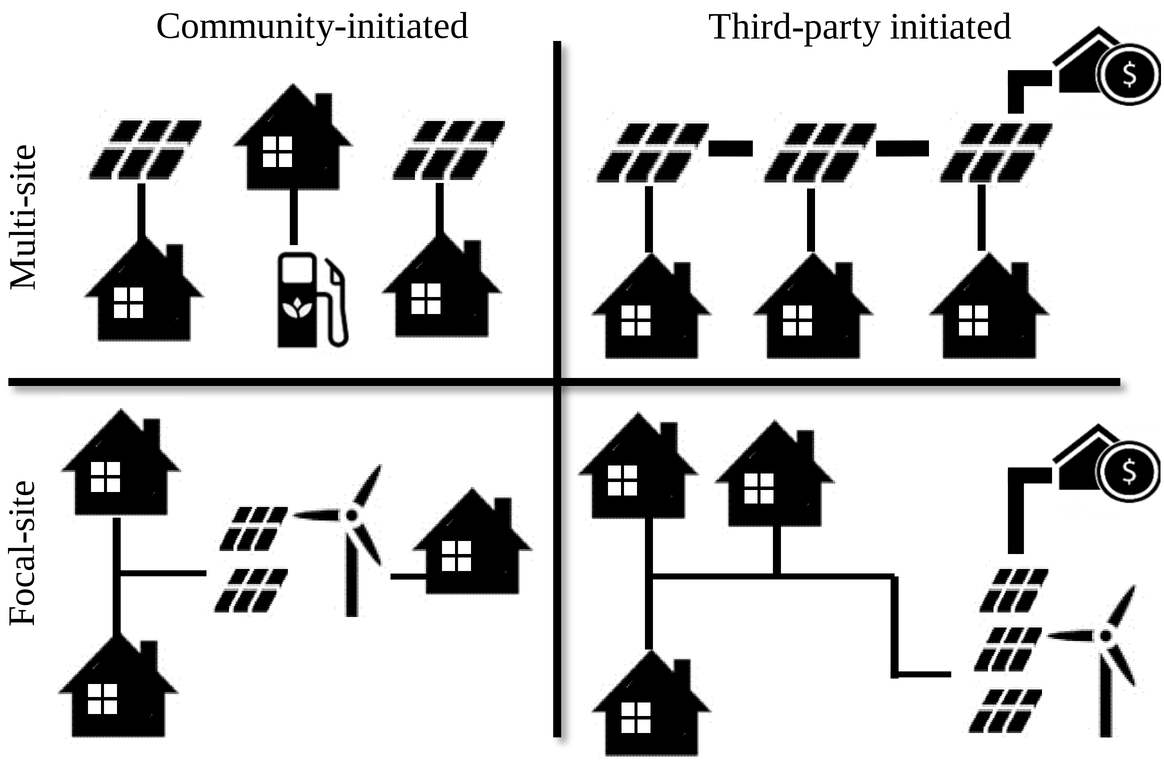

Figure 3.3: Models of prosumer collectives based on initiating entity and configuration

A *community-initiated multi-site* collective often comprises individual prosumers eventually coming together as a community as they realize the benefits of collective efforts. If the collective shares distributed energy resources in a focal site among its prosumers, this is referred to as a *community-initiated focal-site* collective. *Third-party initiated multi-site* collectives and *third-party initiated focal-site* collectives are initiated by third-parties, and are located on multiple sites or a single site, respectively [5].

3.3.5 Organizational Structures of Prosumer Collectives

Residential prosumer collectives can be commonly set up under one of three organizational structures: informal working groups; cooperatives; or commercial entities [13, 205, 206, 229, 230]. Such structures vary in scope and activities, depending on the collective's size and prosumers' characteristics (e.g. skills, priorities, aspired degree of autonomy) [10, 16]. Depending on the scale, legalities and regulatory context governing a prosumer collective, its members may or may not be its shareholders. However, this is not covered in the scope of this thesis.

The common organizational structures of prosumer collectives are identified in the following subsections.

Informal Working Group

An informal working group works closely with the prosumer collective, and is often set up to promote the collective, or may be attached to a political party or another group in the local community. Informal working groups are dynamic, and in case of committed members and strong leadership with multiple activities, they may go through formalization six months to two years after their formation [13, 230].

Cooperative Group

A cooperative is an organization whose members collectively own an energy company which often aligns itself to a large energy company with similar sustainable energy objectives [13, 205, 206]. Prosumer collectives aiming to meet their electricity demand and export surplus electricity for financial benefits commonly form cooperatives. More recently, regional energy cooperatives have been formed in a number of countries to enable local cooperatives to aggregate their efforts at a regional level, and have their voices heard more broadly while keeping their autonomy and profits locally bound in their communities [13].

Commercial Organization

A prosumer collective may choose to operate as a commercial organization. The main objective of this commercial venture is generating income and sustaining business relationships with energy customers [13, 205]. While an energy cooperative is more oriented towards meeting the objectives of the local community, a commercial organization is more customer-oriented and income-driven. Such commercial organizations, however, may suffer from a lack of trust from community members if community objectives are marginalized against commercial interests [45].

The next section investigates example prosumer collectives from around the world, to highlight their current status, the challenges they are facing, and how smart grid opportunities are supporting their development.

3.3.6 Example Prosumer Collectives

Thousands of residential prosumer collectives exist around the world today [7–9, 13, 45, 46], integrating a wide mix of distributed generation and storage, and smart grid capabilities. Some of those collectives use solar PV and battery storage, while others share wind turbines and biomass resources. Some are merely equipped with smart meters, while others use advanced energy management platforms and control technologies. In this section, four example prosumer collectives from the Netherlands, Scotland, Canada, and Australia are presented.

PowerMatching City

PowerMatching City is a residential community in Groningen, Netherlands. It is a third-party initiated European pilot project with multi-site DER. The project, which started in 2007, investigates smart ways to manage electricity and heat supply and demand in a residential community. Unlike average Dutch families, the residents of PowerMatching City are sustainability advocates and early adopters of clean technologies with a motivation to collectively contribute to a sustainable and smart energy transition in residential communities [212].

The collective comprises 42 households equipped with smart meters, smart home appliances, heat pumps, rooftop solar PV, micro combined heat and power (micro-CHP) systems, and batteries. The collective has a smart transformer station, which detects demand peaks for potential reductions, thus enabling lower capacity [212].

The houses are also virtually connected to electric vehicles (via software tools for simulation purposes), to add the scenario of charging electric vehicles to the collective in case homeowners do not have any. Additionally, electric scooters used by prosumers are equipped with smart chips to allow them to be charged intelligently using locally generated clean energy at the most optimum times [212, 231].

Each house is equipped with an energy monitor, installed on a tablet, displaying real-time power flows and historical household energy use, and the collective's energy consumption and production. The energy monitor can be used to adjust the thermostat, and recommend the best times to use certain appliances (e.g. dishwasher, dryer, and vacuum cleaner) [212].

The core control system of the collective is *PowerMatcher* – a smart energy management software system that optimally balances energy supply and demand in the collective, by leveraging electricity tariffs, prosumer priorities, micro-generation, and transformer status. The software achieves this in two ways: by automatically shifting the operation of certain smart appliances (e.g. smart washing machine) to cheaper off-peak periods or periods with abundant micro-generation; and by buying/selling energy from/to the grid at optimal prices for prosumers [231].

Some houses are equipped with *PowerRouter*, which is similar to PowerMatcher. PowerRouter intelligently decides whether to use micro-generation from solar PV and micro CHP straight away, feed it into the grid, or store it in batteries for later use, especially to charge electric vehicles, so as to maximize self-consumption and financial benefits [212, 231].

This project has been implemented in two phases. The first phase investigated the technical viability and real-life conditions of flexibly using and exchanging power flows and heat across the collective, whereas the second phase studied the market mechanisms under a smart grid infrastructure offering flexibility [231].

The principal outcome of the project is that smart energy systems are technically feasible, and can provide energy demand flexibility to create strong economic values. Flexible demand in the community benefited all stakeholders: energy providers, the grid operator, and prosumers. The grid operator avoided investment and maintenance costs for the grid infrastructure, while energy providers purchased energy at more competitive market prices as they were able to efficiently balance energy demand with micro-generation, and reduce peak loads. Prosumers achieved cost savings in return for their flexible energy practices and collaborated to maintain a sustainable community with a reduced carbon footprint [212, 231].

The foremost recommendation that came out of this project is the vital need for demonstrating fair distribution of flexibility among prosumer collective stakeholders [212]. In turn, this informs the work conducted herein, and highlights the need to further investigate issues around fairness and flexibility in prosumer collectives.

Smart Fintry Community

The Smart Fintry pilot project, launched in 2016 in Fintry, Scotland, demonstrates electricity trading, where consumers can buy electricity from neighbouring prosumers via a peer-to-peer trading platform. This community-initiated prosumer collective with multi-site DER comprises 100 households, 3 wind turbines with a total capacity of 80 kW, solar PV panels totalling 50 kW, and a biogas plant of 1.1 MWe, and aims to create a replicable local energy economy to be adopted across communities in the UK [225, 232]. Prosumers in this collective are mostly innovators and early adopters, as the community builds upon a history of engagement and involvement in local sustainability projects by the Fintry Development Trust [220].

The village of Fintry suffers from high energy costs due to its remote location, and from old infrastructure and inefficient energy consumption. The Smart Fintry Community is tackling such challenges by installing smart meters, wireless communications and distributed energy resources, and aiming to balance local energy supply and demand. The objectives of the community include: (1) reducing energy costs and carbon emissions; (2) alleviating fuel poverty; (3) overcoming contractual barriers preventing direct linkages between prosumers and consumers; (4) enhancing economic resilience and local value; and (5) developing a policy framework for demand-side energy management in prosumer collectives [225, 232, 233].

To achieve its objectives, the community is developing a number of deliverables and investigating various issues under the assumption that a local energy market will seek to optimally balance local energy supply and demand. In 2016, Smart Fintry launched Fintry Local – a bespoke tariff providing cheaper unit rates to community residents for each kWh used from the collective's 100% renewable electricity, which can help an average household annually save up to £100. Residents also get to access an energy dashboard to see how much energy they are using, when, and by which household appliances and systems [225].

The collective is collaborating with the distribution system operator to develop a measurement and control system to provide real-time data relating to network operation. Furthermore, the community is focusing on investigating four aspects around how to reduce peak demand, forecast local supply and demand, characterize demand flexibility, and become a community energy supplier and trade electricity to the grid [225, 233].

Drake Landing Solar Community

The Drake Landing Solar Community is a purpose-built residential neighbourhood of 52 homes in Alberta, Canada, which was completed in August 2007 [234] in one of the sunniest places in Canada [235]. It is a third-party initiated prosumer collective with focal-site DER. This collective's prosumers can be considered early majority, as houses were sold at competitive prices comparable to conventional houses, which may have attracted homebuyers that may not be sustainability enthusiasts.

The collective uses solar thermal energy generated from an 800-panel garage-mounted array for space and water heating in community households. During a typical summer day, the panels generate a peak of 1.5 MW of thermal power. The abundant heat generated from the panels during summer months is stored underground for heating needs during winter months, by means of a district heating system comprising a combination of short-term and long-term seasonal thermal energy storage [234]. The homeowners can monitor the thermal power flow in the district heating system via an app [235].

Houses in Drake Landing are 30% more efficient than conventional homes, and have yearly greenhouse gas emissions that are approximately 5 tonnes lower than those of conventional homes [234]. The collective is considered a world pioneer in providing over 90% of its space heating and 50% of its water heating from solar thermal energy. The collective's surplus heating needs are met by natural gas supplies [234].

Prosumers in Drake Landing pay a fixed monthly rate, around $70, to maintain the solar system infrastructure, and the collective itself is revenue neutral [235]. This raises a question around whether it is fair to equally distribute monthly heating fees among prosumers, although their energy usage may be relatively different. Issues around implementing fairness in prosumer collectives need investigation, especially with regards to distributing fees/rewards.

Hepburn Wind Community

Hepburn Wind is the first community wind park in Australia. Built in Leonards Hill, north-west of Melbourne, the collective began generating electricity in 2011, using two turbines totalling 4.1 MW, which is enough to power 2,300 homes [236]. It is a community-initiated prosumer collective with a focal-site wind farm, where prosumers are regarded as innovators and early adopters, as this unique project is the first of its kind in Australia.

The collective began as an informal working group then turned into a cooperative, the Hepburn Wind Cooperative, which manages the farm, funds community projects, and distributes financial returns to prosumers [236]. Electricity produced in the Hepburn Wind prosumer collective is fed into the grid and sold at the National Electricity Market price to the collective's electricity retail partner, Powershop [237, 238]. Before the wind turbines were installed, electricity consumed in the community was mostly generated more than 400 km away in coal-fired power plants. As local electricity production reduces power losses in transmission networks, every kWh produced by the prosumer collective displaces 1.1 kWh produced elsewhere [237, 238].

In 2016, the collective became a certified B Corp – a for-profit company certified to meet rigorous standards in environmental and social transparency, accountability and performance. A B Corp is to business like fair trade is to coffee [239, 240]. The collective provides a benefit sharing model to its prosumers and the wider community, and makes the collective's reports freely available online [237]. The collective's efforts to create a benefit sharing model and provide fair access to information highlight the need for investigating issues around fair distribution and transparency, which are crucial in collective settings.

As shown in the example collectives presented, although many drivers support the growth of prosumer collectives, several challenges still persist, such as characterizing demand flexibility, deploying fairness in distributing fees and flexibility, and generally meeting standards of social and environmental transparency. The next section underpins the need to incorporate demand flexibility and fairness measures in prosumer collectives, and generally enable more dynamic demand response in prosumers collectives.

3.4 Managing Energy in Prosumer Collectives

Collectively implementing demand response, whether for consumers or prosumers, helps scale participation to achieve demand reduction quotas and strengthen market power, and helps optimize energy demand among multiple household appliances and systems to reduce demand variability and improve forecast. Prosumerism offers increased benefits, compared to consumerism, e.g. by helping create additional income from trading/selling electricity, and achieve autonomy and energy self-sufficiency.

Although balancing electricity demand with intermittent supply from renewables presents a challenge for prosumers, collectively balancing demand with supply – in prosumer collectives – can enable an improved balance between supply and demand especially in light of flexible demand and smart grid capabilities.

After investigating example prosumer collectives and reviewing the literature, stimulating demand flexibility and fairness has been identified as key to creating dynamic demand response for prosumer collectives, as highlighted in the next two sections, respectively.

3.4.1 Need for Flexible Demand

Prosumers largely adopt intermittent generation, using wind turbines and rooftop and community solar, whose supply is variable, thus raising reliability concerns from distribution companies and grid operators (as presented in Section 2.3.1) such as creating grid stresses and safety hazards [241–243]. Experiences from countries integrating variable renewable energy resources (e.g. Germany) indicate several challenges with the technical integration and associated market mechanisms of intermittent DER [62], especially issues around overvoltage and thermal limits in the distribution network [244–246].

To mitigate the effects of intermittent electricity supply in prosumer collectives, means of enabling flexibility are becoming available with varying complexities and underlying technologies [62]. One notable way of dealing with variable supply is creating flexible demand to match this supply [62, 88].

Based on existing literature, creating flexible demand in prosumer collectives may take various shapes, including shifting demand to coincide with the collective's microgeneration, trading electricity between production and consumption units within the collective or between collectives, drawing energy from neighbours' batteries, and selling electricity to the grid or to other collectives [18, 20, 21, 27]. Such interactions are complicated on many levels, and thus require new business models and offerings to readily accommodate the layers added by both prosumerism and collectivism [88, 189, 201, 247, 248].

Such findings inform the overall research aim of this thesis, by underpinning the need to consider flexible demand when developing improved demand response offerings for prosumer collectives in light of a smart grid infrastructure.

3.4.2 Need for Fairness

Concepts from ethics, philosophy and justice can play a crucial role in informing energy decision-making by consumers and prosumers [30, 249, 250]. Energy justice can be used to comprehend how values get shaped into energy systems, and help inform energy decision-making [30], by applying principles of justice to energy consumption, production, policy, activism, and security, and to climate change [251].

Sovacool et al.[30, p. 436] define the concept of energy justice as "a global energy system that fairly disseminates both the benefits and costs of energy services, and one that has representative and impartial energy decision-making." Energy justice integrates aspects from procedural justice and distributive justice [30]. Procedural justice deals with the processes of decision-making (e.g. equitable access to information, the right to participate), while distributive justice is concerned with the distribution of decision-making outcomes (fair distribution of energy costs, subsidies, profits, etc.) [29, 30, 250, 251]. Both aspects of justice can help in comprehending and assessing the processes and outcomes of low-carbon energy transitions in collective settings [29].

The notion of justice in many modern systems focuses on the concept of fairness [30]. The literature underlines that failure to disseminate fairness and equity may cause a lack of social acceptance in prosumer collectives [31, 32]. Exploring the concept of fairness, from the lens of procedural and distributive justice, can therefore assist in understanding and evaluating the processes and outcomes of prosumer collectives.

The concept of fairness has been investigated broadly in residential energy management [252–260]. However, limited literature exists around fairness for prosumer collectives, where fairness often is only a part of research investigations and is poorly explained and/or formulated.

Cornelusse et al. propose a mathematical model to fairly allocate profits among prosumers in a community micro-grid where costs and revenues come from different streams [261]. Moret and Pinson assess fairness in prosumer collectives where individual prosumers share energy at the collective-level, to demonstrate that fairness in a collective can be included in distributed negotiations to prevent strategic behaviour [262]. Wang and Huang design an incentive mechanism to encourage energy trading between interconnected micro-grids and fair sharing of benefits [263].

Such findings inform the overall research goal of this thesis, by highlighting the need to consider aspects of fairness in dynamic demand response offerings. Current demand response practices target individual consumers not collectives of prosumers, and tend to focus on technicalities like resource response time, availability, trigger, compensation, performance, etc. [18, 22, 63, 264], rather than social considerations. Interweaving technical and social aspects in demand response can play a crucial role in developing collective socio-technical settings, e.g. prosumer collectives.

Enabling dynamic demand response practices should ideally be conducted by grid stakeholders, such as grid operators, electricity retailers, etc. Nevertheless, such entities do not necessarily have the capabilities required to develop those practices and disseminate them among prosumer collectives. The next section outlines the lack of enabling solutions provided by top actors to prosumer collectives.

3.4.3 Lack of Enabling Solutions by Top Actors

In the context of the electricity sector, the term "top actors" is used to refer to established actors such as grid operators, distribution system operators, and electricity retailers. In contrast, "bottom actors" are electricity end-users. In the context of this thesis, the term bottom actors is used to refer to residential prosumers.

The transformative capacity of established actors in a sector is often low, as their ability to create variety is generally limited and their resources tend to be deployed to stabilize their existing structures [136].

The dominant business model in the electricity sector is the traditional corporate utility model, where electric utilities profit from relying on increasing the energy units sold to end-users [265]. As this business model is driven by unit volume, it pushes the energy value chain towards increasing throughput and locks stakeholders into unsustainable approaches [266].

Literature on innovative business models in the energy sector has been largely focusing on approaches used to market new technologies (e.g. energy storage and electric vehicles) [267, 268]. There is generally a lack, however, in innovative business models and solutions offered or enabled by top actors to accommodate distributed renewable generation [136, 269–271].

Some top actors do deal with individual prosumers despite the distributed nature of those prosumers. However, the processes such prosumers go through, e.g. to install DER, is often long and inefficient, which creates not only a burden for top actors but also delays for prosumers, especially as the number of prosumers grows. The inefficiency of such processes rather than the distributed nature of prosumers may be one of the factors behind the slowness of top actors. Streamlining processes targeting prosumers (e.g. applying for DER interconnection requests online, automating the processing of those requests) may play a role in improving top actor products and services to prosumers and collectives.

Demand response programs are currently structured with top actors on one side and consumers on the other side, and are not well set up to support prosumers, particularly around managing prosumers' interactions and associated flows of power, data and money. For top actors to accommodate such interactions and flows, they need to leverage smart grid capabilities and innovative business models to create value for bottom actors and themselves [269].

Although the majority of top actors are slow in catering for prosumerism and collectivism, very few top actors are trying to stay relevant, by launching new products and services to serve prosumers and collectives (e.g. Veridian Connections in Canada, and Vector Limited in New Zealand, which are both electricity distribution companies). Yet, those top actors are mainly providing new offerings in collaboration with middle actors. For example, Vector Limited is partnering with Tesla to provide battery storage solutions to its residential customers, and Veridian Connections is collaborating with Opus One Solutions, a smart grid software company, to use its software solutions to optimize power flows in a local residential prosumer community integrating solar panels and batteries.

The lack of enabling digital solutions provided by top actors to prosumer collectives has played a vital role in the emergence of new actors that facilitate dynamic demand response for such collectives. Those catalysts of change, referred to herein as "middle actors", are needed to better link top and bottom actors in prosumer collectives, and enable change towards more dynamic demand response. Middle actors should ideally help collectives efficiently manage their power flows and associated data exchanges and money transactions, while supporting top actors in maintaining grid reliability and customer satisfaction.

The next section investigates the rise of middle actors serving prosumer collectives, and shows how this has implications for our work in terms of enabling new products and services in light of a smart grid infrastructure.

3.5 The Rise of Middle Actors

Change catalysts are generally needed to help with transitions to new systems. The emergence of distributed energy resources and smart grid technologies for households propose value that can be captured by actors sitting between top and bottom actors in prosumer collectives. Middle actors can help prosumers overcome barriers (intermittent supply, lack of fairness within a collective, etc.) by leveraging enablers (smart grid metering and controls, innovative models for fair distribution, etc.).

3.5.1 Middle Actors Serving Collectives

Despite being highly complicated, energy systems are often simplified into energy supply and demand, or top and bottom actors [272, 273]. This oversimplified division often neglects the various interactions and actors in "the middle", as it assumes that top and bottom actors merely meet in a middle point that sits in between them [274]. This division additionally assumes that once the tools enabling change in energy systems are available (smart technologies, incentives, etc.), change will occur, which in turn overlooks the need for actors that mediate and aggregate efforts [274].

The terms middle actors and intermediaries are both used in the literature. Middle actors have three functions: mediating, enabling and aggregating, where they play a vital change catalyst role [9, 116, 274]. A middle actor can have a wide range of agency and capacity, and can be responsible for a single function or multiple ones [9, 116, 207, 275]. Intermediaries, in contrast, are mainly assumed to lack independent agency and capacity of their own, and have priorities shaped by surrounding factors [276, 277] but no priorities of their own [274, 276]. The term and role of "middle actors" is thus preferred and used in this thesis, as it reflects a more active and integrative role between top and bottom actors.

In the transition to collective prosumerism, a lot of change is occurring bottom-up very rapidly (such as the rise of prosumers). Yet, top actors are mostly not responding to this change at the same pace, because of their slow processes and limited capacities. In turn, this mismatch has made room for emerging middle actors to put innovative thinking and tools into use by developing new offerings needed to support the growth of prosumer collectives.

The rise of middle actors and their smart grid offerings to prosumer collectives is happening so fast that there is very little literature in this area. Based on reviewing the available literature and pilot projects, middle actors are most likely to offer products and services that enable dynamic demand response in one or more of the following areas: (1) virtual power plant, (2) technology for optimized resource use, (3) dynamic electricity pricing, (4) peer-to-peer transactions within a community, and (5) aggregation [9, 207, 275, 278, 279].

Example middle actors that may act in some capacity in relation to prosumers and prosumer collectives include: energy service companies, energy software and hardware providers, non-governmental organizations, governmental energy agencies, research and development centres, industry associations, and innovation centres. Middle actors may serve prosumer collectives directly (e.g. by giving them tools to enable selling or trading electricity), or may collaborate with top actors to strengthen their offerings to prosumers and prosumer collectives [279].

3.6 Summary

The emergence of residential prosumer collectives, which dominantly integrate intermittent micro-generation, brings challenges around creating flexible demand to match with intermittent supply. Yet, smart grids offer various technologies and features, which can enable demand flexibility in prosumer collectives. This chapter has discussed how smart grids are generally supporting the rise of prosumer collectives, and has identified key points to inform how smart grid opportunities (e.g. scheduling energy demand between home appliances and batteries, trading electricity between households) can be leveraged to create dynamic demand response for residential prosumer collectives.

Reviewing the emergence of prosumer collectives and four example collectives has identified demand flexibility and fairness as key aspects to be taken into account in dynamic demand response solutions for prosumer collectives. The lack of innovative solutions provided by top actors has been also identified, which has, in turn, ignited a new wave of middle actors for catalyzing the interactions between top actors and prosumer collectives, and developing enabling solutions for dynamic demand response.

The findings of this chapter, in addition to those presented in Chapter 2, inform the overall research aim of this thesis around how smart grid opportunities can be leveraged to improve demand response for residential prosumer collectives. The remainder of this thesis investigates how middle actors are shaping innovative solutions in this space, and focuses on issues around fairness and demand flexibility.

Chapter 4 outlines the methodology based on which the third and fourth research questions of this thesis are addressed. Chapter 5 addresses the third question by investigating the emergence of middle actors and their offerings in detail, identifying the challenges they face and the associated implications for dynamic demand response, and exploring how the future may unfold for such actors. Chapter 6 addresses the fourth question around how to foster fairness in software solutions enabling dynamic demand response for residential collectives.

Chapter 4

Research Methodology

4.1 Introduction

The first two research questions posed by this thesis have been addressed by literature review, as presented in Chapters 2 and 3. Chapter 2 includes a review on the current status of energy demand management and the opportunities enabled by smart grids notably for improving demand response practices to meet the needs of prosumer collectives. In Chapter 3, a review is presented on how smart grid opportunities are generally supporting the emergence of prosumer collectives, which has identified the need to further investigate key aspects, namely fairness and demand flexibility, and middle actors, which are helping develop innovative smart grid offerings for residential prosumer collectives.

By building on the literature review and to address the overall aim of this thesis, two additional research questions have been posed. The third research question investigates how middle actors are shaping smart grid offerings for residential prosumer collectives and how this implicates dynamic demand response. The fourth research question investigates how to incorporate fairness in dynamic demand response solutions targeting residential collectives.

This chapter elaborates on the socio-technical nature of this research, and presents the rationale for the methodological approach taken to investigate the third and fourth research questions. The chapter also discusses the methods used to conduct the social and technical work streams of the research, and sets the scene for the next chapters.

4.2 Approach Taken to Perceive Research Topic

This research takes a position that sees the world as physically measurable and as interpreted through people's eyes. The power grid is a multifaceted socio-technical system comprising a social network of organizational players which build, operate, maintain, and use its technical infrastructure [280], in addition to individual and collective end-users whose electricity usage is mainly driven by their needs, behaviours, preferences, choices, and appliances [281, 282].

The power grid is progressively incorporating distributed energy technologies in households, due to their increasing affordability, modularity, and high technical efficiency. Such an evolving adoption creates new relationships between people and technologies, and gives rise to prosumerism where energy can be produced and stored at the demand side and not solely at the supply side. Not only are individual households adopting prosumerism, but prosumer collectives are also forming due to the various benefits of collectively managing energy supply and demand.

Managing power flows in prosumer collectives is challenging when intermittent micro-generation is used. Innovative demand response approaches are needed to balance such intermittent supply with the highly variable demand patterns of households [157, 280, 283].

In residential prosumer collectives, new complex interactions and relationships are developing among individuals, households and communities [284, 285]. The growth of such intricate interactions in a socio-technical context raises expectations. A successful transition from individual consumers to prosumer collectives is expected to demonstrate social concepts, such as fairness.

Conventional electricity system incumbents may not necessarily cope with the rapid changes and new interactions occurring at the demand side of the grid, especially in prosumer collectives. The market is seeing a rise in innovative businesses developing offerings for prosumer collectives, to enable improved and active management of energy in such collectives. As modern society increasingly demands user- and application-centric solutions to emerging problems, which may not have previously existed, integrating knowledge from various disciplines becomes essential [286].

Conducting research on dynamic demand response in residential prosumer collectives requires more than one disciplinary approach: it needs to draw from both technical and social understandings of the situation [287]. The next section presents the epistemology underlying this research, and explains the reasoning behind leveraging social and technical knowledge to answer the research questions.

4.3 Research Approach

Amid the rise of prosumerism in the residential sector, dynamic management of power flows in prosumer collectives presents a challenge as it may not necessarily leverage much knowledge and practices from well-established demand response activities. Such activities are mainly static (e.g. time-of-use pricing), and primarily serve the consuming side of individual households. Similarly, knowledge leveraged from demand response activities used by industrial and commercial end-users is inadequate, as the demand patterns of such users are quite predictable, as opposed to the dynamic patterns in residential prosumer collectives.

Designing dynamic demand response for residential prosumer collectives needs to leverage new knowledge to tackle the dynamic interactions between prosumers' energy practices, social norms, and material cultures [288]. New understandings are needed to grasp the prosumerism element and collectivism of such collectives. Building such a broad range of understandings requires drawing from social and technical knowledge of the situation [287].

A socio-technical system is the most relevant concept relating to energy [289]. Thus, the transition to more distributed energy systems requires a thorough assessment of their evolution in the social and the technical dimensions [157]. Unfortunately, the effect of the dynamics of new energy technologies and their associated social response on locally distributed energy systems is often overlooked [157, 281, 290].

Existing literature on distributed energy systems mainly takes a technocratic approach, which investigates integrating them into existing infrastructure in optimal ways [291, 292]. A review of 4,444 full-length articles on energy studies published in three leading energy journals between 1999 and 2013 showed a general lack of using social science methods and interdisciplinarity, with only 12.6% of articles relying, fully or partially, on methods and tools from social science [281].

To have a more holistic understanding of and create new knowledge about such a new and multi-faceted topic, it is essential to use multiple disciplines to conduct research. Combining more than one discipline can take a number of forms, one of which is interdisciplinary research. Undertaking interdisciplinary studies helps researchers investigate broad topics and answer complex questions, by drawing knowledge from more than one discipline to inform research methods and find solutions [293]. Interdisciplinary research creates its own conceptual understanding of a topic, and thus provides more coherent results [286], by integrating knowledge and methods rather than adding them together [293] [294].

A number of definitions can be used to describe interdisciplinary research. The definition given by the US National Research Council is referenced herein, as it provides a clear and comprehensive description of interdisciplinary research,

> *Interdisciplinary research is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice [294].*

To better address the questions posed by the thesis, an interdisciplinary approach is used, where knowledge is drawn from social science, computer science and power systems engineering. A socio-technical approach is chosen to integrate social and technical knowledge from these three disciplines.

Knowledge stemming from a socio-technical system, such as the smart power grid or a residential prosumer collective, can take the form of either qualitative or quantitative data. For example, data from smart meters or solar PV inverters is quantitative, while data about middle actors' aspirations and the challenges facing collective prosumerism is qualitative. To tackle challenging interdisciplinary research questions, create coherent discussions, and leverage both qualitative and quantitative data, mixed methods research presents an appropriate pathway.

Mixed methods "involve the collection, analysis, and integration of quantitative and qualitative data in a single or multiphase study" [295, p. 224], and are used to tackle challenging questions by pushing the boundaries of long believed assumptions about ways to scope and build knowledge [33]. The richness of using mixed methods lies in the integrated and generalized results they produce through combining qualitative data (e.g. words and narratives) with qualitative data (e.g. numerical data) [33].

Commonly, researchers consider using mixed methods for five reasons: (1) triangulation, (2) complementarity, (3) development, (4) initiation, and (5) expansion [33]. In triangulation, the researcher uses more than one method to examine the same dimension of a problem, while in complementarity, mixed methods help develop a fuller understanding of the problem in hand. Both approaches are used to cross-validate research findings when multiple methods produce comparable data.

Mixed methods can also be used to create synergy in the development of a research project, where the results from one method help inform the other method. Initiation is another reason for using mixed methods, whereby the findings of one study may trigger further questions and additional explanations requiring the initiation of a new study. In expansion, the researcher broadens the study and continuously pursues new research questions.

In this work, mixed methods are used to provide complementarity, by developing an understanding of the emergence of middle actors and their offerings to prosumer collectives, and the challenges facing them. Mixed methods are also used herein to provide development, where the social findings are used to inform the technical stream of work. The next section presents the methodological approach to addressing the research questions.

4.4 Methodological Approach to Addressing Research Questions

The first two questions posed by this research have been addressed in the previous chapters, while the other two are yet to be tackled. This section presents the methodological approach taken to investigate the third and fourth questions.

Addressing the first two questions in Chapters 2 and 3 has set the scene for the remaining research questions. The third question explores the role of middle actors in shaping smart grid offerings and the implications for dynamic demand response in residential prosumer collectives. The fourth question investigates how to technically foster fairness in dynamic demand response offerings in such collectives. The two questions undertake different inquiry pathways, and thus they each invite a different research method. The third research question asks:

How are middle actors shaping smart grid offerings, and what are the implications for dynamic demand response in residential prosumer collectives?

New players are emerging in the smart power grid arena, to fill the gap left by existing incumbents who do not offer appropriate solutions for groups of prosumers. Middle actors are emerging, and playing a role in catalyzing the link and progress between top and bottom actors in prosumer collectives.

Investigating the role of middle actors in shaping smart grid offerings for residential prosumer collectives and the underlying implications for dynamic demand response is a new topic that has not been previously explored. To answer the third research question, an investigation is conducted through a social science lens to explore (1) what smart grid products and services are being developed by middle actors to serve prosumer collectives, and (2) what this means for dynamic demand response for such collectives.

This investigation draws from social and socio-technical knowledge and uses a qualitative method to gather and analyze data from interviews conducted with "actual" middle actors serving "virtual" prosumers and prosumer collectives (virtual in the sense that no interviews have been conducted with them, as the focus herein is on middle actors). The findings are also social and socio-technical, and they feed into the concluding chapter of the thesis. The findings additionally inform the fourth research question, which is more technically oriented and is given as follows,

How can fairness be fostered in dynamic demand response for residential collectives?

As previously mentioned, the literature review underpinned the need to deploy social concepts such as fairness in dynamic demand response for households adopting new energy technologies and wishing to collectivize their resources. Applying fairness, especially in distributing responsibilities or benefits, supports and encourages the sense of collaboration in such collectives.

Integrating social dimensions in power systems presents a challenge. The fourth research question seeks ways to adopt fairness in demand response activities designed for prosumer collectives. This study draws from technical and socio-technical knowledge and uses a quantitative method to analyze data to include socially inspired reasoning into automated decision-making for demand response. The findings of this piece of work are both technical and socio-technical, and they feed into the concluding chapter of the thesis.

As discussed, qualitative and quantitative methods are used to gather and analyze data in order to answer the third and fourth research questions, respectively. The next section details the methods used.

4.5 Methods

This research uses mixed methods to gather and analyze knowledge from three disciplines: social science, computer science and power systems engineering. In such socio-technical research, it is important to have a conceptual start by creating a model to theorize the expected connections between the social and technical elements of the research [296]. Figure 4.1, adopted from reference [296], illustrates the links between the different knowledge, methods and data used.

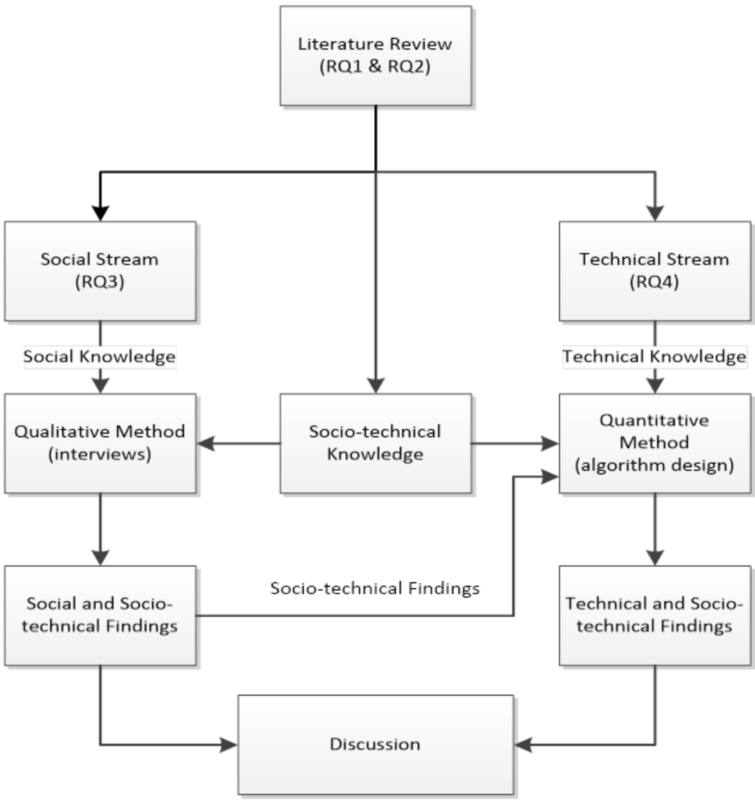

Figure 4.1: A conceptual model for the socio-technical research conducted

After addressing the first two research questions in a literature review, the thesis is principally structured as two streams. Social and socio-technical knowledge inform the qualitative research, which produces social and socio-technical findings. Similarly, technical and socio-technical knowledge as well as findings from the qualitative research inform the quantitative research, to produce technical and socio-technical findings. The literature review and research findings are intertwined in the concluding chapter, to highlight links, novelty and how the future may unfold for this research topic.

The next two sections present the qualitative and quantitative methods used in the social and technical streams, respectively.

4.5.1 Qualitative Method

The third research question investigates the ways in which middle actors shape smart grid offerings and the implications on dynamic demand response in residential prosumer collectives. To answer this question, a qualitative research method will be used. Data will be gathered through semi-structured interviews conducted with executives working at companies providing current and potential offerings for dynamic demand response in residential prosumer collectives.

The aim of the interviews is to learn more about the companies, their offerings and the values they help create, and their executives' personal thoughts on the future trends and challenges emerging in this space. Interview questions can be found in Appendix B.

Interview participants are executives (founders, managers, etc.) working in new businesses – middle actors – with potential or existing products or services in five categories that can enable dynamic demand response: (1) virtual power plant, (2) technology for optimized resource use, (3) dynamic electricity pricing, (4) peer-to-peer transactions within a community, and (5) aggregation.

A total of 15 new businesses will be recruited from around the world based on their existing or potential role in developing smart grid offerings enabling dynamic demand response in prosumer collectives. Investigating new middle actors from around the world can help provide a fuller understanding of how such businesses operate in different regulatory, technical and socio-economic environments, compared with an investigation that focuses on a specific country and context.

In addition to interviewing executives from those new businesses, an interview will be conducted with an executive working in a top actor entity, e.g. a distribution system operator, to understand how such an actor may perceive and interact with emerging middle actors. Additionally, an interview will be conducted with an executive from a well-established and long-running business specializing in traditional demand response practices, in order to explore how this business may be catering for prosumerism in contrast with what new middle actors are developing.

Professional networking websites (e.g. Linkedin) offer a good starting point to find potential interview participants, who will then be contacted directly through such websites, via email, or on social media (e.g. Twitter). Participants will be asked to have an interview in person where possible, or an individual phone/Skype interview if a face to face interview is not possible.

Each participant will be asked to answer questions about their company, and its solutions and values; the ways in which company solutions provide value (enable demand flexibility, fairness, etc.); and their personal views on how the future is unfolding for dynamic demand response in residential prosumer collectives.

All the interviews will be recorded in audio format, with explicit permission provided by the participants. Before starting the interview, each participant will be asked to sign a consent form for in-person interviews, or to agree to the terms laid out in the consent form for phone/Skype interviews. Where data from the interviews is used, every attempt will be made to preserve the anonymity of companies and participants.

The collected data will be analyzed using NVivo software, by conducting thematic analysis to induce common themes from interview transcripts. After familiarizing myself with the transcripts, I will cluster the important features of the data – with the research question(s) in mind – and identify each feature with a code. Then, I will search within each set of coded data and between codes to identify potential patterns of meaning which address the research question(s) and provide comprehensive analysis through a coherent story. Interview findings and analysis are presented in Chapter 5.

4.5.2 Quantitative Method

To tackle the social questions in a technical context, various frameworks, systems, and methods are becoming available to help adopt social understandings in technical systems, and spawn interdisciplinary socio-technical work.

The last decade has witnessed a growing body of work on optimization methods relating to distributed generation from renewable energy sources [297]. Optimization typically involves the maximization or minimization of a specific objective, the *objective function*, within specific limits, the *design constraints*. The parameters that can be adjusted to achieve that objective within those constraints are referred to as *design variables* [298].

In the case of prosumer collectives, optimization can be used to solve several problems, e.g. scheduling prosumers' home appliances and batteries among a collective so as to maximize self-sufficiency from distributed generation, or specifying the best times to sell electricity from distributed generation while maximizing the collective's profit.

To focus on strategic interactions among stakeholders of prosumer collectives, game theory – a conceptual and formal analytical framework – can be used to study such complex interactions [299, 300]. To address the fairness notion in prosumer collectives, a solution concept from game theory, namely the Shapley value [301], can be used to provide a conceptual basis for distributing a reward (or penalty) among a number of prosumers.

In the quantitative and more technical work stream of this research, two software mechanisms will be developed using computer modelling. The first is a fair share allocator for distributing the income of the collective from selling electricity among prosumers based on their contribution in reaching the quota of electricity to be exported. The second mechanism aims at trading off the minimum loss of utility experienced by a collective of households in order to achieve fairness in distributing loss of utility among a collective of households.

The technical data required for the two mechanisms will be collected from case studies, recommendations from pilot projects, retailers' websites, and free online datasets. Example data includes smart meter electricity use, electricity tariffs, etc. Each of the two software mechanisms represents a specific quantitative approach to manage numerical data from households, communities, and the power grid.

4.6 Discussion

Applying social innovations to the electricity sector is indispensable. Social innovations create revolutionary ideas and strategies that establish new interdisciplinary relationships between previously separate entities, with the aim of meeting social needs. Engaged end-users whose needs are socially catered for may interact efficiently and reliably in the electric power system.

By looking at the big picture, the power grid is a multi-faceted socio-technical system. As an integral part of the power grid, a collective of residential prosumers is equally a socio-technical system, with various supply and demand profiles. Such profiles are driven by a myriad of needs, behaviours and technicalities spanning prosumers, their community, the grid, and the ecosystem governing their interactions.

Incorporating social user-centric features in the design of many technologies today helps meet users' aspirations and needs. Emerging energy technologies are no exception, especially those needed in highly social settings such as residential collectives. Bringing social dimensions to such a technical system, however, is a complicated task that can either reinforce the system or weaken it if inappropriately addressed.

This chapter explored the socio-technical nature of this research, and presented the basis for the mixed research methods approach taken to investigate the third and fourth research questions. The detailed qualitative and quantitative methods used to conduct the social and technical work streams of the research were presented, which sets the scene for the next chapters.

A wave of new businesses and products is helping prosumers and prosumer collectives better meet their dynamic demand response needs, and pushing more innovation into top electricity system actors' offerings. The qualitative method helps address the social dimension of the research by conducting interviews with executives from companies with existing offerings or potential solutions targeting prosumer collectives.

Understanding how the business around such offerings is growing, and how social factors are being taken into account in those offerings helps address the third research question, by identifying the role of middle actors and the associated repercussions on dynamic demand response for such collectives. Additionally, interview findings help shape the social orientation of the technicalities of dynamic demand response solutions, and thus feed into the investigation of the fourth research question and help in understanding how the future is unfolding in this area.

In investigating the fourth research question, which looks into how to integrate fairness in dynamic demand response for residential collectives, the focus becomes more quantitative and technical. The question explores how to implement fairness in distributing revenue and loss of utility among prosumer and consumer collectives, respectively.

This thesis provides a novel socio-technical investigation on the new layer of middle actors catering for the needs of top electricity actors and residential prosumer collectives. The work herein looks into the smart grid offerings provided by those middle actors and the implications for dynamic demand response in such collectives.

The next two chapters address the third and fourth research questions, which present the social and technical work streams, respectively. Chapter 5 presents and discusses the findings of the interview questions regarding middle actors' smart grid offerings and associated implications for dynamic demand response in residential prosumer collectives. Chapter 6 investigates improved software mechanisms to adopt fairness in dynamic demand response for residential collectives.

Chapter 5

Interview Findings and Analysis

Research Question 3 – How are middle actors shaping smart grid offerings, and what are the implications for dynamic demand response in residential prosumer collectives?

5.1 Introduction

The third research question investigates the ways in which new businesses (i.e. middle actors) are developing offerings to enable dynamic demand response which may be suitable for use by residential prosumer collectives (i.e. bottom actors), and explores resulting implications. This question is addressed through the social research conducted in this thesis. Tackling this research question helps address the overall aim of this thesis, which focuses on how smart grid offerings can be leveraged to improve dynamic demand response for residential prosumer collectives.

To help answer this question, data was gathered via 15 semi-structured interviews conducted with executives (e.g. founders, senior employees) working in new companies with potential or existing products or services in five categories enabling dynamic demand response: (1) virtual power plant, (2) technology for optimized resource use, (3) dynamic electricity pricing, (4) peer-to-peer transactions within a community, and (5) aggregation.

Two additional interviews have been conducted, one with an executive working in a distribution system operator, and another with an executive working in a well-established company specializing in providing traditional demand response solutions and aggregation services. These additional interviews are important in understanding how a top actor (grid operator, etc.) may perceive and deal with new middle actors, and how an established business specializing in traditional demand response caters for prosumerism in contrast with new businesses.

The profiles of the interviewed companies are listed in Section 5.2. More details about the interview process are available in Section 4.5.1, and the interview questions are listed in Appendix B. Those questions have been selected such that to fill the gaps identified in the literature review findings.

This chapter presents the interview findings based on the themes inferred from interview transcripts, following the process introduced in the Methodology chapter. Based on the findings, the chapter presents how demand-side changes and the slow response of top actors to changing customer expectations are resulting in new businesses with innovative products and services to serve prosumers. The chapter also discusses the future challenges facing dynamic demand response targeting prosumer collectives, such as the lack of scalable business models, adequate regulatory mechanisms, and collaborative efforts between involved stakeholders.

Drawing from the interviews, this chapter starts by briefly presenting the new products and services made available by the interviewed executives from middle actor companies to prosumers, both individuals and collectives. After discussing the slow pace of top actors that has driven the emergence of new middle actors, the chapter moves on to elaborate on the bottlenecks being resolved by middle actors and presents their main business models and company principles. Then, a section is dedicated to elaborating on the innovative offerings and customer-centric values (e.g. fairness and flexibility) the companies are integrating into the solutions they provide to prosumers.

Lastly, the chapter discusses how offerings are expected to evolve for the management of energy supply and demand, especially in relation to prosumer collectives, and what challenges lie ahead in this area. A summary of concluding remarks is available at the end of the chapter.

Novelty in this chapter includes: (1) investigating the emergence of new businesses (middle actors) who are catalyzing the interactions between top actors and prosumer collectives; (2) exploring how smart grid opportunities are creating a new wave of dynamic demand response offerings; (3) identifying the main categories of dynamic demand response solutions being developed today; and (4) extending the literature around what fairness means for new businesses developing smart grid offerings for prosumer collectives.

5.2 New Businesses

In the interviews, 17 executives from 17 companies have been interviewed. The following subsections briefly list the profiles of those companies, including company ID (used throughout this chapter to maintain anonymity), description, selection category, location(s), and date founded.

Company A is an electricity retailer that provides access to wholesale electricity prices to households and small businesses through online software tools. Customers need to have smart meters, but are not bound by fixed term contracts. Through online tools, customers can access real-time electricity prices, a 4-hour price forecast and energy savings tips, and can thus change their energy usage accordingly. The company objective comprises providing a fair and transparent service for its customers and helping end energy poverty in New Zealand. More recently, the company started offering a service to help prosumer households sell their surplus electricity to the grid.
Category – Dynamic Electricity Pricing
Country – New Zealand
Founded – 2014

Company B is an electricity retailer that provides access to wholesale electricity prices and flat rate subscriptions to households and small businesses. The company offers to upgrade customer meters to smart meters, to help them view their energy usage in real-time via online software tools. It also provides customers with weekly insights into their energy usage and energy saving tips, to help them gain control of their electricity bills. More recently, the company started offering a solar feed-in tariff to prosumers, where they can sell their electricity to the grid.
Category – Dynamic Electricity Pricing
Country – Australia
Founded – 2015

Company C is a provider of distributed energy storage systems and energy management tools for residential and business customers with solar PV. The company also provides energy management solutions for electric utilities needing to gain visibility and control over the distributed energy resources of their prosumer customers. Surplus energy from the company's prosumer customers is aggregated in a virtual pool, where

it can be sold upon request to electric utilities or third-parties.
Category – Virtual Power Plant
Country – USA and Australia
Founded – 2009

Company D is a provider of distributed energy storage systems to households and small businesses with solar PV. The company also manages a virtual online community of its battery owners, where they can share their surplus energy with each other at lower prices from the grid. Selling excess energy from the community is handled by the company for its community members. Monthly fees are paid by community members to the company in return for managing the metering infrastructure and energy management software. Since 2016, community members pay a flat rate for their electricity from the community.
Category – Virtual Power Plant
Country – USA and Europe
Founded – 2010

Company E is a well-established and long-running company specializing in demand response, billing and energy procurement solutions for electric utilities, and commercial and industrial customers. More recently, the company merged with a solution provider (founded in 2008) specializing in managing distributed energy generation and storage resources, in order to be inclusive of prosumers.
Category – Aggregation
Country – North America, Europe and Asia Pacific
Founded – 2001

Company F provides software solutions and services to electric utilities, and residential, commercial and industrial customers to help them manage and aggregate distributed energy resources for optimum network operations and market access.
Category – Virtual Power Plant
Country – Australia and Singapore
Founded – 2010

Company G provides hardware and software solutions and services to integrate and manage Internet of Things (IoT) devices (e.g. sensors and actuators) used in resi-

dential, commercial and industrial premises integrating distributed energy generation and storage resources.
Category – Optimized Resource Use
Country – Germany and France
Founded – 2010

Company H helps electric utilities offer energy management software solutions to households and small businesses integrating solar PV and battery storage. Such solutions help manage customers' distributed energy production and consumption units so as to optimize network operations and create virtual power plants. The company also provides solutions directly to prosumers, to help them manage their solar and battery resources.
Category – Virtual Power Plant
Country – Australia
Founded – 2014

Company I offers software solutions to electric utilities to help them balance their customers' distributed energy production with consumption and aggregate resources to optimize network operations and create virtual power plants. The company also provides electric utilities with customer engagement software to help their customers control their assets (e.g. smart thermostats, energy storage).
Category – Virtual Power Plant
Country – USA, Europe and Asia Pacific
Founded – 2011

Company J provides customer engagement solutions to electric utilities to help them build strong relationships with their customers and educate those customers with energy usage and cost insights. The company also provides electric utilities with a behavioral demand response solution that personalizes energy saving goals and can be configured for both incentive and non-incentive based demand response programs.
Category – Optimized Resource Use
Country – USA and Asia Pacific
Founded – 2011

Company K helps communities develop renewable energy solutions by providing

them with a set of products and services. One of their products is a hardware and software system for solar energy providers to monitor, control and provide payment options to their customers. Examples of their services include renewable energy system design, community business plan development, and landscape and visual impact assessment.
Category – Optimized Resource Use
Country – Scotland
Founded – 2011

Company L provides various solutions for direct use by prosumers, or through retailers. One of their applications enables prosumers to trade their electricity with consumers and receive real-time payments in return, where consumers can choose their clean energy source. Another application allows collectives of prosumers that share ownership of renewable energy assets to buy and sell their electricity to the wholesale electricity market and distribute income to prosumers.
Category – Peer-to-peer Trading
Country – Australia
Founded – 2016

Company M provides a software and hardware platform that connects prosumers with batteries and consumers with prosumers generating electricity from solar PV, wind turbines, and biogas, by matching energy demand with supply and balancing grid frequency fluctuations. The company can also aggregate and sell surplus electricity from prosumers to the wholesale electricity market.
Category – Virtual Power Plant
Country – Europe
Founded – 2009

Company N is an electricity retailer providing residential consumers and prosumers with software tools that can help them change their energy usage so as to benefit from more local and renewable energy. The company also helps solar prosumers sell their excess electricity to the grid.
Category – Peer-to-peer Trading
Country – New Zealand
Founded – 2012

Company O offers electric utilities and prosumer collectives a software platform to enable prosumers and consumers to sell, buy, and gift clean energy within local communities. The company aims to eventually enable electric vehicles charging with local energy and provide energy analytics to network companies to support improved electricity pricing structures.
Category – Peer-to-peer Trading
Country – New Zealand
Founded – 2015

Company P provides solar PV-based hot water systems to residential customers, where they can harness solar energy to heat their domestic water and save on electricity bills.
Category – Optimized Resource Use
Country – New Zealand
Founded – 2011

Company Q owns and operates the electricity distribution network in specific parts of New Zealand. More recently, the company started supporting the installation and use of distributed energy resources, such as solar PV and electric vehicles. The company is responsible for approving installations of distributed generation (e.g. solar PV, wind turbines, and micro-hydro) for both small and large customers, and it maintains a number of electric vehicle charging stations and uses electric vehicles in its fleet.
Category – Distribution System Operator
Country – New Zealand
Founded – 1998

5.3 New Offerings

The emergence of prosumers and prosumer collectives is creating new expectations around balancing energy demand and supply, and new opportunities for building innovative businesses and offerings. This section briefly overviews the new offerings provided by the interviewed companies to individual prosumers and prosumer collectives, respectively.

5.3.1 Offerings for Individual Prosumers

Most interviewed businesses have installed their solutions at individual prosumer premises, either for demonstration purposes in partnership with electric utilities or for everyday usage at prosumers' premises. The remaining businesses are still either in the process of developing solutions for individual prosumers, or principally target prosumer collectives. Below are the main types of offerings provided to individual prosumers.

Battery Storage

The emergence of battery systems is trending as a key solution to prosumers needing to store electricity for later use or trade. Company D, which provides integrated solutions for distributed energy storage and solar PV, has thousands of installed batteries worldwide, as mentioned by their executive,

> *We have installed more than 13,000 batteries worldwide in the last 6 years. We are the market leader in Europe at least (Company D).*

As further explained by the following quote, the battery system their company provides is modular and scalable, to meet the various demand needs of prosumers,

> *Our system is a scalable storage unit. It starts with 2 kWh and can be extended till 16 kWh, in 8 incremental steps. Why do we do this? Because we realized that there are different energy demand requirements in households, different numbers of people, and of course different appliance usages. For example, some people use oil or gas as a heating source; others may use electric heating, which means they need a bigger storage unit to supply their energy demand (Company D).*

Prosumers are turning to modular battery solutions to meet their needs for storing electricity, and sizing for those batteries is mainly based on household electricity demand, number of inhabitants, and appliance usage.

Another offering built by middle actors is providing real-time feedback to battery owners. Company C is a US market leader specializing in solar batteries and virtual power plant software. This company's executive mentioned that more than 650 of their battery storage systems have been installed in the field, mostly in households. This company expects the number of installed systems to double after orders are installed for a couple of utility programs in New York and Australia.

This executive elaborates on prosumers' ability to access the metrics of their battery systems as follows,

> *Prosumers that have the battery now can access a mobile application that shows them how much power is in the battery, what is happening, where is the power going, is it going into the battery or serving the home or going out to the grid. The app shows those metrics; the technology that underlines those kind of metrics is in customers' hands (Company C).*

Using this company's offering, prosumers can access the metrics of their installed battery systems (e.g. battery power level) via a mobile application.

It is not only battery manufacturers that are involved in trialling and installing battery systems for prosumers; Company B, which provides dynamic electricity prices to customers in Australia, is engaged in a trial with businesses in Victoria to install battery systems in residential households.

Based on the interviews, battery storage systems are becoming increasingly available in the market for households to store electricity, and maximize associated benefits (e.g. use stored energy for household demand in case of high electricity prices or grid emergencies). Batteries are becoming more modular and scalable, while they are increasingly integrating with feedback systems to satisfy prosumers' awareness. Using smart devices (smartphones, tablets, etc.), prosumers can easily access information about their battery system performance.

Distributed Energy Control and Optimization

Company F provides software solutions for controlling and optimizing distributed energy generation and storage. This company serves prosumers at various scales, and is pairing with distribution networks in Australia to run trials in residential areas with solar rooftops. The following is quoted from their executive's interview,

> *Examples of prosumers we are serving are places like Melbourne airport, right down to the individual households. We have projects in residential households which are run by distribution companies as part of a trial program for solar rooftops (Company F).*

This company and similar businesses are developing advanced software platforms to help major electricity retailers and distribution companies run trial projects for solar rooftops in Australian households.

On the other side of the world, Company G has worked with utilities, like British Gas in the UK and City Power in South Africa, on pilot projects supporting controls for optimizing energy usage across prosumers' household appliances and distributed energy resources (heat pumps, washing machines, solar panels, battery storage, etc.). Currently, the company is running a similar pilot with EDP which is a leading electric utility in Portugal.

Automated Demand Response

The underlying concept of automated demand response (ADR) is the same as demand response, where end-users are requested to change their demand from normal consumption patterns. However, in ADR, there is no human intervention – automated signals are sent to end-users' devices, which enact based on a preprogrammed plan for demand reduction and demand response event specifics. Using ADR, the following systems can be controlled: lighting, heating, air conditioning, motors, pumps, fans, air compressors, and process equipment.

Automated demand response is a reliable and cost-effective demand-side management mechanism used by network operators in grid situations requiring real-time responsiveness and no human intervention (e.g. power shortages). It is becoming increasingly preferred to using backup generators, mostly those using natural gas, especially with the growing numbers of prosumers at the distribution level.

Using smart meters in ADR enables accurate compensations for households, because it allows more elaborate comparisons between baseline demand use with the performance of a household during a demand response event. Although ADR may be implemented for consumers as well as prosumers, engaging in ADR may sometimes make more sense for prosumers with batteries, as energy may be drawn from prosumers' batteries during demand response events without inconveniences for prosumers.

The interviews revealed that ADR is provided by some of the companies being interviewed. The offerings provided by Company I, for example, help households achieve demand flexibility by equipping their households with the "energy internet" (within the home) where various smart devices and distributed energy resources (smart thermostats, solar PV, batteries, etc.) are interconnected to serve the objectives of households in participating in demand response events.

This company is providing their solution to the New Hampshire Electricity Cooperative – a large member-owned electric distribution company in New England. The software solution enables the cooperative to implement four automated demand response programs, which help reduce the capacity and transmission charges paid by the cooperative. In one of the programs, the “Peak Plus”, the software controls internet-connected space and water heating devices and window air conditioners in households, so as to lower their energy use during demand response events.

This company is also supporting Oklahoma Gas and Electric in their “Bring Your Own Thermostat” program. This electric utility had previously offered a program providing only one thermostat model to their customers, but the program proved to be unsustainable due to continuous technology improvements. Thus, this new program, in collaboration with Company I, provides more choice to customers by offering a wide range of smart thermostats for them to choose from.

Furthermore, the company is enabling Portland General Electric to roll out a program, which sends notifications for demand response events to 70,000 customers, followed by measurement and verification processes to allocate rewards to participants accordingly.

Although both programs do not uniquely target prosumers, they reflect a new trend in managing demand flexibility by actively implementing ADR controls to serve consumers as well as prosumers. Such programs can be seen as a step towards enabling demand flexibility amongst residential dwellings via the interconnectivity, controls and optimizations of the energy internet.

Energy Disaggregation

The process of identifying loads or appliances in operation from aggregated energy consumption data is referred to as energy disaggregation. Company J provides appliance energy disaggregation software to households; this software can be used by both prosumers and consumers to gain insight into their appliance-level electricity usage patterns. In an offering that uniquely serves prosumers, the company provides a software platform for disaggregating solar PV power in households. The software identifies how much solar power is being generated by the arrays, and how much of that power is being consumed in the household. The company executive elaborates on the solar disaggregation solution, as follows,

> *In Australia, almost every retailer is trying to sell solar because it is one way they can make extra money other than selling electricity. Solar will be sold anyway so they may as well be a part of that. Our app will work on top of it. For battery storage and electric vehicles, we are currently working on integrating them in our software applications (Company J).*

Enabling prosumers to know how much of their solar array is actually being used to power their households can help them assess the value of their micro-generation, and make decisions around trading their energy with others or selling it to the grid. In addition to appliance and solar disaggregation, this company is expanding its offerings to integrate battery storage and electric vehicles, which may be attributed to the growing interest in distributed storage.

Dynamic Electricity Pricing

Another stream of offerings that empowers households in general, whether prosumers or consumers, individuals or collectives, is dynamic electricity pricing. Generally, dynamic electricity tariffs provide an incentive to residential consumers to change their electricity demand to cheaper off-peak hours. Prosumers benefit in a similar way to consumers, but have additional flexibility where they may use their micro-generation or storage during peak demand hours instead of changing their demand patterns. Companies A and B provide dynamic tariffs to customers in New Zealand and Australia, respectively, and more recently, they have both started enabling their prosumers to export their electricity to the grid.

Online Electricity Trading

Trading electricity is changing from conventional trading between generators or retailers on one side and residential consumers on the other side, to software-enabled trading amongst a wider range of stakeholders (e.g. between residential prosumers and consumers). Electricity trading platforms enable prosumers and consumers to sell and buy electricity using online tools, respectively. Such platforms basically work by matching electricity demand with supply at fixed points in time, e.g. every half an hour. Via online tools (website, mobile app, etc.), a consumer is shown a list of prosumers within proximity and given the options to choose and prioritize prosumers and electricity prices of interest. Prosumers set their selling price and can visualize and control who buys electricity from them.

Based on location and preferences, online trading platforms (also referred to as marketplace) matches demand and supply for the trading prosumers and consumers within a local distribution network, and communicates accordingly with the controls of prosumers' distributed energy resources to feed a specific amount of electricity into the grid. The consumer uses electricity from the grid based on the matched price in the trading platform until their metered usage reaches the amount purchased.

Company L in Australia and Company N in New Zealand provide online trading platforms to prosumers wanting to sell electricity to the grid or directly to consumers. Company L provides a blockchain-based peer-to-peer online electricity marketplace in Australia. In an unregulated environment, this marketplace enables prosumers to directly trade power generated from their micro-generation with consumers, without needing an energy retailer as an intermediary, and receive real-time payments in return. In a regulated environment, the company enables retailers to empower their customers to sell electricity to the grid.

The company has integrated its platform at a local sustainable and affordable housing project, and is looking to expand its reach to New Zealand, by working on a trial project comprising 500 sites nationwide (potentially including residential communities and schools).

5.3.2 Offerings for Prosumer Collectives

Although offerings for individual prosumers are also relevant to collectives, some offerings uniquely target collectives. The interviews show that while many of the offerings serving individual prosumers have gone beyond the pilot phase, and are being rolled out to households, offerings targeting prosumer collectives remain largely in the concept phase or are operating as pilot projects.

Solutions for individual prosumers tend to be based on household-level systems, such as home battery storage, interconnected home appliances, and micro-generation controls. Solutions for prosumer collectives, however, are fundamentally set up to optimize power flows between supply and demand points among households at a more aggregate level, to deliver maximum benefits, e.g. reach energy self-sufficiency, or sell electricity at the best price.

Virtual Power Plant

A virtual power plant (VPP) basically aggregates a network of distributed generation and storage, and flexible loads (i.e. have a potential to be used at different times and levels of operation). In a VPP, the goal is to allocate power flows between supply and demand loads so as to alleviate demand peaks in the grid, enable flexibility management and trade electricity in the market on behalf of prosumers.

Company H provides software that controls and optimizes power flows for prosumer collectives, and is involved in a pilot project in a prosumer collective in Australia, as described below,

> *We are about to do an embedded network in a grid-connected multi-residential with solar PV and batteries, and we also have an off-grid micro-grid pilot consisting of 35 houses. We develop solutions to optimize power flows within a community. One house has PV and another has batteries and another has particular consumption patterns. We can optimize the flow of energy between them to deliver maximum benefits, however that is defined (Company H).*

An embedded network, also referred to as a secondary network, is a physical electricity distribution network that is not owned by a distribution company but rather by a third-party (i.e. one that manages a residential community, an airport, a commercial building, etc.). Control points around embedded networks are managed by the network owner.

Company C is working on a pilot, comprising 34 homes in downtown Sacremento, California. As described by the executive, prosumer homeowners in the pilot received solar PV, battery storage systems, smart thermostats and smart plugs as part-paid by their mortgage. Payback for those installations is in the form of savings on electricity bills.

This pilot setup enables prosumers to schedule demand to match with supply, and get value from dynamic prices by using electricity at cheaper periods. The executive believes that new energy aggregation trends are currently transforming the market, where energy produced from micro-generation or stored in batteries in prosumer households can collectively be traded in an organized market, particularly in California.

Aggregating storage capacities is another method of localized optimization. The executive from Company I mentioned that they are finalizing an agreement around delivering a storage aggregation platform, which manages clusters of residential battery storage.

Company B is sourcing batteries within 50-km areas in Australia, to control them during certain times of the day to reduce network congestion; their executive expects this arrangement to grow into a peer-to-peer marketplace to facilitate trading between prosumers and simultaneously reduce network stresses.

Although most prosumer collectives discussed in the interviews were physical communities of households that are geographically co-located, a couple of companies focused on virtual collectives, i.e. dispersed prosumers collectivized through the company's offerings. A virtual collective can be considered a subset of a virtual power plant. Company D created a virtual collective consisting of battery storage owners of its intelligent battery systems, comprising more than 3000 households. As explained by their executive, there are two main sides to evolving their virtual community:

> *On one hand, there is everything about electricity, so sharing electricity and accessing the trading market. On the other hand, we are working on smart home appliances. This takes a while to develop so for now we have smart plugs to control certain appliances and connect them to the battery. Now, those plugs also integrate with smart heaters connected to the battery to optimize the use of electricity in the household (Company D).*

The executive expanded on community members, saying:

> *You can think of community members as one step closer to having a smart home than non-members. Everyone can be a producer and a consumer. You do not sign a direct contract with a specific person; you sign a contract with us and get electricity from the big pool (Company D).*

Members of virtual communities can exist anywhere around the grid, unlike co-located members of physical communities. A prosumer that is part of the virtual community and wishes to trade his surplus electricity feeds it into one point of the grid, where it goes into a "virtual pool" of electricity. A consumer that is part of the collective buys from the virtual pool by purchasing electricity from that prosumer and drawing it from the grid. Virtual communities connect individual prosumers around the grid and use software solutions to automatically handle electricity trading transactions.

Another instance of virtual communities was discussed by the executive of Company G. His company is developing a virtual community to provide flexibility services for the grid, where demand response volumes aggregated from community members can be traded in the market, in return for a flat rate guaranteed for 20 years. Expanding further, but on geographically co-located communities, the executive said:

> *The same principle with virtual communities can be applied to more geographically located or limited communities. There is a concrete project we are working on with a large real estate development company in Germany. These guys want to have independent energy resources, with the grid being the secondary supply, so that production and management can be done locally. It is an interesting project (Company G).*

Automated Demand Response

As explained in Section 5.3.1, automated demand response helps customers reduce the efforts required to participate in DR programs and achieve set load reductions, while still earning rewards in return for DR participation. For network operators, ADR helps reduce the operating costs of DR programs while maintaining the reliability of DR resources and guaranteeing real-time responsiveness without human intervention during periods of peak demand.

Participating in ADR may be easier for collectives of prosumers rather than individual ones (who would mainly draw from stored energy), as they can integrate the preprogrammed demand reduction plan of ADR with a plan to optimize power flows amongst themselves during DR events to each achieve demand reductions. Such collective action can also open the doors for prosumer collectives to participate in DR programs requiring bigger demand reductions by aggregating their DR resources and benefiting from additional rewards.

In Australia, a substation upgrade deferral program is being run by a distribution company in cooperation with Company F. As described by the company executive, households get paid for dispatching their assets:

> *We are paying households up to $10/kWh to dispatch assets, and the main share of the benefits in this regard is driven by the network benefits which can be realized (Company F).*

In this context, dispatching an asset (i.e. load) means to turn it off or use less electricity to power it. Dispatch requests are basically sent to large numbers of end-users by a distribution company or a grid operator in certain times of the day, based on grid status and needs. Signals from such requests can switch the load off or reduce its power usage. Network benefits resulting from dispatching assets include flexibly matching grid supply and demand, avoiding grid frequency disturbances which affect power quality, and meeting demand in case of generation shortage.

In this project, deferring a substation upgrade is assisted by having dispatchable loads within that substation, reflecting a collective of end-users, whether prosumers and/or consumers. However, prosumers, especially those with battery storage or non-intermittent micro-generation, have the advantage of being able to be more flexible than consumers in providing dispatchability as requested, because they can flexibly turn to their local electricity supply, rather than grid supply, to meet their demand. For prosumer collectives, it even makes more sense to provide load dispatchability, by collaborating in turning off or reducing their loads in return for monetary incentives. In this case, prosumer collectives may experience less inconvenience than consumer collectives or individual prosumers, as they can better balance their supply and demand power flows amongst themselves.

The interview discussions about offerings to prosumers, both individuals and collectives, have shown that businesses primarily focusing on developing offerings to individual prosumers are also interested in prosumer collectives. Such businesses see collectives as a normal extension to individual pockets of prosumers, and either have current or prospective plans to expand their offerings to collectives. For example, when asked about their involvement in prosumer collectives, the executive of Company N, which offers an online electricity trading platform, said:

> *We are definitely looking into it. We might put batteries in a street on a distribution network or in communities with embedded networks. But at this stage, it is only for individuals (Company N).*

Similarly, Company P is eager to expand offerings to serve prosumer collectives via supporting respective utility programs. At the moment, the system developed by the company uses solar PV to heat water, and surplus energy generated from the panels can either be fed into the grid or used in-house. The surplus generated from current array sizes may not be enough to meet household energy needs other than water heating, therefore the company aims at upgrading its systems to serve at an aggregate level such that power flows are optimally managed across prosumers.

Additionally, the executive from Company J talked about his encounter with a professor from the National University of Singapore in a utility show in Bangkok, and how this professor's research team is trialling a prosumer community on an island in Singapore to study its cost effectiveness in powering islands with no electricity access in Indonesia. Although this company is not currently targeting collectives, its executive talked about the growing opportunities arising in collective prosumerism, which are encouraging the company to consider serving communities.

Having outlined various solutions being offered to prosumers, both individuals and collectives, the next section sheds light on the slow pace of top actors in serving rapidly emerging prosumers, which has created opportunities for these middle actors to provide innovative offerings to prosumers.

Online Electricity Trading

Trading electricity online is also available to prosumer collectives. Company O offers electric utilities and prosumer collectives an online electricity marketplace which can enable prosumers and consumers to sell, buy or gift clean electricity within local communities. The company supports prosumer collectives with solar PV, micro-hydro and micro-wind installations in New Zealand. The company is building relationships with prosumer collectives interested in using its platform, as described below:

> *We are in touch with a number of communities who are interested in investing or have already invested in micro-generation technologies, and are interested in what the marketplace overlay might be (Company O).*

Company L in Australia provides a software application enabling prosumer collectives sharing ownership of distributed generation assets to buy and sell their electricity to the wholesale electricity market and distribute shared income among prosumers.

5.4 Top Actors Are Slow

As elaborated in Section 3.4.3, top actors of the electricity sector are traditional supply-side stakeholders who provide offerings to serve electricity end-users (both consumers and prosumers). Example top actors include grid operators, distribution system operators, electricity retailers, and aggregators. As with the literature (see references [136, 269–271, 279]), the interviews show that top actors of the electricity sector commonly lag in terms of enabling prosumers with innovative offerings to meet their energy demand management needs.

This difference in the pace of change between top actors and prosumers has germinated new companies, collaborations, and solutions to cater for the growing needs of prosumers, as presented in previous sections. The results of the interviews suggest that four main reasons are behind the slowness of top actors to respond to changing needs and opportunities.

5.4.1 Lack of Knowledge

Some top actors lack knowledge of their prosumers and do not fully understand their needs. For example, while the founders of Company C were working with a distribution company and a utility switchgear company to make and install a quick vent for the distribution grid, they noticed that both companies lacked knowledge about electricity end-users of the power grid. As the company executive said:

> *The company founders saw an emerging problem on the grid, specifically in California and other states along the West Coast. As the number of solar customers increased, especially residential customers, the volume of electricity moving back to the grid was increasing. They saw that this would put more stress on utility distribution equipment, and utilities would need to spend more money on operating costs to maintain and replace distribution-level equipment. At the same time, they also recognized that utilities really did not have any way to see or understand or evaluate what was happening at the customer-side of the meter (Company C).*

When top actors lack knowledge and data about how their customers are changing, this leaves a gap of potentially unfulfilled needs and creates opportunities for new actors to meet those needs.

5.4.2 Lack of Appropriate Pricing Mechanisms

Another reason behind the tardiness of top actors is the lack of appropriate pricing mechanisms. The executive from Company H believes that networks and retailers are unprepared to provide appropriate electricity pricing schemes that enable scalable prosumerism. As quoted from that executive:

> *We have sites running for households, but we are a little bit ahead of the curve than networks and retailers; I do not think they are ready to provide pricing mechanisms that make this scalable (Company H).*

The need for new robust pricing structures is further highlighted by the executive from Company B, who thinks that the rapid changes in regulations and the high uptake of distributed generation need new pricing mechanisms:

> *The core of the pricing structure needs to be resilient in a world that has high amounts of distributed energy and changing regulations. That is why we were funded by three big entities and a Chinese bank, to operate in the space of developing a business model around distributed generation (Company B).*

While an Australian dynamic pricing retailer like Company B is being funded to work towards a new business model around distributed generation, Company A (a New

Zealand retailer that also offers dynamic tariffs) thinks that prosumerism is interesting but presents a tiny market in New Zealand because the majority of the market is still only buying electricity. Interestingly, a few months after the interview, this retailer started offering a service enabling prosumers to sell their excess electricity to the grid.

Slow Markets and Processes

Another reason behind the weak engagement of top actors with prosumers is the tardiness (and sometimes resistance) of certain electricity markets to adopt new technologies, and accommodate process changes and new market actors. As the executive from Company G expressed, his company initially started operating in France. However, the slowness of that market and its processes pushed the company to create a service company in Germany, where the market is more developed, with three other parties to leverage faster market processes and promote its value proposition.

The executive further compared between utilities and a large real estate developer his company is working with, to highlight the lag of top actors in this rapidly changing space:

> *Those guys of the real estate developer are turning faster than the utilities into the new energy technologies world and they want to expand the service and control the cost of operation and ownership. So, they are really getting towards PV production and battery storage, making it as autonomous as possible. And the surplus can be stored, managed, or traded elsewhere (Company G).*

The executive from Company K thinks that intermediaries are needed to handhold local prosumer projects and lobby for them at the government because it is difficult for those projects to be doing all what they need to do in addition to lobbying:

> *We now have local authorities that are finally stepping in, and they are also in a great position to be lobbying for and hand holding those little local projects. It is impossible for those projects to do lobbying as well as the other stuff they are meant to be doing. An intermediary step is needed; they need intermediaries or local authorities to be doing that for them (Company K).*

The executive from Company Q, which is an electricity distribution company, believes that prosumerism will evolve regardless of whether they want it to happen or not, and thinks that distribution companies need to adapt:

It is going to happen, regardless if we wanted it to happen or not. We cannot tell customers what to do; even though solar power is more expensive than grid power at the moment. Regardless of what we do, customers will end up supplying their energy through alternative means. We have to adapt (Company Q).

This quote from an executive working in a distribution company reflects a relatively passive role, where such companies see themselves as adapting to customers' choices to supply their energy through alternative resources (e.g. solar PV).

Careful with Revenue Streams

In addition to the aforementioned reasons, top actors are slow because they tend to be cautious in the approaches they take to generate revenue, as further expressed by the same executive:

Utilities are a bit slow; dinosaurs. They know there is a need to do something because they know that only moving electrons will not make money for them anymore and that revenue shares will drop. But they are extremely cautious in whatever they do (Company G).

Interviewees generally thought that electricity market incumbents lack the means to fully understand and support prosumers in order to provide them with viable solutions that meet their needs. However, it is important to mention that not all top actors are slow in responding to the needs of prosumers (as described in Section 3.4.3).

The next section focuses on the rise of middle actors and the innovative models and solutions they are bringing to fulfill the needs of prosumers, while safeguarding grid stability and reliability.

5.5 Middle Actors are Emerging

As the upsurge of prosumerism in residential areas is changing the demand-side of the grid, new businesses are providing new offerings and services where top actors fail to provide adequate solutions and support. The following sections present the gaps middle actors are filling, and the new business models and principles they are bringing to the power grid.

5.5.1 Filling the Gap

Middle actors are either supporting prosumers directly, or assisting top actors to support prosumers, in order to achieve various goals. Such goals give value to different stakeholders, e.g. maximize self-consumption for prosumers, and maintain grid stability and reliability for grid operators and network companies. This section presents the main issues middle actors are resolving to fill the gaps left by top electricity market actors.

Maximize Self-Consumption

An essential reason behind installing micro-generation and using distributed storage (e.g. home batteries, EVs) in residential dwellings is satisfying a desire for energy self-consumption, and ideally maximizing it. As the executive of Company D explained, prosumers ideally want to meet their demand using their local micro-generation to avoid dealing with big energy providers which continuously increase tariffs and often deliver poor services to their customers.

Maximizing prosumers' self-consumption (or energy autarky, as the company executive prefers to call it) is one of the primary issues middle actors are addressing. Company D, since its launch in 2010, has had the aim of maximizing prosumers' energy autarky.

To achieve 100% autarky for prosumers, the company progressed through two stages. Initially, the company sold battery systems to environmentally-conscious households with micro-generation. After a few years, even though the prices of distributed resources started falling and the company sales doubled every year, the original objective to achieve 100% autarky for customers remained unsatisfied. The cause of this and the way in which it was dealt with are elaborated as follows:

> *We have realized that the battery alone does not help the household be completely self-sufficient. At some point, any battery and PV system owner will have some residual energy demand that he has to get from the grid. This left the company vision unsatisfied. The autarky was not technically 100% achievable in that sense, so the idea was to find a way to get the last couple of percent out of the hands of the conventional energy providers to have 100% autarky for prosumers. That is when the virtual community came into play, where the residual energy demand is now provided by other prosumers (PV, wind, biogas, etc.) from the community (Company D).*

Because 100% autarky was not always attainable for prosumers with micro-generation and distributed storage, the company leveraged a virtual community of prosumers to maximize their self-consumption:

> *The idea is to exchange energy among community members, to achieve energy autarky together. We provide a platform for prosumers to share excess energy and get energy from the community in situations where they are not able to provide it for themselves because of the fluctuating supply and demand. Let us say that a prosumer's annual energy demand is 5000 kWh. His degree of autarky is 80%, meaning that he is able to produce and consume only 4000 kWh by himself, so he gets the remaining 1000 kWh from the community instead of the grid (Company D).*

Initially, this company set out to increase prosumers' autarky via providing them with battery systems to store surplus power; but since this offering failed to achieve 100% autarky for prosumers, a virtual community of prosumers was created. This virtual community enables its members to exchange energy among themselves, and thus maximize their energy autarky together and not be dependent on electricity providers.

In addition, Company G is working with a large real estate development company in Germany which aims at having independent energy resources for their customers and only using the power grid as a secondary source of supply. This real estate developer is working with Company G, rather than a utility, to expand their services by getting into PV production and battery storage, trading surplus energy and making that whole system as autonomous as possible. Also, the executive from Company P sees the company helping people become more energy self-sufficient and be in control of their energy, by enabling them to heat water using solar PV instead of solar thermal which can be inefficient if poorly insulated especially if there is a lack of skilled trades people.

Maintain Grid Stability and Reliability

As the numbers of prosumers connected to distribution networks grow, maintaining grid stability and reliability becomes a concern to grid operators and distribution system operators. The variability of intermittent energy resources can cause serious grid stability and power quality issues due to frequency and voltage variations, e.g. damage of grid equipment, thus requiring ongoing management to maintain stable and reliable grid operations.

During a joint project between the founders of Company C and network companies, concerns arose over grid risks (e.g. frequency and voltage fluctuations causing equipment damage [86, 87]) resulting from the growing numbers of prosumers on distribution networks. The lack of utilities' knowledge about prosumers' demand and distributed energy resources triggered the founders of company C to bring new battery storage technology to market to bridge the gap between utilities and prosumers, as explained below:

> *So they saw a way to bring to market a technology that would enable utilities and prosumers to become aligned in how they were supplying and consuming electricity. Where prosumers are putting electricity back onto the grid, instead of damaging equipment, utilities are actually able to make use of it in a productive way or rely on it somehow, whether to improve power quality or relieve congestion in certain areas (Company C).*

By storing and coordinating power flows from intermittent resources, the battery storage technology developed by Company C can help prevent distribution network stresses and distortions in power quality in distribution networks with large numbers of prosumers.

Create Value from Smart Meter Data

Despite the abundance of money put into rolling out smart meters in many residential areas, and the data produced from those meters, such data has been rarely analyzed and utilized fully to create value and improve associated services. To boost research and development around smart meter data analytics, the US Department of Energy launched a grant project under the Arpa-E program. The founders of Company I spotted this opportunity and got together to submit an entry to the project whose objective is described by the company executive as follows:

> *The objective of the project was to extract more value from smart meters, and more specifically to deliver a continuously updated forecast of a million endpoints in less than 10 minutes (Company I).*

The project was set to deliver continuous updates about the forecast loads and power flows across local grids. As explained by the company executive, aside from optimized billing there was hardly any value created from smart meter data, which prompted this project. The founders customized the software they had previously developed to optimize the flow of electrons in an electronic chip in order to serve power flow optimization in power grids. They saw an analogy in the flow of electrons in electronic chips with that in power grids, and leveraged this analogy to start developing offerings to smart homes with complex power flows.

Company J also set out to change the traditional, complicated and expensive ways utilities use to monitor and analyze the electricity use of household appliances. The company founders use high-speed high-precision data from smart meters to disaggregate appliance power usage by type, time and quantity:

> *You can take this single stream of readings from the smart meter and run some mathematical techniques through it to figure out what appliances were being run and when, and how much each of those appliances was consuming on a daily and monthly basis. Traditionally, if you wanted to do that, you had to wire up your home with energy monitors in each of the plug points and that became really tricky when looking at things like air conditioning because they are typically not plugged into the wall but hardwired into the distribution panel. So trying to monitor energy consumption in people's homes was very costly and very few people did it. Maybe a few techy people who enjoy the challenge would give it a go, but to roll that out to customers en masse would be very expensive and very complicated for utilities to do (Company J).*

By analyzing household smart meter data, the following can be identified: the appliances being used, their power demand, and when they are being used. Such a convenient and inexpensive approach to disaggregate household appliances proves to be useful in the case of hardwired systems, such as air conditioners or heat pumps, which consume large amounts of electricity and cannot be easily connected to energy monitors or smart plugs (i.e. plugs that monitor electricity use of plugged appliances).

Leveraging advanced data analytics to create more value from smart meter data is an essential step in developing customer-oriented solutions which benefit various smart grid stakeholders (e.g. prosumers and network operators). Using smart meters with distributed energy resources enables prosumers to get maximum benefits by making informed decisions on how much power to buy or sell and when; additionally, it gives more insight to network operators into prosumers' load and supply patterns which can drive optimal grid operations.

Furthermore, analyzing smart meter data by a middle actor can help create improvements or new business opportunities for another middle actor (e.g. a company providing data analytics can support a company providing communications or hardware infrastructure to improve its offerings).

Enable Flexibility Management

Micro-generation from solar PV and wind power is intermittent and prosumers using such intermittent supply can use flexibility management to optimize power flows with batteries and household loads. Managing flexibility for prosumers is complicated, especially in light of varying technologies and household needs. Middle actors are developing advanced solutions to address the mounting need for flexibility management.

Flexibility management was the main idea behind launching Company G. Before the company was formed, part of its team was working on developing scenarios about smart grid developments and how energy resources will evolve, while the other part of the team was focusing on technologies for device connectivity and internet of things. Their skills and experiences complemented each other and so they launched the company to integrate technology from one side with business acumen from another side, as described in the following quote:

> *This strategy person ran a couple of scenarios on how smart grids can be built and how the energy would evolve. The finding was that all this can be successful if we can get new real flexibility out of decentralized energy resources. So making consumers become prosumers, who are more involved, and acting with a revised value proposition. In the meantime, my colleagues and I were running a company which was doing IoT network management. We connected multiple devices and participated in a couple of research projects on smart homes and everything that was in the hype in 2009. I was actively looking through my network and I connected with this person and some others I knew. We had the technology but no business acumen on what we can do, and they had good business value proposition but no technology. That is how the two teams got together and started the company (Company G).*

The aforementioned examples illustrate ways in which middle actors fill the gaps left by traditional electricity top players in accommodating prosumers. Generally, middle actors develop new technologies, products, and services and facilitate enhanced market conditions to better host emerging prosumers. The innovative business model and cutting-edge technologies leveraged by middle actors, and their relatively smaller teams largely support their fast and energetic pace to keep up to date with the latest industry and business trends, compared to slow top players.

5.5.2 Business Models

As presented in Chapter 3, Section 3.4.3, the traditional business model of top actors is a corporate utility one relying on increasing units sold to customers – which does not capture the emergence of prosumerism. As presented in the same section, literature on innovating business models in the electricity sector has focused on how to market advanced smart grid and distributed energy technologies rather than how such technologies impact electricity market actors and grid operations.

Middle actors use innovative business models to introduce advanced products and services to the demand-side of the power grid. This section presents how the interviewed companies are changing the way business is conducted in the presence of prosumerism.

The majority of the interviewed companies are new companies following a business-to-business (B2B) model where they provide solutions directly to top actor businesses (e.g. electric utilities, and energy service companies). In turn, those top actors then present such solutions to prosumers. In this model, middle actors support top actors in their efforts to provide advanced solutions to prosumers. The following are interview excerpts illustrating how middle actors directly help top actors achieve their goals:

> *We provide the software backend to utilities, retailers, aggregators, and energy service companies, so that they can go ahead and achieve their objectives (Company I)*

> *Most of our engagements so far have been with utilities, energy retailers and network providers. We have not gotten down to the prosumer market at this point. We are a B2B company, so we sell solutions to businesses (Company J).*

> *We run demand response programs for utilities to help with thermal capacity problems for large aggregation programs. We help retailers curtail load during demand response events, and we monetize the backup systems of retailers or networks whenever there is value (Company F).*

On the other hand, some companies follow a business-to-customer model, where they present their offerings directly to prosumers. Those companies mainly provide their customers with products and services for storing energy, trading it within prosumer collectives or selling it to the grid or on the electricity market. Examples include Companies A, B, L, N and O.

5.5.3 Company Principles

As part of the discussion about company emergence, each executive was asked about the main company principles that reflect its mission and values. Numerous principles were mentioned, including reliability, transparency and sustainability. For one company, the top priority is to meet reliability and safety standards, as quoted below:

> *The founders of the company were very connected to the utility industry so their priority was and remains building a system that meets utility requirements from a safety and reliability perspective. That has been the leading priority the entire time, and other things like intelligence and automation come after that (Company C).*

Transparency is another leading principle that is being practised by middle actors. As mentioned in the following quotes, Companies A and B believe transparency is a vital principle to be disseminated, not just with their customers, but within their business and industry:

> *It is hard to do what we do because it is new to customers and it is quite disruptive to the industry and we are playing against the big guys, so we need to be brave. We believe in transparency. It is not just the product we deliver to our customers. Across our business and within the industry, we are trying to be transparent in what we think is the best (Company A).*

> *Transparency has a lot to do with the pricing structure as well. It is a transparent structure. The usage and supply charge transfer to the customer. Again, separating the retailer cost into subscription fees is quite transparent (Company B).*

Sustainability is another important principle adopted by most companies. As presented in the following quote, although Company E takes a commercial focus to be profitable, it takes a green focus as well to replace fossil-fuel based power plants with the demand loads it is helping reduce:

We have a commercial focus. We have to cover our costs and try to make it as profitable as we can. But, we take a green focus because we firmly believe if we take a load off, it replaces fossil fuels burnt in power stations (Company E).

Companies D and L also value green clean energy; the executive from Company D wants "clean energy for all". Company I sees that having a clear environmental impact is the result of providing flexibility features (e.g. enabling and managing elastic energy demand) which helps bring more renewable resources into the power mix.

Company G, on the other hand, first had a strong green outlook to the world then its perspective slightly changed, as elaborated below:

What we learned is that we started with a heavy greenish perspective to what we want to do – better for the world and everybody! Then, we turned to do the bottom line, which is how we can make money while still doing good to customers. The investment of anyone whose objective is to be green has a limit which depends on how rich you are. So we wanted to build software elements that can be turned into a service value proposition that would be more attractive and community oriented. We want to do things better to reduce large investments on the centralized polluting power plants. Somehow we will be good to the world and better at managing what is available (Company G).

The company saw a limit to the amount of investment spent on being green, and thus started focusing on a value proposition that is more attractive and community oriented. This point takes us to the next principle that some middle actors are adopting, which is being community-centric.

A good example of a company that is largely community-centric is Company O, which is trying to move away from individual-based prosumerism towards building prosumer communities. The following quote elaborates on this point:

Our key value is community. One of the problems we see at the moment in solar PV is that you have got individuals. So far relatively wealthy people are installing solar PV and seeing cost advantages to it, but that is really individualized. So what is happening is that there is a disaggregation and individualization of distributed energy and what we want to do is to use that technology to build communities around it (Company O).

Companies G and H also regard being community-centric as a key principle for their companies, where they aim to address their needs of communities rather than the wants.

Another key principle valued by Companies A, D, F and Q is innovation, especially in providing out-of-the-box solutions to prosumers to help them overcome barriers to their growth, and to make the electricity industry interesting in general.

Providing self-sufficiency in energy is another principle that was brought up by the executives of Companies D and P, which they perceive as key to fulfilling the objective of prosumers in relying less on electricity coming from the grid. Profitability is another principle that was valued by Companies C, E, and I.

5.6 Innovative Solutions and Value Creation

A range of smart grid offerings is developed by middle actors to serve the needs of prosumers and prosumer collectives, and add value to households and communities as well as power grids. Based on interview findings, this section presents the trends characterizing offerings and associated value creation for prosumers and collectives, with a focus on enabling solutions for prosumer collectives.

5.6.1 Software versus Hardware

Amid transitioning to a smart grid, the focus in power grid infrastructure has been moving from centralized mechanically-controlled systems towards more automated software-controlled distributed infrastructure. Following the same trend, solutions targeting the demand side are becoming largely software-based. Hardware-based systems serving prosumers (e.g. PV panels and wind turbines) have largely matured during the past decade, reaching high degrees of efficiency and system performance. Core innovation in prosumer products currently lies in building flexible customer-centric software systems that create value and make a difference in prosumers' lives.

Most of the interviewed companies only develop software solutions, a few specialize in developing hardware products, while a few others develop integrated solutions comprising hardware and software components. The move towards software solutions stems from their flexibility, scalability and ease of deployment. Three executives used the term hardware agnostic to describe their company solutions. As an executive of one of the software providers puts it:

We thought there was a great opportunity to build software for third parties as opposed to following an integrated model, so we decided to go software first and software only! And to be absolutely hardware agnostic, by supporting open protocols as well as doing our own integration for those pieces of hardware that did not support open protocols (Company I).

Branching from the software solutions track, several companies tend to see themselves more as software providers providing cloud-based software-as-a-service, rather than energy service providers. When asked to specify the specialization of his company, one executive said:

We will not fit neatly into a single keyword. In this industry, the walls are crumbling. It's more and more about trying to sell software solutions to other businesses (Company I).

The discussion then veered towards company competitors especially those big companies providing aggregation services, where the executive discussed their struggle:

Some aggregators are struggling because the value they are offering is not enough to justify their cost base. They need to maintain a high touch relationship with the utilities, then also good relationships with their customers, plus they have their own hardware and software. That is a lot of weight to carry and maintain, especially that their technologies are proprietary not open source. Any guy who is going around offering energy services and audits can use our software to do the exact same thing, and do whatever else they are doing in terms of energy efficiency and embedded generation, whatever. That is why this company is pushing on the software front these days (Company I).

5.6.2 Enabling Solutions

Based on the interviews, middle actors provide products and services to prosumer collectives principally in four areas, as presented below. Most companies specialize in one of those areas; however, a few companies offer a range of solutions spanning two or three areas.

Virtual Power Plant

Products and services being developed for managing virtual power plants are rapidly emerging globally and being supported by evolving middle actors. The majority of interviewed companies (e.g. Companies C, D, F, G, H, I, L, M) are currently providing, or developing, solutions for virtual power plants, whether as companies' core products and services or basic secondary offerings.

The following are quotes from company executives describing their virtual power plant offerings:

> *We are a VPP company and we link prosumers and consumers all over Europe. Our customers are small and medium scale, and our energy resources are solar power, wind, biogas, and energy generators. We link and aggregate electricity, and provide control for this energy (Company M).*

> *We monitor and control electrical assets – we are really good in switching stuff on and off! We have got a portfolio of VPP which allows electric utilities to roll our technology across their customers, where they bundle those customers as part of network support or asset management tools (Company F).*

> *We are a software provider offering customized VPP cloud-based solutions (Company I).*

While those executives explicitly used the term VPP to describe their offerings, other executives focused on the terms connectivity, control and optimization to label their solutions which are essential functionalities of virtual power plants. The following quotes illustrate those descriptions:

> *Our company develops software that can optimize energy usage of diverse devices based on flexibility plans for energy usage patterns at households. We are taking heat pumps, solar panels, battery storage, washing machines, smart meters basically everything that can be communicating we want to connect with. We are looking at two aspects: the external conditions like weather, temperature, radiation, and so on, and the market aspect around new energy trading trends over the next 24-36 hours. We put all that together and we shake it very strongly to give us a schedule that we can revise and send to the devices which will act accordingly. That schedule is revised*

every 5-10 minutes, depending on customer choice, and we can extract flexibility volumes that can be sold to the trading exchange (Company G).

We are basically a software company, but we have an embedded control unit and a standard compliant physical interface to the network which enable our software to connect various devices into one platform to get consistent data. We can connect to solar inverters, battery management systems, power meters, and load controllers. We connect directly to devices and can remotely configure them, so we get much richer data than we would by just using current transformers. We get a lot of access data, statuses and alerts, temperatures, cell-level measurement from batteries, etc. (Company H).

This executive starts by describing how their software connects to physical devices and what type of data is collected from those devices. Then, he elaborates on their cloud-based software and the values it provides.

This all connects to a cloud platform, which is a decentralized computing platform providing real-time data. We also provide a portal to end-users for real-time analytics and control for individual units but also across groups of units. This solution can be used by solar integrators to provide consistent engagement with customers and by electricity retailers and commercial facility manages to get reliable data and effective controls regardless of the system they have (Company H).

Another solution enabling virtual power plants is that of Company D, which describes batteries as the control center of household energy. This company sells smart plugs together with their batteries, and enables household energy activities based on three priorities as described below:

The battery tells the smart plugs to activate in situations where there is excess energy in the household. The top priority in a household is to supply household requirements, so appliances, plugs, etc. The next priority is charging the battery, so it is full when the sun sets. The third priority is supplying devices connected to smart plugs and those used for space and water heating (e.g. heat pumps and heating rods) (Company D).

In addition to using excess energy to produce electricity, this company is investigating the revival of an existing technology, such as heating rods, where surplus micro-generation can be used to smartly heat water as detailed below:

We are looking into using excess energy for heating purposes in households. You can put the heating rod in a water tank, and whenever there is excess energy produced the rod will heat up your 300-litre water tank. This is not a new idea heating rods have been used for ages. Now, we implement the heating rod in the priority cascade, where the battery decides when to send energy to the heating rod to heat water for the radiator, or for showers and kitchens (Company D).

Company C provides an integrated hardware and software system that controls virtual power plants for individual or collective prosumers, as described in the following quote:

Our hardware system includes lithium ion batteries and electronic components. This system integrates with rooftop solar PV, and connects to the home and to the grid. The integrated system manages in real-time all those power flows and reports real-time metrics about those flows. Our software allows utilities to aggregate and control these individual battery systems and get real-time information and visibility into the power flows in and out of each battery and view aggregate metrics about the fleet of batteries (Company C).

Automated Demand Response

A number of the interviewed companies provide solutions that enable automated demand response, including Companies D, E, F, I, J, M, N, P, and Q. For example, Company J provides a set of tools to network companies to enable them to shave demand in constrained areas by engaging residential customers in demand response programs. More details on those tools are presented below:

We provide mobile apps to customers to monitor their home energy consumption by appliance. We also give them a bullseye projection so they know during the month if their bill is likely to be much higher than normal so they can make some energy changes to bring it back in line (Company J).

Providing customers with appliance-level energy usage can help them make more informed decisions about lowering their home energy bill, and taking part in demand response events rolled out by network companies. Additionally, Company J helps its customers compare their usage against similar households, and not only engages with them through mobile apps but through emails, SMS and letters as well, as described in the following quote:

> *Moreover, we give them neighbourhood comparisons, not only for their total energy usage but also for appliance-level usage. For example, we would let them know if they are using 50% more air conditioning compared to a group of people living in similar sized homes with a similar number of occupants, and in a similar climatic area. We also engage with customers through emails, SMS and letters (Company J).*

As described in an earlier section, Company J also helps its prosumers disaggregate the amount of energy their households use from solar panels versus mains power.

While the solutions of Company J focus on household energy monitoring and customer engagement to enable demand response, most solutions are motivated by automated controls in households. An example is Company I, which interconnects and controls home energy devices (e.g. smart thermostats, smart water heaters, and batteries) to help users change their energy usage during demand response events. Such solutions enable demand flexibility for both prosumers and consumers by leveraging connectivity, controls and communication technologies.

Company P provides a different type of automated control, by prioritizing water heating using solar PV, then directing surplus solar power to be used in households or fed into the grid based on prosumers' choice.

As for Company F, it helps electric utilities and retailers run their demand response programs by providing them with cloud-based automation platforms and customer-specific applications on top of that to help manage their peak loads. Similarly, Company C provides electric utilities with an integrated software and hardware platform to run their demand response programs. Rather than enabling behavioural demand response by sending customers notifications to change their demand, Company C offers a solution where customer loads are automatically fed with stored energy from batteries during a demand response event. This takes place behind the scenes without customers' inputs; customers' electricity needs are still being met, but from batteries rather than the grid.

Company M, which mainly serves VPP, enables demand flexibility via sending its customers a schedule with recommended time slots to use energy based on their historical usage, their micro-generation source, and spot market electricity prices.

Online Electricity Trading

Companies providing trading services to prosumers mainly conduct trades via online peer-to-peer marketplaces or electricity market trades. Trading electricity through online platforms (e.g. Companies L, N, and O) mainly adopts peer-to-peer trading between prosumers and consumers sharing the same distribution network. The concept of peer-to-peer trading has been gaining a lot of interest in the past few years, and several companies are using it to enable prosumers to sell their electricity directly to local consumers without needing third-party intermediaries. As the executives from Companies L and O put it:

> *Our trading platform is increasing the likelihood of people's benefits from their rooftop PV installations. Our residential prosumers improve the economic return of their investment in micro-generation by selling energy to their neighbours of the distribution network at rates typically higher than regulated pay-back rates you get from the retailer. There are also consumers buying that excess at a rate less than the regulated residential energy tariffs. One of our drivers is to help prosumers that can afford PV and storage but are unfairly impacted by the dynamics of the network prices (Company L).*

> *At the moment, if you have excess energy generated from PV, that energy goes back to your energy retailer, and you have no choice or control over when and or how that is distributed or who gets the benefit of that excess energy. With our platform, you will be connected to a local consumer within your neighbourhood or town, so it gives you more choice and flexibility over what and when that energy goes to this consumer. This is a virtual connection. You cannot guarantee that a kilowatt generated goes to a specific person; it is not a DHL package. Essentially, it is capacity produced matched with capacity consumed (Company O).*

By not having to sell electricity back to the grid (i.e. retailer), prosumers are not governed by network tariffs and can choose which consumers to sell their electricity to and at what prices. Such trading platforms enable flexible trading transactions between local prosumers and consumers.

Although the term peer-to-peer is used by Companies L and N to describe the essence of their trading platforms, the executive from Company O is against using this term, describing it as a fashionable buzzword that is inaccurate as follows:

Actually, we have banned the use of "peer-to-peer" within our company because you cannot actually trade peer-to-peer kilowatts in a physical sense, so we tend to think of it as a decentralized marketplace. Peer-to-peer has become a fashionable buzzword for things and does not accurately describe what we do. Some of the other players in this space around the world say that they are the Airbnb or the Uber of Energy but that is not a true description of the actual business model. We can think of this model as providing a new tariff for trading electricity, and we put the user experience as the over layer that allows the prosumer and consumer to locally connect and have the experience that they are in the same community (Company O).

Online electricity marketplaces largely leverage the peer-to-peer concept in trading, but use different models and technologies to implement their platforms. For example, Company D offers a virtual community where prosumers and consumers can exchange electricity and collectively achieve energy autarky. The executive of Company D describes community benefits as follows:

You become a member of the community by paying a monthly fee of 19.99 Euros. As a community member, you get access to various offerings. One of them is access to favourable electricity prices, and this is where the community energy exchange starts. You can buy a kWh for 23 cents, which is 6 cents under the current market price of energy in Germany. Another offering is a voucher code which allows you to get a discount of 1875 Euros on your first battery, starting with the smallest unit of 2 kWh, and covering all sizes (Company D).

Another example is Company L which uses block-chain technology to guarantee safe and secure trading by coupling energy transactions, which track electricity from production to consumption points, with financial transactions, where payments are made from buyers (i.e. consumers) to sellers (i.e. prosumers).

On the other hand, the executive from Company I thinks that Company L is over-investing in using block-chain technology in online electricity trading within a distribution network:

You do not really need block-chain technology to trade electricity, because you already have a meter there. Those people are definitely over-investing and trying to short-circuit distribution companies (Company I).

As for trading electricity at the market-level, Company M delivers trading services to prosumers, by aggregating their energy resources (e.g. solar PV, micro-wind and biogas) and administering their spot market trades.

> *We also trade the energy under the spot market. We bundle and aggregate energy, and also provide administration services to our clients. It is like group management (Company M).*

Company K, on the other hand, facilitates electricity export projects for prosumer collectives by providing them with business planning and project management to help them take their energy to the market.

Dynamic Electricity Pricing

As for electricity retailers providing dynamic tariffs, the two companies that have been interviewed largely focus on enhancing customer energy experience and follow the same business model where their retailer fees are fixed irrespective of customers' energy use. Unlike traditional retailers, they do not benefit as customers' energy demand increases.

Yet, the two companies offer different tariff mechanisms. Company A, based in New Zealand, passes wholesale market prices to customers in addition to transmission, distribution, metering and tax charges. On the other hand, Company B, based in Australia, passes to customers its expected cost-to-serve (i.e. cost covering business activities and overhead for a customer account), which is a hedged cost that might fluctuate during the day, so it is quite similar to a time-of-use tariff. In addition, Company B is more involved than Company A in trials looking into using new distributed technologies in distribution networks. Company A is involved in a trial to install battery storage in households, and another one looking at reducing electricity network constraints in particular sections of the grid by controlling batteries via a peer-to-peer trading platform between prosumers and consumers.

Company A mainly sees itself as a platform and product company, but a retailer at the same time. The company wanted to use digital technology to change energy experience for customers, as described in the following quote:

> *When we started the company, we wanted to transform energy experience for customers and we wanted to use technology to do that with digital business. But we needed to sell it to someone, so we decided to sell it to ourselves. We did not think that the big guys will buy our solution because it is disruptive to them. We decided if we want to prove a value for the platform or products*

that we want to deliver, we need a retail business to do that. We got a retail arm which is a traditional electricity retailer and everything that comes with it (Company A).

As the company wanted to change customers' energy experience and thought that top electricity market players would not be interested in a disruptive business model that uses digital technology, the company decided to start as a retail business to deliver new experiences and products to customers.

Company A basically provides its customers with transparent prices reflecting wholesale electricity market prices, and additional features to help them make informed decisions around their household electricity demand. More on the digital platform displaying dynamic prices is quoted below:

Through transparent electricity prices, customers get a sense of the price signals and different prices at different times of the day. We provide our customers with smart digital tools that allow them to have a choice. You may choose to use the heater to heat your home no matter what the price is, but you might choose a different price for using your dishwasher and your washing machine. That smart digital platform is delivered on a web app and a mobile app. They have information tools they can go to if they want to use them (Company A).

While dynamic prices can be accessed at customers' convenience when needed, via a web or mobile app, Company A proactively delivers information to its customers to keep them informed with more control over their demand for energy, as described below:

We provide customers with proactive tools which tells them when certain things happen, e.g. alerts for high prices. And rather than telling the customer once a month what their bill is and often the customer is in shock, we tell them every single day what their bill already is. This is our approach to serve our customers and keep them informed (Company A).

On the other hand, Company B sees itself as a service provider with pricing structures that are resilient to a future full of distributed energy technologies; it does not consider itself a commodity provider like traditional retailing businesses. This is further elaborated as follows:

In a future with lots of distributed energy resources, the retailer who makes the money from a lot of consumption is not resilient to that sort of future. Our pricing structure is different; it separates out the retailing cost into a fixed fee. Regardless of how much the customer uses, we see the same profit from the customer – we are no longer incentivized to make the customer use as much energy as possible. Our incentive is much more aligned with being a service company and doing what the customer wants. If that is to help them reduce their energy use, then we will do that (Company B).

In addition to providing a dynamic pricing mechanisms, Company B develops a portal where customers can login to see their energy usage data, to know what energy they are using and the cost implication of their usage. They also offer more added value to their customers like forecasting their usage patterns, working out their optimal solar solution, and providing them with power saving tips.

Company B is also developing its portfolio of solar and battery products, as it sees growth in this area, as quoted below:

We think that any business that needs to be a major player in distributed energy needs to have a retail arm because it needs a retail relationship with customers. You can effectively manage the whole customer energy experience, including solar, batteries, whatever. We want to be involved in the whole relationship. In the background, we are working on solar and storage products. We just had our first set of solar sales come through, which is based on the analysis we got based on customer data and optimizing a solution for them and going out and having a retailer solution, too. We are looking to try to open up these value streams to customers and be one of the first businesses engaging in fleet management for distributed generation and storage (Company B).

5.6.3 Benefits to Prosumers and Collectives

When asked about the incentives their solutions provide to prosumers, company executives mentioned various incentives including being green and independent of big energy retailers, earning and saving money, and accessing markets and electricity usage metrics. This section elaborates on prosumers' incentives to use new emerging products to meet their energy needs in households and communities.

Be Green

Based on the interviews, early adopters of prosumerism have been largely motivated by environmental concerns and being "green" through using local renewable micro-generation to meet their demand for energy. Even as DER prices drop and prosumers become increasingly motivated by monetary incentives, interviewees agreed that environmental motives remain an incentive for residential prosumers to use DER and its associated solutions, and residential consumers to support prosumerism. As the executive from Company N puts it:

> *People with solar panels are getting a financial incentive, and those buying energy are supporting solar investment and that is key. They get to save the polar bear! (Company N).*

As electricity users become more aware of the impacts of climate change, they also see value in knowing where their energy comes from (e.g. its carbon footprint), as explained in the following quote:

> *Our customers do care about the price, system state and carbon emissions. They find it appealing and easy to use our carbon emissions proposition, which shows them the amount of carbon emissions that is produced in New Zealand at any point in time. They see value from using it (Company A).*

Maximize Self-consumption of Energy

One of the strongest incentives for prosumers to use new emerging solutions, such as those provided by interviewed companies, is to maximize their self-consumption from local micro-generation installed in their households and communities. This largely stems from prosumers' disappointment with top electricity sector players, especially retailers with increasing energy prices and monopolizing activities, and prosumers' need to become more independent of those players. Especially as battery prices dropped, prosumers became more incentivized to use battery storage to maximize their self-consumption, and become "rebels" in breaking free from electricity sector monopolies.

The following quote by the executive from Company D sheds light on both aforementioned incentives:

> *The incentives of early adopters were based on environmental concerns and disappointments with the big energy companies who have been monopolizing*

the energy market with increasing prices. Storage systems increase the independence of prosumers who have a green attitude and those who are rebels in the energy sector who say "hey, I do not want to be connected to the big energy provider anymore" (Company D).

Another reason that motivates maximizing self-consumption is the drop in feed-in tariffs in some countries, e.g. Germany. This regulatory change motivated prosumers to use batteries in order to increase their self-consumption from local energy resources and save money on buying electricity from the grid, rather than earn reduced money from selling electricity to the grid. This is further explained in the quote below:

Until 2010, there has been an understanding, at least in the German market, that if you buy a PV system, you get a high feed-in tariff from the government so it is an investment that pays back in 10 years, and afterwards you still get 30 Euro cents per kWh. It was a money generating rooftop. Then the feed-in tariff dropped in 2011 to a level below the energy price, so you got less for the feed-in than you pay to buy electricity from the grid. That was the turning point for storage systems. They became attractive to existing and prospective PV owners because self-consumption was key to saving money instead of earning it from the feed-in tariff (Company D).

Drops in feed-in tariffs transformed the concept of money generating solar rooftops towards money saving batteries, where prosumers benefit from using electricity from their local micro-generation rather than selling it to the grid.

Gain Financial Benefits

Two financial benefits stood out as motives for prosumers to use new solutions provided by middle actors: benefiting from flat energy rates and accessing electricity markets.

Some companies, e.g. Companies G and D, provide new flat-rate services where prosumers pay a fixed price for their electricity bill no matter how much energy they use, and this rate remains fixed for years. This is not to be confused with flat electricity tariffs offered by conventional electricity retailers. The following quote illustrates the flat-rate service offered to prosumers by Company G:

The essence incentive would be the flat-rate service, so your bill today is fixed for the next 20 years and you will not pay more. So, you are signing a contract, getting a flat-rate guarantee, and also increasing the value of *your home by adding equipment like PV and batteries. You are basically investing and paying your investment through your energy bill (Company G).*

The idea is that the company installs a mix of rooftop solar, batteries and household devices (e.g. heat pumps) in homes, together with a VPP control system that manages power flows across this equipment. This investment is paid back by prosumers through flat electricity rates over 20 years.

Company D offers a different model for flat rates for households that are members of their virtual community and use up to 4250 kWh or up to 5500 kWh of electricity, because those energy consumptions fall in the center of the average household energy demand in Germany. As a minimum requirement to get this flat rate, those houses need to have a minimum amount of kW peak PV and battery size installed. More details on the flat rate offered by Company D are in the following quote:

Why do we do this? Because we know from the combination of a certain size of PV system and battery storage system, there will be a certain amount of energy independence. So, you will be able to provide up to 80% of your energy requirements yourself. And we promise to pay the last 20-25% for you. This offer is only available to members of our virtual community and there is no additional cost besides the community membership fee (Company D).

In this model for flat rates, the company promises to cover the expenses of additional energy requirements not met by the local energy resources of prosumers who are members of the company's virtual community. But how does the company manage to cover those costs? This question is addressed in the following quote:

We earn money by helping stabilize the grid and pay for the flat rate offered to community members. There is a problem in many grids that have added renewable energy resources because of fluctuation issues. So at times, there is a lot of energy floating in the power grid and the excess energy has to go somewhere. In the electricity market in Germany, there is a platform where network providers basically pay institutions to take excess energy from the grid in order to stabilize it; it is a network stabilizer mechanism. We aggregate the capacity of community batteries to form a VPP and use software to digitally control and combine those batteries into one big battery. In times when there is excess energy in the grid, we offer our VPP to take this energy *and receive money for it and that is how we finance the flat rate (Company D).*

By aggregating and controlling prosumers' batteries to receive excess energy that is stressing the power grid, Company D generates revenue which is then used to finance prosumers' energy demand that is not covered by their local energy resources (around 20-25% of total household energy demand).

Another financial benefit motivating prosumers to leverage new solutions provided by emerging middle actors is gaining access to electricity markets. Prosumers trading their surplus energy access the electricity market through services such as those provided by Companies L, M, N, O. Prosumers aggregating resources for demand response, on the other hand, benefit from associated returns on joining demand response programs like those enabled by Companies C, E, F, H, and I.

The executive from Company K, which facilitates power export projects for prosumer collectives, believes that members of collectives are incentivized and proud once their export projects start making profits and creating value.

Benefit from Transparency

The benefit of accessing transparent electricity prices and real-time energy use analytics is a strong incentive to prosumers and consumers alike to seek emerging energy demand solutions. Companies like A and B offer dynamic electricity tariffs reflecting wholesale market prices; those tariffs are transparently broken down for customers to understand what they are paying for. Additionally, transparency is also achieved by tools that help customers gain insight into their household energy usage.

As described in the following quote, the customers of Company A benefit from the transparency in detailing electricity bill costs:

Our customers benefit from transparency; we show them the real cost. Our customers get a bill every month, and we do a lovely little wack that breaks up the bill and shows them exactly how much they are paying for generation, transmission and distribution to get the electrons to their door. We also show them the cost of the meter and our charges. There is a lot of benefit that we talk a lot around price signals, so that our customers understand how they are doing, how it is benefitting them over time, and how they can improve if they want to benefit even further (Company A).

In addition to accessing daily energy usage patterns via a mobile application or a desktop dashboard, customers of Company A benefit from data mining for unfamiliar usage patterns, as illustrated below:

> *We also mine for unusual patterns. There has been a number of stories where customers have ended up with big bills and they do not understand why. When you analyze these, you get things like a high load which is absolutely constant, which indicates something like a hot water cylinder that is on all the time (Company A).*

On the other hand, Company D provides transparency to its customers by showing them how much production is happening within the virtual community via an online platform. As elaborated by the company executive below:

> *It is important to have transparency because we understand that the grid is one big energy pool and there is difficulty to follow a certain electron from a producer to a consumer. So we try to improve the situation by allowing people to understand the production patterns in the community (Company D).*

These incentives gained by prosumers as a result of using solutions from interviewed companies are very likely to be relevant to prosumer collectives. Environmental concerns can especially motivate community-initiated prosumer collectives to form and grow. Maximizing self-consumption of energy is a strong drive for prosumers to collectively manage their energy supply and demand, to reduce demand uncertainties and share supply resources among themselves.

Prosumer collectives can also be strongly driven by the financial benefits, e.g. gaining market access, enabled by emerging solutions offered by new middle actors. Aggregating resources (e.g. surplus energy or demand response) can strengthen the market power of prosumers and result in additional monetary benefits for the prosumer collective.

5.6.4 Fairness

When asked about how their solutions are providing fairness, company executives had a number of opinions and ideas around what fairness means for them and their companies, and how it is currently or can be potentially implemented in offerings targeting prosumers.

Provide Transparency

Retailers offering dynamic prices largely believe they deliver fairness to their customers via providing transparent pricing mechanisms that largely reflect wholesale market prices, as opposed to the fixed rates of conventional retailers. Examples include Companies A and B, which break down the structure of their electricity bill to show their customers how costs are distributed on generation, transmission, distribution, tax charges and company charges. This is highlighted by the executive of Company A in the following quote:

> *Our model is actually fair. It is the true cost passing through to the customer. There is no hiding anything. It is completely transparent. Our model is the fairest way we can think of retailing by giving our customers true appreciation of what is happening in the market in any point in time. It gives them real choice and control (Company A).*

Enable Electricity Market Access

For online electricity trading platforms, fairness lies in providing prosumers and collectives with market access to sell their electricity to consumers who have freedom of choice in shopping for their electricity from the sources they desire. The following quote by the executive from Company N sheds light on this:

> *By having a marketplace that is over the top of the spot market and allowing consumers to choose energy generated from prosumers' solar power rather than a retailer, then it is actually giving customers more choice and that is extremely fair (Company N).*

Such marketplaces are especially appealing to prosumers in regulatory environments requiring them to sell surplus energy to retailers, as is the case in Australia, for example. As prosumers sell their electricity directly to consumers at tariffs higher than retailers' buy-back tariffs but typically lower than regulated residential electricity tariffs, they monetize their investment in distributed generation and provide consumers with better rates than conventional retailers.

The executive from Company L, which offers a block-chain based peer-to-peer electricity marketplace in Australia, assumed he is a prosumer to describe his point of view on fairness as follows:

If I am making investment in distributed generation, and I am able to realize the full value of investment via online trading rather than being forced to sell for a cheaper rate to the retailer, then this is absolute fairness in the way prosumers monetize their investment (Company L).

As for providers of battery storage, they see their batteries as a fair alternative to selling surplus energy to the grid at low tariffs. Until 2010 in Germany, prosumers with solar PV received high feed-in tariffs they basically had money-generating rooftops. In 2011, feed-in tariffs dropped below retail electricity tariffs. Thus, selling energy to the grid made less sense, and storage became a better option, as described by the executive of Company D:

The drop in feed-in tariffs was the turning point for storage systems which became more attractive to existing and prospective PV owners, because self-consumption was key to saving money instead of earning money from the feed-in tariff (Company D).

After the drop in feed-in tariffs, self-consumption made more sense to prosumers than selling energy to the grid and losing the value of their investment. Providers of batteries thus see their solutions delivering fairness to prosumers in cases of dropping feed-in tariffs.

Develop Fair Mechanisms

Some companies use specific mechanisms to deploy fairness in their business model and solutions. As an example, Company B, which already provides a transparent electricity pricing structure, implements fairness further through avoiding cross subsidies and paying prosumers fair feed-in tariffs, as elaborated below:

We do not cross subsidize high users with low users and with that respect I think it is very fair. We also try to pay prosumers a fair price for the energy they send back to the grid. I think in that respect, our pricing structure is very fair, too (Company B).

The executive from Company C sees his company providing fairness by helping prosumers use clean energy and reduce their electricity bills, and by providing utilities with tools to help them address bigger questions, as elaborated below:

The storage assets we provide can defer the need for transmission and distribution infrastructure upgrades by alleviating the amount of load that needs *to be served. Utilities can avoid the cost of paying for energy, capacity and equipment to serve peak load that would normally be spread across the base rate. There are a lot of society benefits of DER. We are helping utilities answer the bigger questions like what are the best rate structures to be implemented? What's the fairest business model? How should the utility structure its operations in a way that provides fair access to resources for everyone? (Company C).*

As discussed by this executive, fairness for Company C takes a more holistic view in implementing fairness, where it sees itself as an agent enabling electric utilities address questions about how they can use business models and financial structures to fairly disseminate benefits, prices, and resources to the society.

To expand on this, the same executive also thinks that legalities need to be modified to be fairer and take various technologies into account to create fair and safe markets for prosumer technologies, as mentioned in the following quote:

You have old regulations that served their purpose very well. But there is a system of laws that was developed at a certain time and place, and now those laws have to be modified somewhat to make markets fair and include the different technology capabilities available into account, and make fair rules for participation. There is a lot of information out there, and there is not one way to do things. So it is about creating a path for legal entities to modify their laws to create a fair and safe market for prosumer technologies (Company C).

Additionally, the services provided by Company K deliver fairness to prosumer collectives, by supporting them in creating strong business models to compete with electric utilities and share energy assets with them:

Fairness is the whole reason we are in this business. Why would energy assets be in the hand of 6 big utility companies? It does not make sense. We need to actually distribute these assets and the wealth generated by them (Company K).

An interesting point about fairness was brought up by the executive from Company I who thinks that Company L is being unfair by short-circuiting distribution networks through its peer-to-peer block-chain based trading platform which enables electricity trading within a distribution network. The following quote provides an elaborating on this point:

If you talk about fairness, then I think those people at [Company L] are not really remunerating the distribution network because their idea is that they would not pay for distribution, so I think there is a fairness issue here. I believe you can optimize around the grid, but I believe this whole "let us live without the grid thing" is silly. Honestly, the problems that [Company L] is trying to address are at the macro-level and can be solved with a fair feed-in tariff or a net-metering clause (Company I).

This point around unfairness to distribution networks is additionally pointed out by the executive from Company Q, who thinks that it is unfair for prosumers using solar PV to get discounts from distribution companies, as elaborated below:

Solar PV makes an impact on the local street distribution. If there is so much congestion at the local level, then the network will require upgrading at that street level. At that level, people using solar PV are creating cost on the electricity delivery system. They want to get discount from us, but in reality they should be paying us more (Company Q).

Both quotes highlight the point that fairness is not just about a specific metric or feature to be implemented in this product or that service. It is a bigger issue that needs to be holistically addressed across involved stakeholders, e.g. prosumers, electric utilities, distribution networks, and regulatory bodies.

5.6.5 Flexibility

When asked about how their company solutions enable energy demand flexibility, executives had a number of interpretations for the word "flexibility" – which went beyond demand flexibility which is explained in Section 2.5.2).

All executives affirmed that their company solutions provide flexibility in one way or another. Some companies focus on one aspect of flexibility, e.g. demand flexibility – where prosumers are flexible in changing their demand for energy. Other companies interpret flexibility in a broader sense, e.g. providing flexible market access and trade opportunities for prosumers to sell their surplus electricity at their own rates and times.

Based on the interviews, two main themes have been identified for enabling prosumers to be more flexible: (1) incentivizing flexibility and (2) enabling flexibility. An example of incentivizing flexibility is providing dynamic electricity prices that encourage customers to change their energy demand in return for monetary savings or use their stored energy instead of buying electricity from the power grid. On the other hand, an example of enabling flexibility is offering advanced optimization and control solutions that flexibly coordinate power flows between micro-generation, batteries, and loads in prosumer collectives.

Incentivize Flexibility

Companies A and B are examples of companies that incentivize flexibility by providing pricing mechanisms that leverage dynamic tariffs in New Zealand and Australia, respectively. In the case of Company A, customers are exposed to wholesale electricity market prices, and provided with an online dashboard and a mobile application to monitor forecasted half-hourly prices. Additionally, customers get tips for reducing energy usage, and information about their potential savings compared to their previous flat tariffs and to date with the company.

Providing dynamic tariffs to customers and engaging them using different tools can help them make informed adjustments to be more flexible, e.g. by having their energy-based activities around cheaper hours, or trading their surplus energy to others and using their stored energy during peak hours.

The following quote elaborates on the responsiveness and savings of the customers of Company A:

> *We provide a whole lot of tools to help our customers benchmark themselves and do some behavioural changes that benefit them. Most of our customer lifetime-to-date savings are around 20%, which is way above the 6-7% savings that have always been available by switching between flat-rate retailers. We got some customers that are a little bit beyond 50% of their total bill; they are people who are hosing it. They are really responsive to the price and take advantage of it (Company A).*

While achieving monetary savings is a common and strong incentive for being flexible, executives have pointed out that environmental and social incentives are increasingly motivating people to be flexible. For example, they note that some customers are being flexible by changing their energy usage to coincide with the clean power generated from their solar rooftops, or pay more money to access clean electricity generated from their local school.

Enable Flexibility

As for enabling flexibility, companies have various notions. For several companies (e.g. C, D, F, G, H and I), flexibility is enabled by optimally coordinating the power flows between demand loads, micro-generation and batteries to achieve prosumers' objectives. Other companies, such as L, M, N, and O, empower their prosumers with flexibility by allowing them to trade surplus energy to other customers.

Additionally, demand flexibility can be enabled by providing appropriate engagement tools and services for customers, as is the case for Company J, which offers applications for household energy disaggregation and demand response management.

As shown, customer engagement is a common factor found in interviewees' views on both incentivizing and enabling flexibility, e.g. the various tools provided by Companies A and J, respectively. Having more engaged customers creates opportunities around integrating flexibility in their energy behaviours and practices. The next section is dedicated to customer choice and engagement.

5.6.6 Customer Choice and Engagement

Although there was no direct interview question around customer choice and engagement, a strong thread of engaging customers and giving them more choice was induced especially from discussions about incentives, flexibility and fairness.

An example of a company that directly engages its customers through providing them with more choice is Company A. In the mobile app of this company, one of the tabs is called "Choice". The company empowers its customers with more choice by giving them real-time updates on their dynamic electricity prices, forecast price dips and spikes, and carbon emissions associated with the electricity they use. Additionally, the company provides its customers with data on their energy consumption patterns and forecast bill. The following quote illustrates how dynamic price updates give customers more choice:

> *Through transparent electricity prices, customers get a sense of the price signals and different prices at different times of the day. We provide our customers with smart digital tools that allow them to have a choice. You may choose to use the heater to heat your home no matter what the price is, but you might choose a different price for using your dishwasher and your washing machine. That smart digital platform is delivered on a web app and a mobile app (Company A).*

In other cases, a company enables top actors, e.g. electric utilities and retailers, with customer engagement tools. An example is Company J, which develops tools to monitor the usage of household appliances, and forecast electricity bills to alert customers to make changes to their energy activities if needed. The following quote elaborates how Company J engages residential customers to support them in making informed decisions around their energy use:

> *We provide a number of things. We provide an application that runs on a suite of media. So we provide mobile apps for customers to monitor their energy consumption at home by appliance. We give them a bullseye projection so they know during the month if their bill is likely to be much higher than normal so they can make some energy changes before the end of the month to bring it back into line. We give them neighbourhood comparisons, not only for their total energy usage but also energy usage by appliance measured. We would let them know for example if they are using 50% more air conditioning compared to a group of people living in similar sized homes, similar number of occupants, and a similar climatic area. We also engage with customers through emails, SMS, and letters (Company J).*

Company tools give additional insights to customers by comparing their total household and appliance-level energy usage against similar sized households with a similar number of occupants and climatic area. The company does not only rely on mobile applications, but also uses different channels to engage with customers, e.g. emails, SMS and letters.

On the other hand, the executive from Company P highlighted that while it makes sense to give customers more choice and control, it is important to consider the level of control. As an example, the executive said that customers should not have to worry about something like water heating by connecting or switching away the PV arrays connected to the heater, and that they are unlikely to want that level of control.

This point was additionally emphasized by the executive from Company A, who said that customers do not have to keep tracking half-hourly electricity prices to make more informed decisions and save on their bills. As elaborated further, while 50% of their customers do not engage heavily in price signals, they at least broadly know what they prices might look like. Having information tools allows different levels and engagement and more informed decisions, as highlighted in the quote below:

> *Customers got very good information tools that allow them to engage at*

different levels. You can watch it on your phone or your iPad; you can set alerts. You do not have to keep an eye on what the prices are doing every half an hour. They get a sense of what they are doing. A whole lot of tools that help them benchmark and if they need to do some behavioural changes that benefit them (Company A).

Not needing to track half-hourly prices was also brought up by the executive from Company O. This executive emphasized that their platform allows prosumers to choose how much energy they want to sell and when, and gives them price options to choose from instead of having them monitor half-hourly prices and working out what price they should sell their energy at. After discussing a range of products and services provided by new middle actors to emerging prosumer households and communities, the next section sheds light on an important matter, which is the customer feedback those middle actors receive about their solutions.

5.6.7 Customer Feedback

One of the questions posed to interviewees was on the feedback their companies get from customers. In this context, customers include both bottom actors (e.g. prosumers) and top actors (e.g. electric utilities) using their solutions. Both positive and negative feedbacks were discussed, as presented in this section.

Positive Feedback

A common feedback received by companies offering dynamic retailing and online electricity trading was that their customers (i.e. prosumers and consumers) felt highly engaged, as illustrated by the following quotes:

They really like what we are doing. They are engaging. Our solutions may appeal just to the geeks and greenies, but we are moving mainstream month by month in terms of the profiles of our customers. We do know that a lot of them are already engaged, they really like it, and they are asking for new things and making suggestions on product enhancement. They are not only engaged with the product we have done so far, but they started to think about things we should do next (Company A).

We have got really great engagement from the communities that we have dealt with. They are quite blown away that there is a potential for a local *marketplace in the same way that some of us go to a local farmers market. You could essentially have a local market for energy (Company O).*

As customers become engaged with appealing products and associated services that add value to the way they manage their energy supply and demand, they become keen on sharing their time and feedback to improve current solutions and suggest new ones.

Enjoying good user experience is another positive feedback some companies have received from their customers (i.e. prosumers and consumers). The executive from Company B says that feedback received via the company website indicates that customers are highly impressed with its service and support team which helps them through their journey with the company.

In addition, the executive from Company A stated that he is proud that the company topped customer satisfaction in its first year, 2015, with 96% which is reported to be the highest in the industry based on a yearly customer survey undertaken by a trusted and independent entity in New Zealand.

Some companies have been praised by customers (mainly businesses) for making complex solutions seem easy. As highlighted by the executive from Company H, customers like their simple solutions, which stem from the company's design philosophy of simplifying the complexities of combinations of loads, batteries and solar PV. Similarly, Company I receives positive feedback from customers (i.e. businesses) impressed with the company's cloud-based compatible software and its fast deployment time in the field.

Other companies have received positive feedback around their ability to enable prosumers to be independent but able to share their energy, as elaborated in the following quotes:

Customers appreciate that their investment is covered by the energy bill, and that they can be autonomous from the network and able to co-finance their independence (Company G).

People love the idea of the community; they really favour sharing their excess energy rather than selling it to the grid (Company D).

Customers love the idea of being able to take control about owning the extra capacity. We find a lot of prosumers excited about the concept of sharing their energy. One may say "my mom is living down the road, with her pension, she cannot afford to pay for PV, so Id like to gift her my energy *just to help her out". It is the whole idea of the sharing economy (Company L).*

Negative Feedback

The main negative criticism brought up during discussions about customer feedback was that some products, e.g. batteries and associated VPP control systems, remain relatively expensive. Based on the views of a couple of executives from Companies C and P, such premium prices are the result of building high-end technologies to high standards.

5.7 Future Insights

This section presents the future insights in this space, which include executives' thoughts on evolving company solutions, the futures of energy demand management and residential prosumer collectives, and the challenges ahead.

5.7.1 Evolve Current Solutions

Interviewed executives generally agreed that their companies are working hard and smart to stay relevant, especially in the micro-generation and battery storage space which is growing rapidly, by improving current offerings and developing innovative ones. This is highlighted by the executive from Company I in the following quote:

> *I think it is about catching the wave that is coming. There are lots of ongoing discussions on the distributed energy front and storage aggregation. It is a binary thing, either you are in or out. We are trying our best to become relevant in that space, and be the solution of choice for utilities and energy service providers. It is a very liquid market, so it is important to get these accounts early (Company I).*

In such a competitive and rapidly growing market, it is crucial for middle actors to acquire key customer accounts, whether prosumers and their collectives or top actors, by continuously evolving their solutions to fit customer needs. Two trends have been identified in evolving current company solutions, as presented below.

Evolve Vertically

To stay up to date and maintain customer satisfaction, companies tend to evolve vertically by integrating new features to their solutions, and enhancing the performance of its existing technologies and platforms. This works to ensure that offered products and services accommodate more customer choice and provide seamless user experience.

Company I, for example, is growing its current solution portfolio vertically at no additional costs to customers by constantly adding new features to its software applications, and improving its forecasting algorithms. Additionally, as solar and wind power is being deployed more aggressively around the grid, the company is looking at making its flexibility management offerings more customizable to better cater for those intermittent energy resources. Furthermore, the company is looking at improving its user interface to make it more visual and intuitive.

Another example is Company C, which is integrating more flexibility around its different inverter and battery options to better accommodate customer needs, and adding more intelligence to its solutions to enable running different grid services across hundreds of thousands of DER.

Providing real-time data analysis is another example of vertical enhancement that some companies are investigating, as the case with Companies E and J. The executive from Company J elaborates that as smart meters deliver more granular data, deploying real-time analytics in their existing solutions becomes essential to better predict household usage for end-users:

> *I think the biggest improvement is going to come from smart meters getting smarter. Right now in New Zealand and Victoria in Australia, data is delivered to the retailer every 30 minutes, but they only get the data a day late! So there is a real-time issue that the end-user can only see what they did today tomorrow, with a granularity of 30 minutes. So as the data gets delivered faster and faster, the biggest improvement will come from seeing a lot more appliances in real-time. Our prediction of household appliance usage varies given the granularity of the data (Company J).*

Evolve Horizontally

Leveraging new technologies, diversifying their offerings and spreading geographically to new markets enable companies to evolve horizontally. Examples include Company M, which has extended its market in 2016 to Poland, Netherlands and Belgium, and

Company D, which is looking at globally expanding its virtual community and using block-chain technology to revolutionize its energy exchange transactions.

Additionally, due to policy changes that impacted the progress of several community energy projects in the UK, Company K had to diversify its services to become active in international fronts, by becoming involved in a number of solar PV projects in India, Brazil, and Chile. On the other hand, Company D is diversifying its offerings beyond batteries and moving more broadly towards providing smart home solutions:

> *We are becoming less of a battery storage solution provider, and more of a smart home appliance provider. We are diversifying very quickly away from the battery. It is still in the center, but it gets supplemented by all these smart home products and services (Company D).*

The company sees value in broadening the range of its solutions beyond battery-focused products and moving towards smart connected appliances for households, e.g. smart heaters, smart plugs, heating rods.

Having presented executives' thoughts on how their companies are progressing their products and services, their views on the future of energy demand management and prosumer collectives are elaborated in the next two sections.

5.7.2 Future of Energy Demand Management

Interview discussions around the future of energy demand management put forward various predictions. This section presents the main future trends they suggested regarding energy demand management.

From Demand Response to Flexibility Management

One of the strongest future trends anticipated for energy demand management is the transition from conventional behavioural demand response programs towards the broader concept of automated flexibility management of DER. This transition serves the growing need to automate and optimize complex power flows between supply and demand points especially in light of the increased penetration of DER.

Today, behavioural demand response is regarded as the cheapest and most efficient practice where residential customers are sent notifications to reduce their energy use during peak demand hours. However, with the rise in device connectivity, flexibility management is gaining ground. This is elaborated by the executive from Company I as follows:

I think that today probably what makes more sense is these behavioural programs; they are the cheapest and most efficient thing you can probably do. Now as appliances are gaining connectivity, it becomes very easy for people to register those devices on flexibility programs. And the more connectivity on the appliance front, the more software solutions that are going to be used by energy service providers to aggregate that flexibility (Company I).

In addition to increased connectivity, the emergence of prosumers further underpins the necessity to move away from demand response towards managing DER, as highlighted by the executive from Company F as follows:

The big shift in general is the move away from demand management and response, and more towards distributed energy resource management (Company F).

Furthermore, the automated side of flexibility management has been elaborated in the following quote by the executive from Company C:

As we move forward, the ideal for demand response is to have some sort of combination of automated and behavioural changes. So, on the automated side, we are feeding the customer loads with stored energy from the battery during a demand response event. That happens behind the scenes without the customer input because their electricity needs are still being met; it is just that they are not being met by the grid but by the battery. Today, we are taking an automated approach where the customers do not have to do anything and they do not really notice any difference from a comfort perspective because the battery is still providing them with what they need while meeting the utility needs as well (Company C).

In automating flexibility management, it is important to maintain end-users' comfort levels and cause minimal disruption to their energy activities; ideally, they should not notice a difference.

From Capacity Provision to Power Quality

Another future trend going hand in hand with the move from behavioural demand response towards flexibility management is moving the focus away from capacity provision and more towards power quality. Behavioural demand response basically frees capacity, and providing capacity has been a main concern for demand response activities. However, as the focus shifts towards flexibly managing DER, power quality will become a bigger concern for utilities and network operators, as the executive from Company F anticipates:

> *It will not be about having one large customer at the end of the distribution feeder, but about having and dealing with 400 small customers on the feeder. It will be about power quality rather than capacity. People will no longer say "I need to shave 1 MW off my peak". It will be more like "I need to shave 1 MW off my peak and coordinate these solar inverters and batteries in order to deal with frequency issues here and voltage issues there".*

As DER increasingly penetrate the power grid, power quality issues arise, mainly due to voltage fluctuations caused by power surges (e.g. switching on/off of equipment, circuit overload).

From Centralized to Decentralized Power Grids

Another trend that is currently present but expected to grow further is the shift from centralized towards decentralized grid architectures and resources, which is largely due to the emergence of distributed energy technologies, as described by the executive from Company O in the following quote:

> *Our electric grid is going back to the way that someone like Thomas Edison first thought of local distribution networks where supply and control are at a much more local level. In the 20th Century, when we wanted to get electricity to everyone around the country, the sensible thing to do was to build national grids. It was a wise investment. But the technologies that have arrived mean that we are going to see that shift back to much more local grids. The national grid itself will become much more of a big battery, or a big backup for the local networks (Company O).*

Additionally, the executive from Company D emphasizes the decentralization trend of the power grid, saying that it costs less for the society:

> *I believe it will be further decentralized, because the cost for the society is less than centralized systems (Company D).*

The executive from Company A sees two schools of thought around the future of power grids: one that is centrally managed and coordinated and another which is distributed and in the hands of the customers. He thinks that the latter model will prevail.

A few executives think grid connections will become obsolete at some point and off-grid systems will emerge. Nevertheless, most executives dismiss this idea and believe that existing power grid connections will stay relevant but top electricity actors (e.g. electric utilities and retailers) will experience major disruptions so as to accommodate emergent prosumers.

5.7.3 Future of Residential Prosumer Collectives

This section presents the main themes highlighting the future of residential prosumer collectives, as predicted by the interviewed executives.

More than Energy

While discussing prosumer collectives of the future, executives tended to look at the big picture of how different elements of urban areas will eventually fit together, and not just focus on groups of prosumer dwellings. This is illustrated in the following quotes by the executives from Companies E and C, respectively.

> *It is not just about homes. It is about transportation, public buildings, and schools. It is about doing things in a new way. People are working together because they are realizing they can share their rooftop PV panels, or use EV and e-bikes. That is where the social side is developing. The social communities want this way of life (Company E).*

> *The future of prosumer communities depends on a lot of things. It depends a lot on the future of dwellings and housing, where prosumers and consumers will be living, and what type of geography they will be dealing with. Are we dealing with apartment buildings or remote housing communities and things of that nature? (Company C)*

Those executives think that the future of residential prosumer communities will depend on a number of factors that need to be considered altogether, including energy, housing options, transportation, geographies. Additionally, they see social communities embracing a new lifestyle where they can use energy resources in new ways. It is more than just energy; it is a mixture of energy, buildings, transport, community action, etc.

Smarter and More Real-time Technologies

Executives see residential prosumer collectives of the future as a lot smarter and with additional real-time capabilities and resiliency. The following quotes from the executive from Companies E and L, respectively, illustrate such views:

> *The future is going to go into near or real-time. The metering using internet of things (IoT) is now possible to make real-time response, but we have to get the cost drivers and all the signals in place to make that doable and a lot of that has to be automated. That is where you are going to need a lot of smart. I do not call them home energy management systems because they are more than that; they are home integration systems integrating homes together into communities onto one sub-station and making sure it is integrated for flexibility to different markets. The technology for all this exists but we just need to make commercial sense out of it (Company E).*

> *Those collectives will become more resilient to the impacts of weather and climate change. The technology and distribution networks allow for such dynamism to be optimized in an automated kind of way (Company L).*

Executives believe that having more real-time and smarter features in residential prosumer collectives is necessary and doable, but needs efforts to bring the different pieces together and make commercial sense out of it. Prosumer collectives in the future are expected to be resilient to weather hazards and climate change impacts, and comprise communities that integrate homes together which then connect to markets.

More Battery Storage

Executives think that battery storage will gain even more interest and growth in future prosumer collectives, especially as their prices are expected to drop and their efficiencies improve. The following executive from Company J sees batteries as vital to both prosumers and distribution companies:

> *As battery storage prices come down, you'll see many more prosumers wanting them; but also distribution companies that are seeing all sorts of problems arising with more renewables coming online because they have to balance having intermittent renewable energy resources (Company J).*

As elaborated by this executive, batteries help mitigate the impacts of intermittent renewable power by storing energy for use at later times, which can help flatten residential evening peaks. Not only prosumers, but also distribution companies are becoming increasingly interested in using battery storage.

EVs are also considered as grid-connected batteries, and the anticipated growing interest in driving and sharing EVs has been highlighted by some executives, such as that from Company E as elaborated in the following quote:

> *I think all of the intelligence is going to be around EV and EV charging. That is a lifestyle rather than energy management. Your EV is going to be your energy asset because that can fuel your house at night and keep the lights on through high demand periods. We want cars to go electric or semi-electric, and see how car shares will cut emissions. We want to understand how prosumer collectives are building charging stations, solar panels, and hydro and all that within their communities (Company E).*

This executive was very enthusiastic towards EV and even talked about his own EV and how he tracks its charging in real-time on his phone. From his point of view, EVs are energy assets that are driven by lifestyle changes rather than energy management activities. He supports EVs and car sharing, and is interested to see how future prosumer collectives will integrate their various energy assets within their communities.

Prosumers Becoming Paid Nodes

In the future, some executives see prosumers as nodes that are paid by distribution companies for their location on the grid, as prosumer energy assets (e.g. batteries) can help smooth evening peaks in residential areas and mitigate the intermittency of certain resources (e.g. solar PV). The following two quotes from the executives from Companies F and J illustrate this theme:

> *Individuals play a part in this by having a node at the end of a network which is being paid for or funded by somebody else who can benefit from it. Battery and solar providers knock on your door and say hi, I can fix some solar panels and batteries and you will not have to pay for power delivery again, are you OK with that? In the meantime, they are monetizing the assets behind the meter while satisfying your requirements. So it will be more about buying your location and existence on the grid (Company F).*

I have been talking to one of the main distribution companies in Auckland and there is a lot of interest there; they are helping sponsor people putting battery storage in so they can make use of that during evening peaks, when people get back home, so they can use battery storage to smooth out those peaks every day during those critical times (Company J).

Those executives see that prosumers can benefit from their location on the grid by receiving money from top electricity actors (e.g. distribution companies) in return for integrating batteries or solar panels, which can help in regulating power flows around the grid during peak hours or power surges.

A Big Dynamic Prosumer Community

Overall, the future of residential prosumer collectives is expected to be highly dynamic in various ways, as stated by some executives. In the following quote, the executive from Company L believes that prosumer collectives will connect together more dynamically to form larger communities, and that their operations will become non-linear and more active and will be optimally managed in an automated manner:

Residential prosumer collectives will become smaller and more dynamically connected to larger communities and larger sections of the network. Distribution networks allow for dynamism to be optimized in an automated kind of way, so the system will become far less linear and more dynamic in the way it operates (Company L).

This executive sees prosumer collectives becoming smaller but connecting to larger sections of the network to form bigger communities in a dynamic way. This point is further highlighted by the executive from Company N as follows:

I see prosumer collectives emerging in more of a long term as one big prosumer community rather than pockets of closed communities. It is like what happened with the internet, which started with a small local academic network and now we have a fully connected community rather than remaining as pockets (Company N).

There is an analogy in what this executive sees happening to collectives with how the internet evolved from a small local network into a big community that connects everyone.

Another executive sees dynamic changes in the regulatory frameworks of future prosumer collectives especially with the evolution of related regulations around phasing out fossil-fuel based power generation, and increasing renewables, and developing behind-the-meter micro-generation technologies.

The Rise of Virtual Communities

While virtual prosumer communities are already a reality, e.g. those developed by Companies D and G, they are expected to grow in the future. Virtual communities connect prosumers and consumers, who might not be geographically co-located, together to trade energy and engage around electricity as described below by the executive from Company N:

> *By having the data we have and running a matching engine for trade, we build leader boards and a virtual community of like-minded people who are engaged on something that is mundane like electricity (Company N).*

For an ordinary topic like electricity, having virtual communities encourages individuals to share their common interests in trading their surplus energy and discuss electricity related topics. The executive from Company G thinks that the future will comprise both physical and virtual communities to offer more energy independence to end-users, as denoted in the quote below:

> *The future would be virtual and local communities that will offer more energy independence. In Germany, there are 800 communities that are managing energy, so we are going to go into an evolution with those guys who want to be independent and be more in control (Company G).*

The executive also thinks that the same principles can be applied to both physical and virtual communities, as follows:

> *The virtual community we are developing is Germany wide and is a virtual community; the same principles can be applied to more geographically located or limited communities (Company G).*

This is further emphasized by the executive from Company H whose company provides a platform that can enable power flow optimization in both physical and virtual communities. However, this executive currently sees constraints in Australia which may hinder the development of virtual communities and how they knit their virtual groups and provide energy trading, virtual net metering, or virtual power purchase agreements.

On the other hand, the executive from Company O sees trading, whether in virtual or physical communities, as nevertheless a virtual connection, as elaborated below:

> *This is a virtual connection. You cannot guarantee that a kilowatt generated goes to a specific person; it is not a DHL package. Essentially, it is matching generated capacity with consumed capacity. Actually, we have banned the use of peer-to-peer within our company because you cannot actually peer-to-peer kilowatts in a physical sense, so we tend to think of it as a decentralized marketplace (Company O).*

Because the path a specific amount of power takes based on trading transactions cannot be guaranteed, this executive thinks that trading generally is a virtual connection irrelevant of how the community is.

5.7.4 Future Challenges

Despite the increasing interest in and the growth of residential prosumer collectives, a number of challenges face those collectives and associated stakeholders, e.g. electricity retailers, distribution companies, and solution providers. This section details those challenges.

Understanding the Big Picture

When asked about the challenges facing collectives of residential prosumers, a number of executives mentioned that one of the biggest challenges is the lack of a holistic understanding needed to put together the different pieces comprising collective prosumerism. This is elaborated by the executive from Company E as follows:

> *It is hard to put together. No one fully understands how to do it. The big picture in New Zealand is "lifestyle", how all this can come together. If you do all this, you will have minimum emissions and the security of supply and minimum costs as well (Company E).*

This executive sees it as hard to put together the different pieces of prosumer collectives and realizes a lack of a full understanding around this matter. This challenge is further emphasized by the executive from Company N, who sees a need for more collaboration between the different involved parties to achieve their shared vision:

I think the biggest challenge will be getting different parts of the industry to work together when they all have different incentives. There is probably a lot of different parties with a similar vision about the future and that probably needs to have more collaboration. Getting people to work together is the biggest challenge (Company N).

As the executive from Company O thinks, the lack of holistic understanding and integrated collaboration is due to the resistance to change exercised by some electricity sector stakeholders. He thinks that those stakeholders should be brought around to the idea that they need to change and adapt to the rapid emergence of prosumerism. This need for having collaborating stakeholders is further emphasized by the executive from Company C, as follows:

We are still not seeing this on a large scale, not because technology does not exist but because a number of different stakeholders including utilities and regulators have to come together to understand what the capabilities of the technology are, how to use it, and how to make it standard across multiple types of solutions and competing solution providers (Company C).

The challenge to develop this inclusive grasp of the various components of residential prosumer collectives is further emphasized by the executive from Company P, as quoted below:

Many people do not understand how the many different pieces of the power system need to be put together to work. We have never had this situation before. But, now we are starting to get emerging distributed generation from household to household, and we need to make sure people have reliable electricity. If the internet goes down, a few people get really upset. But when electricity goes down, it is a completely different story (Company P).

It is a steep but necessary learning curve for prosumerism stakeholders to collaboratively develop a holistic understanding of the various components needed to well establish residential prosumer collectives. As indicated in the previous quote, electricity outages are critical, so it is important to properly manage the new situation where emerging distributed generation resources are added to households.

If we look from the perspective of energy storage, cooperation between prosumerism stakeholders is a challenge, as electricity cannot be stored in large amounts easily. This is elaborated in the following quote by the executive from Company Q:

Cooperation between different parties is a challenge. Electricity cannot be stored easily. If you have a big enough battery, you would not need a network, would you?! In reality, you cannot really store enough to meet everyone's load at peak time and seasonally because you use more in winter, while a technology like solar PV provides more in summer. Because you have got this storage problem, coordination is the hard part (Company Q).

Developing Scalable Business Models

Another challenge that stood out during interview discussions was that of developing business models to scale residential prosumer collectives beyond sporadic communities and pilot projects. As one of the executives described it:

I think the biggest missing part is the right business model that gives everybody the right incentive to make it happen. The technology is there, the will is there, maybe economics are not quite there in some cases. But there is no clear business model to get all parties to collaborate (Company N).

As pointed out in the previous challenge around the lack of a holistic understanding, various stakeholders need to collaborate in developing the growth of collective prosumerism for households. However, some executives do not see a clear business model yet that governs such collaborations, as previously quoted by the executive from Company N, and further emphasized by that of Company F:

The reality is that the economics at the moment are heavily weighted towards larger producers and consumers. That is because the cost of automating a kW is much cheaper when you do it at the large scale than a small scale. There is no reason why it should not be 3 times the volume it is now. It has to speed up enormously. We need to go there quicker. We see that shift; it gets cheaper all the time. But we have not seen a standalone residential business case which stacked up yet (Company F).

This executive thinks that the volumes at which residential prosumers aggregate need to scale up rapidly to build a strong business case for residential prosumer collectives. He further contrasts commercial and industrial prosumers versus residential ones, as follows:

The household is much more expensive and risky to engage with because you need to explain what it is, convince them, sign a legal agreement, install *kits, and then you get the biggest battery system of 10 kWh. Whereas with commercial and industrial prosumers, they know what they are doing and motivated by the economics. It is almost as expensive to install and you have got 250 kWh. You can aggregate 6 and get 1.5 MW instead of aggregating 150 small systems. A kW is a kW; it does not matter where it is coming from. From a cloud automation perspective, whether it is a mega or a kilo, you move the decimal place; it makes zero difference. What matters is the economics. It is not to say people will not do very good at it but retailers should (Company F).*

Residential prosumer collectives remain small-scale in contrast with commercial and industrial prosumers which aggregate at much bigger scales. With respect to software and automation, controlling a kW or a MW makes no difference. However, from an economic point of view, the stronger business model tilts towards serving large-scale prosumers rather than residential ones. In addition to the issue around lack of scale, one executive pointed out a limitation around residential loads, as follows:

We enable plug and play connectivity and control with solar inverters and battery systems, and then add loads. But the main limitation is that there are not many loads to control in residential settings at the moment (Company H).

While distributed energy resources and electric appliances can be modularly added to households as negative and positive loads, respectively, they remain limited. This limitation in controllable loads thus plays a role in encumbering the development of a viable and scalable business case for residential prosumer collectives.

Furthermore, the executive from Company H thinks that allocating network charges in virtual net metering or local energy trading is a problem which affects developing an economic business model for prosumers, as elaborated in the following quote:

One would expect that local energy traders would pay lower network charges because they are a small part of the network. But at the moment, the rules do not clarify how one can calculate that local component, and it is left to negotiation with the networks which will not negotiate. There are rule changes currently in play, which would hope to make network changes at a local level more transparent, and that will open the door for at least more economic models (Company H).

Transparent allocation of network charges is thus another component to be carefully studied in the challenging process of building strong and economic business models for residential prosumer collectives, especially those with local trading platforms.

Enabling Adequate Regulations

The issue around regulations supporting electricity pricing and market participation has been highlighted as another challenge facing residential prosumer collectives. Several executives think that current regulatory frameworks are inadequate for fairly accommodating large numbers of prosumers beyond pilot projects, and see a need for fairer and more organized regulations to enforce market transformation for prosumers.

The executive from Company C believes it is important to implement a dynamic rate for residential customers on a large scale as opposed to a pilot program, and have laws that enable aggregated distributed energy resources to participate in an organized market. The executive adds an elaboration in the case of the United States, as an advanced economy, as follows:

> *In the United States, what you have is old regulations that served their purpose very well. But that is a system of laws that was developed at a certain place and now they have to be modified somewhat to fair markets and rules for participation, and include the different technology capabilities available into law. I think this is a big challenge. There is a lot of information out there and there is not one way to do things, so it is about creating a path for legal entities to modify their laws to create a fair and safe market for prosumer technologies (Company C).*

It is challenging yet crucial to transform current regulations such that fair rules govern market participation and different technology capabilities for prosumers, especially in a developed country like the US. On the other hand, this executive thinks that the challenge is different for developing countries, where arguments exist about the centralized utilities that do not serve electricity to end-users. He thinks that opportunities in developing countries do not revolve around changing the existing grid, but rather around how to create a paradigm of electricity and power access that has never been available.

The challenge around advancing regulations to support prosumers is further highlighted by the executive from Company A in the following quote:

I think regulation is naturally going to have to change to support innovation and choice for customers. Arguably, there is an element of regulation right now that restricts the viability of prosumers and community groups. That is going to have to evolve and change (Company A).

The lack of adequate regulations supporting prosumerism is challenging, as it restricts the feasibility of individual and collective prosumers. It further restricts new value streams in the form of products and services from reaching prosumers, as elaborated by the executives from Companies B and D in the following quote:

I think the main barrier is the regulatory framework, which is not set up to provide value streams to prosumers for the assets they install in their houses to manage their load, produce or store electricity, or move load around in time and those sort of things. Once a regulatory framework is set up, and this indeed will happen, then some of the barriers will start to fall away (Company B).

Legislation is the challenge! The technology and innovation are faster than the response of the political realm. I know a lot of energy startups in Berlin that have great energy services which cannot be offered today because the regulations do not allow such services. In our case, we are pushing products and services that cannot be applied in some cases due to limitations in regulations. But we have expectations, in terms of weeks or months, after which we can expect to see changes in regulations (Company D).

It is thus important to update existing regulations or develop new regulations that take prosumers into account, especially with respect to their assets, market participation, and technology solutions. To add to the conversation, the executive from Company K also believes that the main challenge facing this field is policy:

It is a policy question above all. You need a government which accepts that we must experiment, because we are at a point where to create new things you have to give them some breathing space and some financial resources to be able to try at something new that cannot on its own emerge in a market setting. They need some buffer time (Company K).

The executive elaborates, saying that governments and politicians need to lift bottom-up efforts of prosumer collectives and provide them with time and resources to encourage broader engagement:

But most politicians do not think that way. And in a setting like that, you will simply refer to very centralized large-scale generation and there will be a limited engagement of citizens in energy generation and management in general. People love the community energy idea, but they just do not know how to make it happen and it is a policy matter. You compare different countries with different levels of civic engagement in energy generation, e.g. compare Denmark or the UK to New Zealand, and you will see that it is all about top down reaching down to bottom up, listening to them and giving them time and resources for broader engagement in this type of activity (Company K).

Regulations and policies governing the setup and development of prosumer collectives present a challenge to the emergence of such collectives; they can either boost growth, or postpone and in some cases completely hinder future expansions. For prosumer collectives to grow, they thus need to be supported by a set of policy tools that provide appropriate incentives, market access, technology solutions, and engagement to involved stakeholders.

Creating Flexibility

One of the challenges brought forward by interviewed executives was the challenge of enabling flexibility. The executive from Company M describes this challenge as follows:

We think that flexibility is the greatest challenge and the biggest asset in the new electricity market of the future. We really focus to protect flexibility potentials (Company M).

For the executive from Company N, they wish to have customers think about flexibility, as elaborated in the following quote:

We have a long-term view to get customers to think about flexibility and make decisions that will benefit them. First, we got to get them engaged. We are phase one of how to build products that get people to care about when they use electricity (Company N).

Managing Social Risks

Some executives pointed out the social risks that may challenge the growth of prosumer collectives. The executive from Company H sees a challenge in dealing with marginalized end-users who are unable to create strong prosumer collectives, as follows:

We need to be mindful of the social risks that marginalize those who are unable to provide more powerful groupings of prosumers. For example, on the coast in Australia, we would find the cost of rural electrification, especially in remote communities, much more expensive. We would find a shift in people's expectations because as you go more decentralized people expect that it is more user pays. But how do we make sure people that have trouble paying can still pay? (Company H).

The same executive adds another factor which may trigger social risks – cross-subsidies, as follows:

People forget that rural electrification got subsidized by urban networks, and if we start having micro-grids and reduce network charges coming from those groups, then we may have social and economic issues emerging (Company H).

The executive is concerned about those who are less well off, and thinks such cross-subsidies may result in social and economic issues.

This is additionally emphasized by the executive from Company Q, who believes that better cost-reflective electricity pricing provided to residential prosumers may cause a real problem because some individuals who have no interest in prosumer technologies and are less likely to afford it may end up paying more. The following quote elaborates this point further:

The real problem is that some of those customers that will pay more are the less likely to afford to pay more. Customers with the cheapest appliances tend to have the worst load factor and the biggest impact on our costs. You can go and buy 2 kW heaters for $13.9 each, plug in three of them, and you will use a lot more power at our peak than you would if you had a $5000 heat pump. Customers who have low capital cost heating, or those who are in rental properties with poor insulation, no double glazing, and no flexibility around work hours some of those customers will automatically end up paying more if we introduce cost-reflective pricing trying to help the rich guy with his solar (Company Q).

If electricity prices are made more cost-reflective in order to provide alternatives to electricity customers to become prosumers, this may cause repercussions where those who cannot afford higher electricity prices may end up paying more.

5.8 Summary

This chapter addressed the third research question in this thesis, which focused on how middle actors are shaping new solutions for residential prosumer collectives and what implications this poses for dynamic demand response practices. This research question helps address the overarching question posed by this thesis, around how smart grid opportunities can be used to provide dynamic demand response for residential prosumer collectives.

The work presented in this chapter comprises the social stream of this research, for which data was collected via semi-structured interviews with executives in businesses providing current or potential solutions enabling dynamic demand response. Interview findings showed that a growing body of new businesses is developing a range of prosumer-oriented solutions targeting individual prosumers as well as collectives.

Based on literature and further underpinned by interview findings, top actors (e.g. network operators, distribution companies) are often not taking a proactive role in catering for the growing needs of prosumers and collectives. This gap resulted in the emergence of middle actors, which work with top actors and directly with bottom actors to overcome barriers and enable new solutions to meet the needs of prosumerism and collectivism.

Interview findings have shown that many new businesses focus on providing solutions that (1) maximize energy self-consumption for prosumers and collectives, (2) maintain grid reliability, (3) create value from smart meter data, and (4) enable flexibility management.

Middle actors are adopting new business models to introduce advanced products and services to residential prosumers. Most of the interviewed companies use a business-to-business model, where they directly serve top actors, which in turn serve prosumers. A few of the companies though follow a business-to-customer model, where they directly serve prosumers and consumers.

Middle actors adopt several principles based on which they align their business priorities and strategies, including meeting reliability and safety standards, integrating transparency with customers and within business processes, adopting sustainability practices, being community-centric, adopting innovation, and attaining profitability.

Based on the interviews, solutions provided by middle actors are largely software-based, which reflects increased flexibility, scalability, and ease of deployment in terms of serving the changing needs of prosumers. Middle actors are providing solutions in four main areas: (1) virtual power plant, (2) automated demand response, (3) dynamic electricity pricing, and (4) online electricity trading. As for how the companies are evolving their current solutions, two trends have been identified: (1) evolving vertically (e.g. by integrating new features and enhancing solution performance), and (2) evolving horizontally (e.g. by leveraging new technologies, diversifying offerings, and spreading to new geographies).

Interview findings have demonstrated that smart grid offerings provided by middle actors provide prosumers and collectives with several benefits, including becoming green, maximizing self-consumption of energy, gaining financial benefits, and benefitting from transparency.

Regarding fairness, executives see it as a topic that needs to be addressed holistically, not just through a specific feature in offerings, where their products are providing fairness through offering transparency to prosumers, enabling them to access electricity markets, and developing fair pricing and legislation mechanisms. As for flexibility, company executives interpreted the word in different ways, where businesses either incentivize flexibility or enable it.

Based on the interviews, there was a strong trend around company efforts to engage customers and provide them with more choices. Some companies directly engage with their customers by offering them additional analytics that improve their decision-making, while other companies enable top actors with customer engagement tools to boost the added value they provide to customers.

Interviewed executives forecast that the future of energy demand management will move from demand response to flexibility management, from capacity provision to power quality, and from centralized to decentralized power grids.

Future residential prosumer collectives are forecast to be affected by a number of factors, including energy resources, housing options, geographies, transport, and community actions. In general, executives agreed that adopting prosumerism in residential collectives is not just about managing energy; it is about embracing a new lifestyle and dealing with energy in new ways.

Future collectives are expected to integrate smarter and more real-time technologies, and more battery storage, and prosumers are expected to become paid nodes where they benefit from their location on the grid by receiving incentives in return for integrating distributed energy resources that help regulate power flows during peak hours or power surges.

A few executives see future residential prosumer collectives connecting to larger sections of the network to eventually form one big prosumer community, while other executives expect virtual communities, which virtually connect prosumers and consumers that are not geographically co-located, to grow. A future where both physical and virtual communities co-exist has been also forecast.

Executives expect future challenges around gaining a holistic understanding of how prosumer collectives in residential areas function, and coordinating efforts between involved stakeholders developing and growing such collectives. Other challenges include developing business models to scale residential prosumer collectives beyond pilot projects, and enabling adequate regulatory frameworks to support their growth.

Other executives underpinned challenges around managing social risks associated with collective prosumerism, especially around dealing with marginalized end-users, who are unable to provide demand flexibility or create and participate in strong prosumer collectives, and may end up paying more due to inefficient cross-subsidies.

As identified in the literature review and further investigated in this chapter, fairness is a key factor to be considered in dynamic demand response solutions targeting collectives. The next chapter addresses the fourth and last research question of this thesis, which focuses on how to incorporate fairness in dynamic demand response solutions for residential collectives.

Chapter 6

Fairness Mechanisms

Research Question 4 – How can fairness be fostered in dynamic demand response for residential collectives?

6.1 Introduction

In prosumer collectives, resources, benefits (and often penalties), and processes are shared among stakeholders (prosumers, distribution company, electricity market, etc.). Considerations around procedural and distributive fairness, which have been presented in Section 3.4.2, are crucial in planning and assessing the processes and outcomes of energy transitions relating to such collective settings [29].

Distributive fairness tends to be more technical than procedural fairness, as it involves distributing quantities rather than qualities. Thus, to address the fourth research question and craft this thesis to contribute to socio-technical literature on prosumer collectives, I focus on investigating distributive fairness.

Based on interview findings, distributive fairness is implemented by middle actors in various ways (see Section 5.6.4). In this chapter, I build on literature and interview findings and investigate (1) how to fairly distribute the revenue of a prosumer collective, from selling electricity to the grid, among its prosumers, and (2) how to fairly allocate loss of utility associated with dynamic demand response among households in a collective.

I present two mechanisms, in the form of software algorithms, to implement those fairness measures, which can be integrated into middle actors' software offerings. The *fair share allocator* targets prosumer collectives, where it is used to distribute the revenue of the collective, from selling electricity to the grid/market, among prosumers based on their contribution in exporting a pre-agreed amount of electricity. The *loss of utlity allocator* targets consumer collectives, and aims to trade off the minimum total loss of utility experienced by consumer households in order to achieve as much fairness as possible in distributing loss of utility among a collective of customers. Both algorithms can be customized to target prosumer as well as consumer collectives.

The algorithms assume that households have smart meters, are connected to the same low-voltage distribution network, but are not physically connected to each other. There is no information sharing between households, and thus privacy issues (e.g. exposing meter data to others) are not a concern. The households assumed herein may not necessarily communicate directly to negotiate forming a coalition, which highlights the importance of a middle actor to coordinate interactions. That middle actor may incorporate the proposed software algorithms in its offerings to residential collectives.

Data, such as smart meter data and records of revenue from selling electricity or providing demand response resources, is shared with the actor responsible for administering electricity sales or demand response for the collectives (a top actor such as a distribution company, a middle actor representing the collective, etc.). Based on the activity undertaken by the collective, binding agreements are put in place and agreed upon between involved stakeholders.

For the fair share allocator, I assume that prosumer households are equipped with rooftop PV that takes up between 20-30 m^2 of the rooftop surface of each house, and generate 2-4 kW of solar electricity per house [302]. I also assume that the households each have a battery with a 13.5 kWh capacity. Such prosumer households are between 25 and 50% energy self-sufficient, can have up to 18 hours of continuous backup power stored in their battery [303], and are assumed to be selling 50% of their solar electricity to the grid. Those assumptions build upon realistic calculations for a collective comprising average one-family prosumer households, and are only used to evaluate the software algorithm developed. Changing those assumptions will change the inputs to the fair share allocator; however, the allocator will still work in a less uniform environment.

For the loss of utility allocator, I assume that appliances in consumer households are participating in a 1-hour demand response event, where appliances automatically shed based on smart grid controls (e.g. heat pumps, which approximately use 1.5 kW on average, shed during the demand response event).

In general, prosumers in a collective do not have to contribute to every event the collective is a part of, e.g. one prosumer may contribute to exporting electricity from the collective to the grid one day, while the next day they may have a big event at home and so need to import some battery stored electricity from their neighbour to cover their demand. Only those prosumers contributing to an event will get a share based on the output of the algorithms developed herein.

The fair share and loss of utility allocators are concerned with distributing shares and loss of utility, respectively, among members of a collective, not forming collectives (i.e. coalition formation). Other algorithms can be developed to form coalitions achieving dynamic internal objectives for the collective (e.g. meeting the energy needs of its prosumers) as well as external obligations (e.g. exporting a certain amount of electricity to the grid).

Novelty in this chapter includes: (1) developing a software algorithm which approximates the fair distribution of a collective's revenue (e.g. from selling electricity) among its prosumers, with high accuracy and reasonable time and memory resources for a collective comprising 400 households; (2) developing a software algorithm which trades off minimum total loss of utility, experienced by a collective of households due to a dynamic demand response event, with fairness in allocating loss of utility among households.

Before discussing the details of those two mechanisms, it is important to first understand the concepts involved in their development. The next section provides an overview of those concepts.

6.2 Background

6.2.1 The Notion of Fairness

As presented in Section 3.4.2, energy justice combines aspects from distributive as well as procedural justice [30]. Distributive justice involves the distribution of outcomes, such as fair distribution of energy costs, while procedural justice deals with processes, such as equitable access to information [29, 30, 250, 251]. Both aspects can help in understanding and assessing the outcomes and processes of prosumer collectives [29].

Fairness influences the behaviour of people in many domains, and can be operationalized in socio-technical settings to help build trust and transparency among involved stakeholders. Issues around fairness and equity largely shape the social acceptance of prosumer collectives [31, 32]. In competitive electricity markets, considering concepts such as fairness plays a role in the acceptance of energy saving and management policies [304].

Prior to discussing how fairness can be implemented in dynamic demand response in residential collectives, cooperative game theory and weighted voting games are first introduced.

6.2.2 Cooperative Game Theory and Weighted Voting Games

Game theory is the study of strategic situations where several decision-makers, also known as players, have decisions that impact one another [299]. It provides a conceptual and formal analytical framework for studying the interactions between those players [300]. Game theory is divided into two branches: non-cooperative and cooperative. Non-cooperative game theory focuses on individual players, while cooperative game theory is concerned with coalitions (groups of households, etc.). Cooperative game theory offers solution concepts with desirable properties (e.g. fairness) which are used in many applications today. A solution concept predicts the result of a game by describing the strategies to be adopted by its players [300, 305].

Joint decision-making and cooperation are important aspects to consider when studying the interactions between players in a cooperative game. Players may have varying preferences, and thus need to agree on a common plan among themselves, and using a voting procedure is one of the possible approaches to agree on such a plan [305].

In a voting procedure, treating all players as equals may not be appropriate as some players may contribute more resources or be more important to the coalition than others [305]. Weighted voting games are used to address this issue, where each player is assigned a non-negative weight and either votes in favour of or against a certain decision (this is analogous to being part of a coalition or not).

If the votes in favour of a decision are equal to or greater than a specific quota, then the decision is agreed on [306], and the players in favour of this decision comprise the winning coalition. Although the weight of a player models his relative importance, the influence of a player on a coalition may not be directly proportional to his weight. The quota of a weighted voting game may require that all players are involved to achiev a winning coalition, meaning that each player can individually go against the decision [305]. For example, to achieve a winning coalition where the quota is 10, player 1 can contribute 9, and player 2 can contribute 1, but then they are both equally important to be part of the coalition to win and either can go against the decision.

In a cooperative game, the *characteristic function* is used to define the value of a coalition of players $N = \{1, \ldots, n\}$. Equation 6.1 denotes this as a function $v : 2^N \rightarrow$

$\{0,1\}$[1] in a weighted voting game for coalition $S \subseteq N$ having weights $w = \{w_1, \ldots, w_n\}$ and a winning quota q. The total weights of a winning coalition (or sub-coalition) (i.e. one where the characteristic function is equal to 1) must meet or exceed the quota q of the game.

$$v(S) = \begin{cases} 1 & \text{if } \sum_{i \in S} w_i \geq q \\ \\ 0 & \text{otherwise} \end{cases} \tag{6.1}$$

6.3 The Shapley Value

The Shapley value – a solution concept from cooperative game theory – provides a conceptual basis for splitting a reward (or penalty, resource, etc.), among players of a game into fair and unique shares [301]. In particular, the Shapley value is useful in super-additive environments[2], where it is more beneficial to form bigger coalitions and where ultimately a grand coalition forms [308].

As this research focuses on collectives of households, then forming bigger coalitions within the context of such collectives does not incur additional costs in infrastructure expansions. In other words, having bigger coalitions can provide benefits to such collectives (e.g. aggregate trades of locally produced energy, or demand response resources) without needing extra investments.

6.3.1 Axioms of Fairness

Given a characteristic function v and a set of players N, the Shapley value, $Sh_j(N, v)$ for each player i, provides a "fair" reward (or penalty) distribution as it satisfies the four axioms of fairness given below. The Shapley value has been proved to be the unique payoff or worth vector that is symmetric, efficient, additive, and assigns zero to a null player [309].

- Symmetry: players with equal contributions are rewarded equally: for coalition S not containing players i and j, if $v(S \cup \{i\}) = v(S \cup \{j\})$, then $Sh_i(N, v) = Sh_j(N, v)$.

[1] 2^N is the set of all subsets of N, including the empty set and N itself.

[2] Superadditivity means that two mutually exclusive coalitions can earn at least as much payoff by joining efforts as they can individually, which means the coalitions are better off if they merge into one. Superadditivity can be denoted as follows for coalitions A and B: if $A \cap B = \phi$, $v(A \cup B) \geq v(A) + v(B)$ [307].

- Efficiency: the total reward given to players is divided among them and has no remainder: $\sum_{i \in N} Sh_i(N, v) = v(N)$.

- Additivity: if two games are added, then the total reward assigned to them is the sum of the reward assigned to each game separately: if v and w are the characteristic functions of two games, then $Sh_i(N, v + w) = Sh_i(N, v) + Sh_i(N, w)$.

- Null Player: players not contributing to the worth of a game receive no reward: for player i, for every coalition S not containing i, if $v(S) = v(S \cup \{i\})$ then $Sh_i(N, v) = 0$.

6.3.2 Formulation

Let us consider a cooperative game (N, v) with characteristic function v, where $v : 2^N \to \mathbb{R}$ and $v(\emptyset) = 0$ for a finite set of players N. Equation 6.2 denotes the Shapley value of player i, $Sh_i(N, v)$ (abbreviated as $Sh_i(v)$ or Sh_i throughout this chapter) – which can be considered the customer's weight in the game. When player i joins coalition S, which is a subset of the grand coalition N, their marginal contribution is denoted by $v(S \cup \{i\}) - v(S)$. The Shapley value, $Sh_i(N, v)$, is the *average marginal contribution* of player i across all possible coalition permutations [3].

$$Sh_i(N, v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|! \, (|N| - |S| - 1)!}{N!} [v(S \cup \{i\}) - v(S)] \tag{6.2}$$

6.3.3 Computation Methods

Computing the Shapley value theoretically has been widely investigated, and precise solutions have been computed for various games, including the voting game, the airport game, and the operations research game [301]. Nevertheless, for a weighted voting game, the computation of the Shapley value has an exponential time complexity as it is NP-hard [311]. Unless $P = NP$[4], it can be proven that the Shapley value cannot be approximated using a polynomial-time algorithm [313].

[3] Permutation is an arrangement of a set of elements in a linear order, which needs to consider all possible orders in which players might join the coalition, and where the number of permutations for a set of n elements is denoted by $n!$ [310].

[4] P is the class of problems that can be solved in polynomial time, while NP is the class of problems for which solutions can be verified in polynomial time [312]. The question of whether $P = NP$ is an open problem, but most computer scientists believe that $P \neq NP$.

In the literature, various methods have been proposed for computing the exact Shapley value for weighted voting games of different coalition sizes (e.g. the Mann and Shapley generating function method [314], Conitzer and Sandholm's method [315], and Ieong and Shoham's method [316]).

The last two methods involve encoding the characteristic function in a specific form, which is only efficient if represented in a succinct manner. Due to the NP-completeness[5] of computing the Shapley value for weighted voting games, this succinct encoding does not generally exist for this class of games. For example, the characteristic function in the method of Conitzer and Sandholm [317] requires decomposition in a way that is not applicable in this research. In this thesis, the first two exact methods are investigated, namely direct enumeration, and the Mann and Shapley generation function method.

For an approximate solution of the Shapley value, a number of estimation methods have been proposed. Monte Carlo simulations have been used by Mann and Shapley [318] to estimate the Shapley value from permutations of a coalition that are randomly sampled. Despite having linear-time complexity, this method lacks details on the sampling technique required, thus limiting its effectiveness [319]. Multi-linear extension and random permutation are two additional approximation methods with linear-time complexity, proposed by Owen [320], and Zlotkin and Rosenschein [321], respectively. However, multi-linear extension has a large approximation error, and random permutation is expected to have a high average error as it randomly chooses only a single permutation.

In this research, the linear-time approximation method proposed by Fatima et al. [319], and the stratified sampling method proposed by Maleki et al. [322] are chosen for approximating the Shapley value.

Direct Enumeration

Directly enumerating the Shapley value is a simple method suitable when there are a small number of players, and is defined by the mathematical formula in Equation 6.2. Nevertheless, using this method for games with large numbers of players is infeasible because its time complexity is exponential (given by $\mathcal{O}\left(2^N\right)$ for N players). Direct enumeration is used to benchmark the accuracy of other computation methods.

[5]If a problem is NP-hard and NP, then it is NP-complete, which means that although it can be verified in polynomial time, it is believed to not have an efficient solution in polynomial time[312].

Mann and Shapley Generating Function Method

This exact method is based on the generating function method proposed by Mann and Shapley [314] and is specific to weighted voting games. The memory usage of this method is intensive, and its time complexity is given by $\mathcal{O}(CN^2)$, where C is the number of possible vote totals [323]. In games where players have similar weights, C is $N+1$, whereas in games where all players have different weights, C is 2^N. Using this method is recommended for large coalition sizes if the majority of players have the same weights [319].

In 1730, generating functions were introduced by Abraham de Moivre [324] to solve the linear recurrence problem[6]. Generating functions can take various forms. An ordinary generating function generates the values of interest $c_{i_1,\ldots,i_n}$ for some combinatorial problem, and involves defining functions as a potentially infinite sum of monomials over a set of variables x_i, i.e. terms of the form $c_{i_1,\ldots,i_n} x_1^{i_1} \ldots, x_n^{i_n}$.

For a weighted voting game of N players, assume that the voting strengths, the total number of votes and the least number of votes required by a winning coalition (the quota) are denoted by (w_1, w_2, ..., w_N), w; and q, respectively. For player i, we define c_{jk} as the number of ways k players, other than player i, can have a sum of j votes in total [314]. To efficiently enumerate the Shapley value exactly, Equation 6.3 can be used.

$$Sh_i = \sum_{k=0}^{N-1} \frac{k!\,(N-k-1)!}{N!} \sum_{j=q-w_i}^{q-1} c_{jk} \tag{6.3}$$

The generating function $g(x,y)$, suggested by David Cantor to compute coefficients c_{jk} of Equation 6.3, is given by Equation 6.4 [314]. This is a polynomial in x and y whose coefficients of $x^j y^k$ are the values c_{jk}. Multiplying $g(x,y) = (1 + x^{w_1} y) \ldots (1 + x^{w_N} y)$ out for any j and k, we get c_{jk} copies of the monomial $x^j y^k$, so $g(x,y) = \sum_{j,k} c_{jk} x^j y^k$.

$$g(x,y) = \prod_{i=1}^{N} (1 + x^{w_i} y) \tag{6.4}$$

Note that as the weights w_i appear in Equation 6.4 as exponents of x, the Mann and Shapley generating function method requires integers rather than real numbers as weights, thus inputs to this algorithm are discretized.

[6] In a linear recurrence, each term in a sequence of values can be defined as a linear function of earlier terms of the sequence [325].

Linear-time Approximation

One of the most efficient linear-time methods used to approximate the Shapley value is the multi-linear extension method proposed by Owen [320]. Nevertheless, this method does not often provide a satisfactory approximation error for weighted voting games [319]. Fatima et al. [319] thus proposed a new algorithm that has a lower approximation error than Owen's.

Assume that $w_1, w_2, \ldots, w_X$ is a random sample of size X drawn from a distribution with a mean of μ and a variance of ν. The mean of this sample has a normal distribution $\mathcal{N}$ with a mean of μ and a variance of ν/X. This rule is used by the linear-time approximation algorithm to find the normal probability distribution, mean, and error (i.e. $\frac{\nu}{X}$) in the estimated weight of a random coalition of size X. The linear-time approximation of the Shapley value of player i in a weighted voting game with N players is denoted by Equation 6.5.

$$Sh_i = \frac{1}{N} \sum_{X=1}^{N} A_i\,(X-1) \tag{6.5}$$

For player i, the approximate marginal contribution to a random coalition of size X is denoted by $A_i(X)$, where $1 \leq X \leq N$; it is the area under the curve defined by the estimated normal distribution, $\mathcal{N}(\mu, \frac{\nu}{X})$, in the interval $[a, b]$, where $a = (q-w_i)/X$, $b = (q-\epsilon)/X$, q is the demand that needs to be curtailed, and ϵ denotes an infinitesimally small quantity. In this work, the value of ϵ used is 10^{-5}; however, other values may be used as differences in results are negligible based on the evaluations conducted herein.

Stratified Sampling

Castro et al. [301] have developed a polynomial-time algorithm called ApproShapley to approximate the Shapley value for a large class of games. Nevertheless, this algorithm has an approximation error bound based on the Central Limit Theorem, making it an asymptotic bound. In other words, the bound only holds as the number of drawn samples increases to infinity. Thus, if a finite number of samples is drawn, an error is introduced [322], or perhaps the error can exceed this bound.

To address this drawback, Maleki et al. [322] proposed an algorithm that uses stratified random sampling to compute an estimation of the Shapley value. Their proposed algorithm assembles a player's marginal contributions into strata (i.e. homogeneous subpopulations) based on coalition size. The results of this algorithm become more precise compared to random sampling when the samples in each stratum are closer to each other in value and the differences between strata are greater.

This algorithm has a theoretical bound on the estimation error, given a confidence threshold, provided that the characteristic function has lower and upper bounds represented by linear functions of the coalition size. This is a valuable attribute. O'Brien [81] also proposed a method to estimate the Shapley value based on stratified sampling. However, the difference is that O'Brien's algorithm estimates the standard deviations of the strata using reinforcement learning, and includes a constraint to guarantee that the estimated values satisfy the efficiency property of the Shapley value. To limit the scope of computation techniques investigated here, only the algorithm proposed by Maleki et al. [322] is investigated.

Equation 6.6 defines the estimation error bound of the stratified sampling algorithm, where ϕ and $\hat{\phi}$ denote the exact and estimated Shapley values, respectively. Additionally, $d = 2\left(b - a\right)$ such that $\forall S \subseteq N$, $a|S| \leq v\left(S\right) \leq b|S|$, according to the method's assumption that $v\left(V\right)$ is bounded by linear functions of the coalition size [322].

$$|\hat{\phi} - \phi| \leq \frac{d\sqrt{-\ln\frac{\delta}{2}}}{\sqrt{m}}\frac{n}{2} \tag{6.6}$$

Equation 6.7 defines the least sample size m required to approximate the Shapley value using stratified sampling given a confidence threshold δ. Here, ϵ is a desired lower bound on the estimation error with a probability of $(1 - \delta)$, and r denotes the range of players' marginal contributions [322].

$$m \geq \lceil\frac{ln\left(\frac{2}{\delta}\right)r^2}{2\epsilon^2}\rceil \tag{6.7}$$

This estimation is very efficient, notably when m is sufficiently large compared to the number of players N. If the error bound of this estimation is compared to that of random sampling, it can be shown that the error of the latter is significantly higher than that given by Equation 6.6 if $m > \frac{(n+1)^2}{4}$[322].

The following two sections present two mechanisms developed to leverage the Shapley value to implement fairness in demand response in residential collectives: the fair share allocator and the loss of utility allocator.

6.4 Fair Share Allocator

In this section, a fair share allocator is developed to fairly distribute the revenue achieved by a collective of prosumers, from selling a pre-agreed amount of electricity to the grid, among prosumers based on their contribution to that amount of electricity. The Shapley value is leveraged to allocate fair shares using exact and approximate computations methods discussed in Section 6.3.3.

6.4.1 Overview and Formulation

A collective of N prosumers with multi-site distributed energy resources may collaborate in exporting a specific amount of electricity to the grid to generate income. This income is then fairly distributed among participating prosumers, based on their contribution in achieving that amount of electricity. The Shapley value can be used to fairly allocate generated income among contributing prosumers.

The problem of fairly distributing rewards, penalties, or resources, among a coalition of households can be considered a weighted voting game, similar to the one defined in Equation 6.1. The characteristic function v, denoted by Equation 6.8, describes the worth of coalition $S \subseteq N = \{1, \ldots, n\}$ prosumers having weights $w = \{w_1, \ldots, w_n\}$ corresponding to the amount of electricity they each export, and a winning quota E representing the amount of electricity to be exported.

To achieve a winning coalition, the aggregate power to be exported by the prosumers of coalition S (or a sub-coalition), represented by their weights, must at least meet the pre-agreed amount of electricity, E. In this case, the winning coalition collectively receives a reward equal to R. Otherwise, the coalition receives no reward.

$$v(S) = \begin{cases} R & \text{if } \sum_{i \in S} w_i \geq E \\ 0 & \text{otherwise} \end{cases} \tag{6.8}$$

The focus herein is on a single winning coalition. Dealing with multiple winning coalitions is not covered in the scope of this research.

6.4.2 Evaluation Scenarios

To evaluate the fair share allocator, two scenarios are used. In the first scenario, the accuracy of the Shapley value computation using the approximation methods is determined for a coalition of 10 prosumers aggregating at least 25 kW of electricity in exchange for a collective reward of 10 units.

In the second scenario, the scalability of the following three methods is investigated: the Mann and Shapley generating function method, linear-time approximation, and stratified sampling. The scalability here focuses on the computation time and the memory use of those methods for coalition sizes ranging between 100 and 1000 prosumers with increments of 100. Coalition sizes at this scale are often reasonable to create a prosumer collective that exports electricity to the grid/market (e.g. a virtual power plant), or a consumer collective that aggregates demand response resources [326, 327].

In both scenarios, samples of prosumer power production are generated from a generalized Pareto distribution, as this distribution provides a realistic representation of a power production curve (i.e. small power production are common for prosumers at this scale, while it is rare to have large power production by such prosumers).

To compute the Shapley value, MATLAB (R2011a) was used on an Intel-i5 CPU with a 64-bit Windows 7 operating system and 8GB RAM[7]. Simulations were run 10 times for each computation method – and average results are reported. Power productions are discretized for the evaluations of the three methods because the weights of the Mann and Shapley generating function method can only be whole numbers[8].

For the stratified sampling method, based on the characteristic function given by Equation 6.8, the value $(b - a)$ used in Equation 6.6 is equal to R (as $a = 0$ and $b = R$), and thus $d = 2R$. Similarly, the value of r used in Equation 6.7, which denotes the range of the marginal contributions of prosumers, is chosen to be R.

6.4.3 Results

To ensure the Shapley value is computed with a relatively high accuracy while maintaining fairness in distributing reward among prosumers of a collective, it is important that approximation computation methods used have a low approximation error.

For the first evaluation scenario, Figure 6.1 illustrates the fair compensations distributed among the coalition of prosumers as computed exactly using direct enumeration (on the x-axis) against that approximated using stratified sampling and linear-time approximation (on the y-axis). Upper and lower dashed lines indicate errors of +10%

[7]The Mann and Shapley method was implemented using convolution of full and sparse matrices, sparse matrices are used to reduce memory usage because they store zero-valued elements more efficiently than full matrices.

[8]It seems likely that this type of discretization would be commonly acceptable by prosumers in a similar way to billing mobile phone calls in minutes or mobile data usage in megabytes.

and −10% of the exact compensation, respectively. As shown, approximations using the stratified sampling method lie closer to exact results represented by the solid line at 45 degrees, which indicates that stratified sampling provides more accurate results than linear-time approximation.

Figure 6.2 illustrates the differences between the values approximated using stratified sampling and those using linear-time approximation, which range between 0.23 and −0.12. The figure highlights the range of differences between the two approximation methods, and indicates that values approximated using linear approximation are predominantly lower than those using stratified sampling, which may result in underestimating fair shares.

As the Shapley values approximated using stratified sampling have values that are closer to directly enumerated values and not underestimated, the stratified sampling method is thus preferred over the linear-time approximation method.

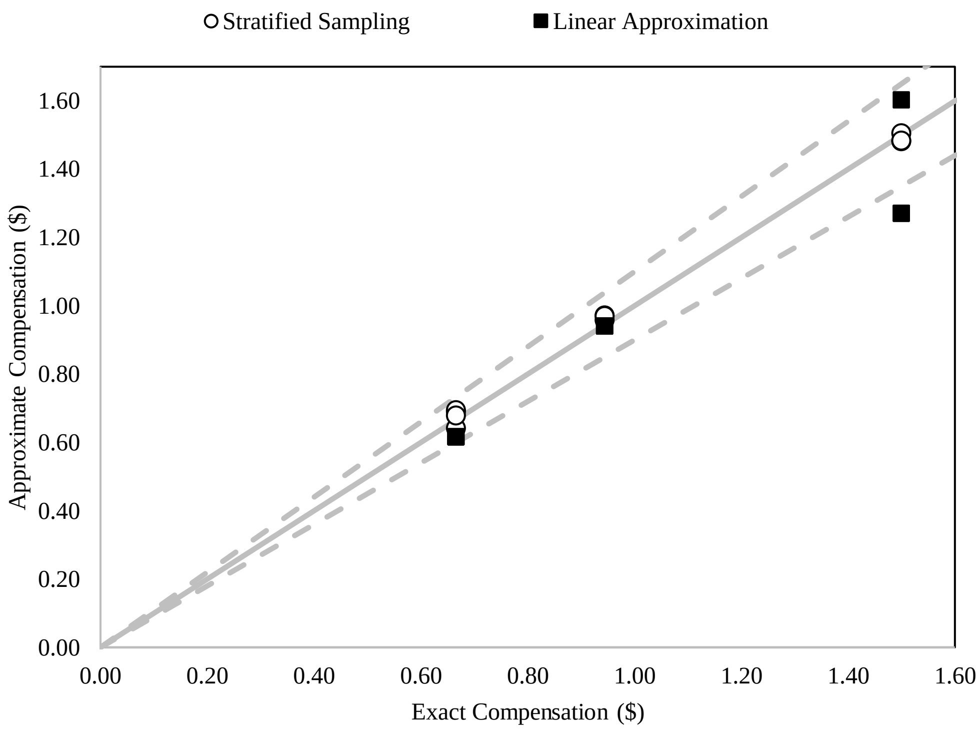

Figure 6.1: Exact prosumer compensation computed using direct enumeration (x-axis) against that approximated using stratified sampling and linear approximation (y-axis)

For the second evaluation scenario, Figure 6.3 shows the computation (CPU) time taken by each method for coalition sizes ranging between 100 and 1000 customers.

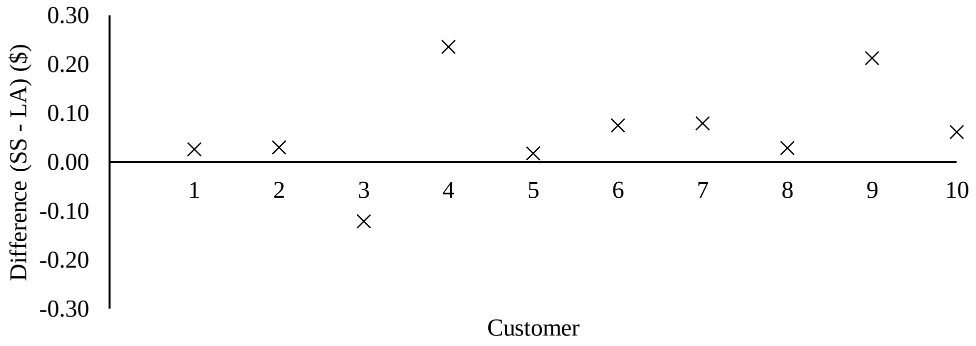

Figure 6.2: Difference between prosumer compensation approximated using stratified sampling and that using linear approximation

As illustrated, the fastest method in terms of computation time is the linear-time approximation method, whereas the stratified sampling method appears to have a polynomial execution time.

Computing the Shapley value using the Mann and Shapley generating function method with sparse matrices (referred to as GF(S) in Figure 6.3) has an exponential time complexity in terms of the number of prosumers, due to prosumers' weight diversity which can increase the possible vote totals up to 2^N; however, it tends to be usable (i.e. has practical computation time and memory usage) up to a coalition size of 400 prosumers.

Using the same method with full matrices (i.e. non-sparse matrices, referred to as GF(NS) in Figure 6.3), results in an abrupt rise in computation (which appears to be exponential), therefore no computations have been conducted using non-sparse matrices for coalition sizes beyond $N = 300$. Full matrices are therefore not recommended for use in the Mann and Shapley generating function method for computing the Shapley value.

Figure 6.4 shows that the linear-time approximation method uses the least amount of allocated memory, while that used by the stratified sampling method is reasonable. The memory usage of the Mann and Shapley generating function method, using sparse matrices, rises rapidly, illustrating the main disadvantage of this method.

6.4.4 Discussion

Prosumer compensation is one important aspect of prosumer collectives exporting electricity to the grid or the electricity market. The fair share allocator developed uses the

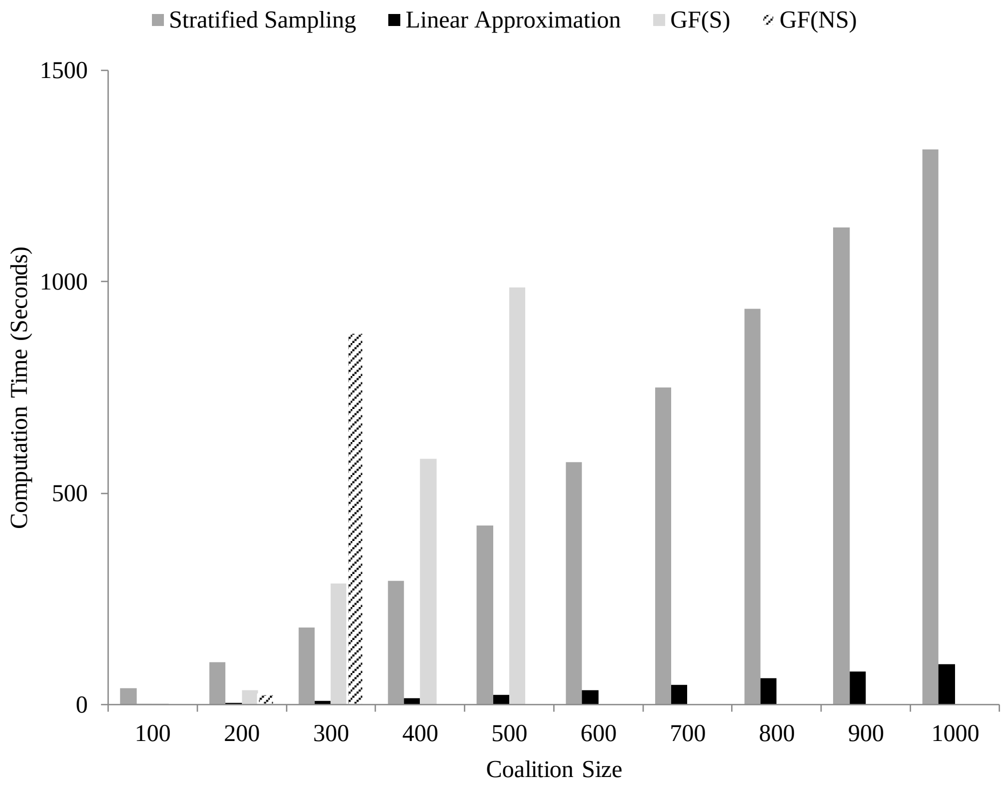

Figure 6.3: The CPU time taken to compute the Shapley value using the three algorithms for coalition sizes between 100 and 1000

Shapley value to fairly distribute the reward gained from contributing in aggregating a specific amount of electricity, to be exported from the collective. Three methods for computing the Shapley value were compared: the Mann and Shapley generating function, linear-time approximation, and stratified sampling, and their accuracy, computation time and dynamic memory allocation were investigated.

The Mann and Shapley generating function method offers an exact computation for the Shapley value, where fairness and accuracy of compensation are guaranteed for customers. However, this computation method uses huge memory resources, and thus is best suited for coalition sizes up to 400 prosumers. For larger coalition sizes, an approximation method which has an error bound, e.g. stratified sampling [322], can be used to compute the Shapley value. This method gives a better approximation for the Shapley value than that of linear-time approximation, which enables the prosumers to be fairly rewarded within a predictable bound.

As discussed in Section 6.1, it is assumed that prosumer households using this allocator are equipped with rooftop solar PV and batteries, and selling at least 50% of

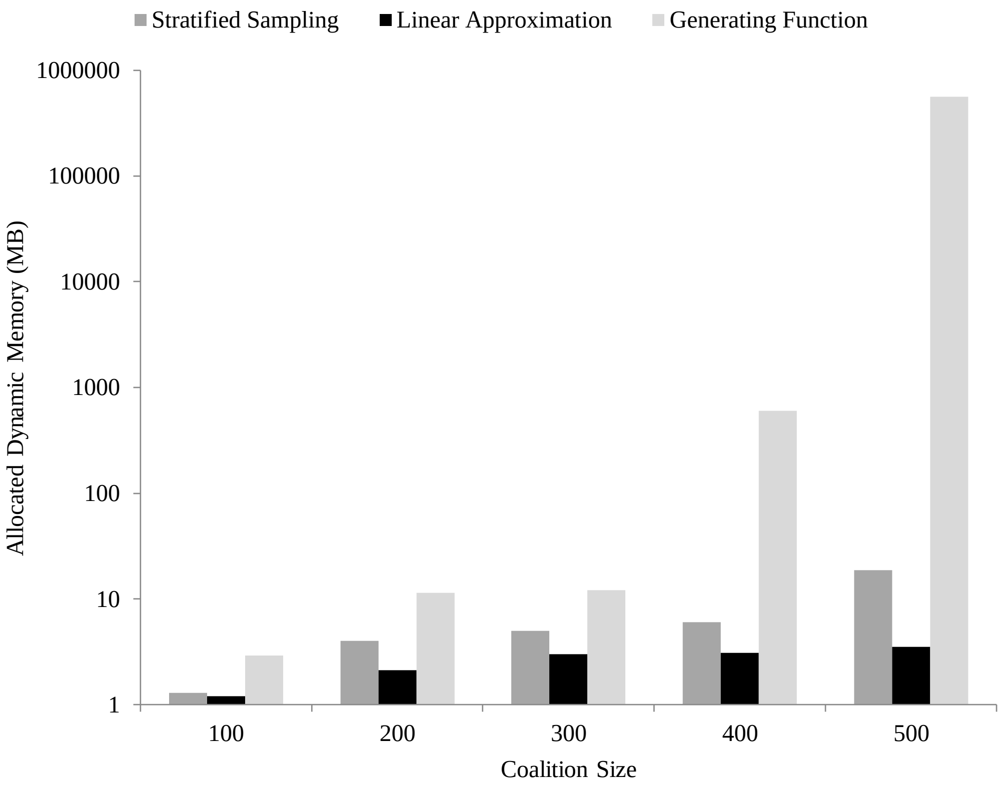

Figure 6.4: The total amount of memory dynamically allocated by MATLAB to each Shapley value computation method for coalition sizes between 100 and 500 prosumers

their solar electricity to the grid/market. A recent study in the UK monitored and analyzed one-minute electricity data for 302 households with PV generation participating in a smart grid demonstration project in the UK. The study found that energy self-consumption is 45% for these households. However, as these households have high gross electricity demand and high day-time consumption, self-consumption in this case can be appropriately reflected by 37.3% for average UK households with PV generation [328].

For a coalition of 400 prosumers, if 200 prosumers have 2 kW solar panels, and the other 200 have 4 kW solar panels, then such a coalition can export at least 600 kW of solar electricity in an hour of sunshine. This is a realistic amount of electricity, for both energy or reserve market power commitments, based on three virtual power plant projects in the US [326].

Having a collective of 400 prosumers is realistic for creating a virtual power plant. The electric utility, Eneco, in the Netherlands, has plans to convince 400 prosumers to join Crowdnett, a virtual power plant aiming at “borrowing” up to 30% of prosumers’ power capacity, and replacing physical backup power plants [329, 330].

Beside being used for prosumer collectives, this fair share allocator can be used to fairly distribute compensation among consumers comprising a collective participating in demand response events. If each consumer in a coalition of 400 sheds their heat pump, or equivalent electricity usage, during a 1-hour demand response event, 600 kW can be shed, which is quite reasonable for partaking in demand response provision in residential areas (some demand response administrators require at least 100 kW to be reduced [327]) [256].

In prosumer collectives, unfairness may seem more likely to deter the adoption of collectivism rather than prosumerism. For example, a prosumer collective – with distributed solar PV on each of its prosumer’s rooftop – is operating in a jurisdiction where the feed-in tariff used to be generous, and the objective of this prosumer collective used to revenue creation from exporting its electricity to the grid. Regulations changed and the feed-in tariff became not as “fair” as it used to be, as prosumers do not see themselves compensated fairly for exporting their collective’s electricity and, in turn, for the investment they have made in their DER. Prosumers of the collective do not find benefit in exporting electricity to the grid anymore, and instead prefer to become energy self-sufficient by consuming their own energy internally in the collective, instead of exporting it. A few of the prosumers do not see benefit in being in the collective anymore, because the return on investment on their DER has decreased, and so drop out of the collective and rely on energy from their DER and the grid. The collective sees a need for buying batteries to maximize their energy self-sufficiency and takes a decision to buy batteries. A number of prosumers see benefit in joining the collective then, especially after their retailer increased electricity tariffs – which they find is “unfair”, and so they become part of the collective to benefit from covering unmet demand from other prosumers rather than the grid.

Having said that, the extent of how unfairness issues may deter collectivism or prosumerism is highly dependent on the context surrounding prosumer collectives and is not discussed within the scope of this thesis.

6.5 Loss of Utility Allocator

This section presents a loss of utility allocator to fairly distribute the loss of utility resulting from DR participation among a collective of customers. Optimizations and

Shapley value computations are leveraged with the aim of trading off the minimum total loss of utility experienced by customers to adjust fairness in distributing loss of utility among a collective of customers.

6.5.1 Overview and Formulation

When it comes to energy use, residential electricity users have varying norms, behaviours, flexibility, availability and enabling technologies, which in turn shape the utilities their households benefit from as a result of using energy. Additionally, the willingness of such users to change their energy use varies, as changing energy activities in households may result in loss of utility for household inhabitants.

Typically, in DR practices targeting industrial and commercial users, such users choose the amount of demand they are willing to reduce, as their energy loads are largely predictable and they mostly rely on backup generators to provide power supply during DR events.

On the other hand, residential users have power loads that are dynamic, and they may not have a full understanding of how their households use energy and how much power load they can reduce during DR events. Therefore, it makes sense for an aggregator (or another middle actor) to allocate loss of utility to residential users based on their household energy usage, grid status and DR event specifics, and the metrics they have agreed on upon initially signing up to a DR program (e.g. availability). This not only helps set appropriate levels of power reduction for households, but also helps middle actors decide whether the power reduction quota of a specific DR event is met and whether additional or fewer DR resources are required.

In addition, it would be regarded as unfair to simply allocate equal power demand reductions that achieve the power reduction quota required during the DR event among residential customers, as their energy needs and flexibility to change demand patterns greatly vary. Thus, it is vital to allocate loss of utility among a coalition of households in a fair way.

Two works investigate the application of fairness to loss of utility in demand response practices. The work of Koutitas [259] proposes two algorithms for scheduling energy using round-robin and priority-based scheduling to quantify loss of utility and achieve fairness. The work of Pournaras et al. [260] demonstrates that it is possible to quantify and control fairness in demand planning, and provides empirical evidence that unfairness associated with loss of utility varies seasonally and is correlated with the demand levels of end-users. The authors in that work also show that high levels of unfairness can result from trying to adjust loads in an optimum way by reducing, shifting, or shedding them. Thus, considering trading off optimality for fairness is important.

This trade-off has not been previously addressed. Thus, this work proposes an algorithm that trades off the minimum total loss of utility experienced by residential electricity users in order to achieve a degree of fairness in distributing loss of utility among those users.

A fair solution, where electricity users receive fair allocations, may not necessarily be achieved by allocations made through computing the *minimum* total loss of utility. A trade-off between optimality and fairness is thus needed to allocate loss of utility in a fair manner among a collective of end-users providing DR resources. The aim of the algorithm proposed herein is to achieve a sub-optimal solution, in terms of the total loss of utility, that allocates loss of utility as fairly as possible amongst a collective of electricity users. This algorithm comprises three steps:

- Compute the minimum total loss of utility that achieves the power demand reduction quota
- Fairly allocate the minimum total loss of utility among a collective of users (subject to capacity constraints)
- Minimally reallocate to achieve a new distribution of loss of utility among users if fair allocations of the minimum total loss of utility do not meet the demand reduction quota

Compute the Minimum Total Loss of Utility

This first step computes the minimum total loss of utility affecting a collective of users (whether prosumers or consumers) and achieving the quota of the power demand (i.e. hourly energy use) to be reduced during a DR event. An optimization is used to benchmark the minimum amount of utility needed to reduce power demand by the requested amount. Note that a collective-wide optimization approach can produce an unfair solution, which drives the need for the second step of the algorithm. Figure 6.5 illustrates the first step of the algorithm in the power and utility spaces.

The behaviour of electricity users tends to conform to the law of diminishing marginal utility, where the utility of a user tends to follow a strictly concave and increasing function [41]. When users select their electricity tariff plans, they often

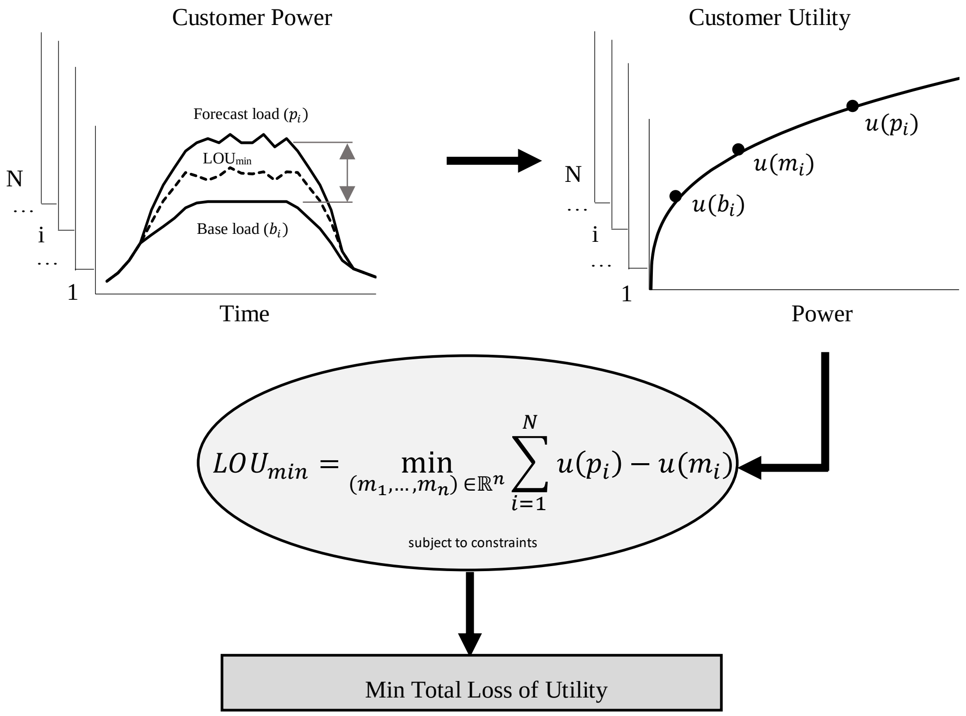

Figure 6.5: Step 1 – computing the minimum loss of utility in the power and utility spaces subject to constraints on m_i

choose plans that match their valuation. Thus, electricity pricing can be used here as a proxy for utility. The scope of this work does not include utility functions negotiated among a collective of users (where users agree together on a shared utility function that reflects their electricity use), or provided by aggregators (where an aggregator assigns a utility function to characterize the electricity use of the collective of users).

In a DR event, the aggregator typically targets electricity users that have a high potential of jointly reducing the required quota of power reduction. Selecting those users can depend on various factors including availability, energy use preferences (e.g. preferred time of use, and appliance use to shed/shift), history of participation in DR events, grid status signals, and event requirements.

In this optimization problem, the objective function is given by Equation 6.9. Assuming that N customers have been chosen to reduce power by a quota Q_{req}, we denote the coalition of chosen customers by $C = \{c_1, ..., c_N\}$. For customer c_i:

- the baseload (i.e. non-flexible load not to be shifted or shed) is denoted by b_i, and is selected based on the historical data of customers' smart meters

- the forecast power use without DR is denoted by p_i, and is selected based on the historical data of customers' smart meters
- the utility function is denoted by u_i, which depends on the service to be curtailed (i.e. electricity), where electricity price is taken as a proxy for utility and thus the utility function represents the customers' electricity price function (which maps from power use to price)
- the resulting power demand (after demand reduction) of each customer during the event is denoted by the decision variable m_i
- the minimum total loss of utility experienced by customers during the DR event is denoted by LOU_{min}

$$LOU_{min} = \min_{(m_1,\ldots,m_n)\in\mathbb{R}^n} \sum_{i=1}^{N} \left(u_i\left(p_i\right) - u_i\left(m_i\right)\right) \tag{6.9}$$

The following three equations denote the optimization constraints. In Equation 6.10, m_i denotes the power demand expected from a customer during the DR event, and if the customer is actually reducing power use then this value is constrained to be less than the forecast power demand without DR: p_i. The lower limit of the resulting power demand, m_i, of this customer is defined by the baseload b_i to ensure power reduction does not affect essential loads (i.e. non-flexible loads) needed by customers.

In Equation 6.11, the power reduced by a customer during the DR event is given by $p_i - m_i$, and has an upper bound set by the maximum approved power reduction set by customer i, which is denoted by $rmax_i$. Upon joining a DR program, each customer is assigned an initial maximum power reduction $rmax_i$ based on agreement with the aggregator. After multiple participations, the value of $rmax_i$ is expected to be reassessed so as to provide realistic data for customers' participation.

In Equation 6.12, the total power reduction achieved by a collective of customers is constrained to equal the power reduction quota Q_{req}, and this reflects that the required power reduction quota needs to be achieved by the collective of customers (i.e. DR resources).

$$b_i < m_i < p_i \qquad \forall i \in \{1, \ldots, n\} \tag{6.10}$$

$$p_i - m_i \leq rmax_i \qquad \forall i \in \{1, \ldots, n\} \tag{6.11}$$

$$Q_{req} = \sum_{i=1}^{N} (p_i - m_i) \tag{6.12}$$

Based on the objective function and optimization constraints, this optimization problem is convex and can be solved using convex optimization techniques [331]. The minimum value of the objective function LOU_{min} given by Equation 6.9 is used to benchmark the loss of utility quota to be distributed fairly amongst the coalition of customers in the two other steps of the algorithm.

Fairly Allocate the Minimum Total Loss of Utility

The second step of the algorithm determines the fair share of power reduction to be allocated to each customer during a DR event. This step involves working in two spaces: utility and power. The data dealt with in the utility space relates to the benefits that customers gain from using electricity. In the power space, data represents power demand and reduction. Figure 6.6 illustrates the second step of the algorithm in the power and utility spaces.

To compute the fair allocations of power demand reduction for each customer participating in the DR event, the Shapley value is used to fairly distribute the minimum total loss of utility computed in the previous step of the algorithm, LOU_{min}, among customers in a collective. Firstly, the Shapley value is computed in the utility space. Secondly, values resulting from this computation are mapped back to the power space to determine the corresponding, yet not final, fair power demand reduction assigned to each customer.

Distributing the minimum total loss of utility, LOU_{min}, fairly among a collective of customers can be considered as a weighted voting game in the utility space, where LOU_{min} is utilized as the winning quota and the value to be distributed among customers. Each customer's weight in this game, denoted by w_i, indicates their agreed maximum possible loss of utility i.

As discussed in Section 6.3.3, computing the Shapley value has an exponential time complexity, and several methods have been proposed to compute its value within reasonable timeframes. The algorithm proposed herein uses the Mann and Shapley generating function method to compute the Shapley value. Although this method is memory-intensive, and has a time complexity that tends to be exponential for large coalitions of players, it has an appropriate computation time for a DR setting including up to 400 customers (as presented in Section 6.4.3).

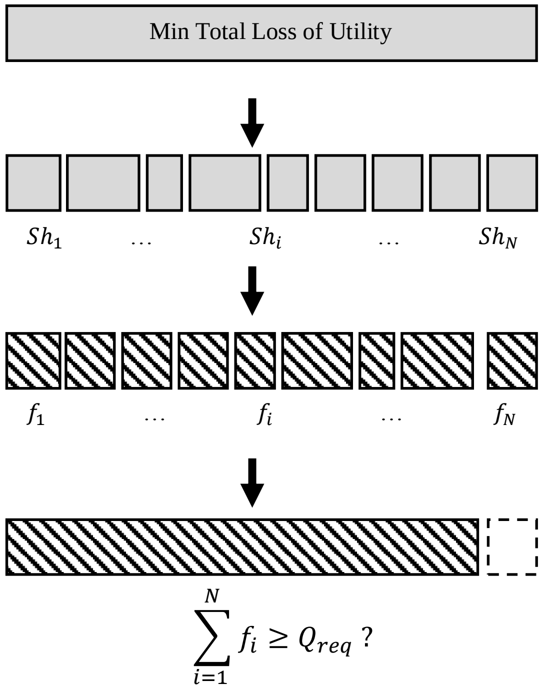

Figure 6.6: Step 2 – fairly allocating the minimum total loss of utility in the power and utility spaces

Equation 6.13 defines the weight w_i of customer i in the weighted voting game, which is assumed to be equal to the customer's maximum possible loss of utility during the DR event. This equality ensures that the maximum shares of customers from discomfort resulting from a DR event are taken into account, in the form of each customer's weight, when accumulating the loss of utility experienced by the collective. This helps leverage maximum benefits from each customer's flexibility (i.e. flexible loads the customer has agreed to reduce), by globally optimizing and aggregating their maximum possible loss of utility in order to reach the required quota LOU_{min} of this weighted voting game. It also ensures that the weight of each customer is linked to the upper bound of demand reduction they have agreed to reduce (without affecting non-flexible base loads).

The customer weight, w_i, equals the difference between the customer's utility when using forecast power without DR and that after reducing forecast power by the maximum power demand reduction agreed to by the customer, $rmax_i$. Equation 6.14 defines the characteristic function of the game, v.

$$w_i = u_i\left(p_i\right) - u_i\left(p_i - rmax_i\right) \tag{6.13}$$

$$v(S) = \begin{cases} LOU_{min} & \text{if } \sum_{i \in S} w_i \geq LOU_{min} \\ \\ 0 & \text{otherwise} \end{cases} \tag{6.14}$$

The Shapley value uses customer weight w_i (i.e. maximum possible loss of utility during the DR event) to divide the minimum total loss of utility LOU_{min} among customers. Note that the efficiency property of the Shapley value, presented in Section 6.3.1, guarantees that $\sum w_i = LOU_{min}$. To determine fair shares in terms of power, the Shapley value in the utility space is mapped to the power space, as shown in Equation 6.15 where the output denotes customers' fair, yet not final, shares of power demand reduction, denoted by f_i.

$$f_i = p_i - u_i^{-1}\left(u_i\left(p_i\right) - Sh_i\right) \tag{6.15}$$

If the total power demand reduction, $\sum_{i=1}^{n} f_i$, fails to achieve the power reduction quota, Q_{req}, an adjustment of the power demand reduction is needed to achieve the quota. This failure to achieve the quota may be the result of the non-linear relationship between power and utility, where each customer may have a different utility function, and the loss of utility distributed among a collective of customers may not add up to the power reduction quota requested from the collective when mapped from utility space to power space and summed.

In addition, in some cases, the Shapley value of a customer (i.e. average marginal contribution made to achieve the minimum total loss of utility LOU_{min}) may be equal to the Shapley value of other customers with higher weights. Assuming a game where players' weights are 3, 4 and 5, and the winning quota is 10, it is only possible to reach the quota if all players contribute, leading to equal Shapley values of 10/3. A corollary of this in the utility space is that the customer's fair proportion of loss of utility (i.e. the Shapley value Sh_i) can exceed the customer's relative weight w_i. This can have an effect in the power space where a fair power reduction f_i exceeds some customers' upper bound on power reduction, $rmax_i$, because the weight of the customer, w_i, is derived from this upper bound.

The next step of the proposed algorithm addresses these issues, and ensures that the power reduction quota is met and customers' upper bounds on power reduction are not exceeded.

Optimize to Match Required Quota

The third step of the proposed algorithm adjusts the loss of utility, through an optimization, to ensure it meets the requested demand reduction quota and does not result in power reductions that exceed those agreed to by customers. Failure to achieve this quota may be due to the non-linear relationship between power and utility, or equal Shapley values for customers with different weights. Figure 6.7 illustrates the third step in the power and utility spaces.

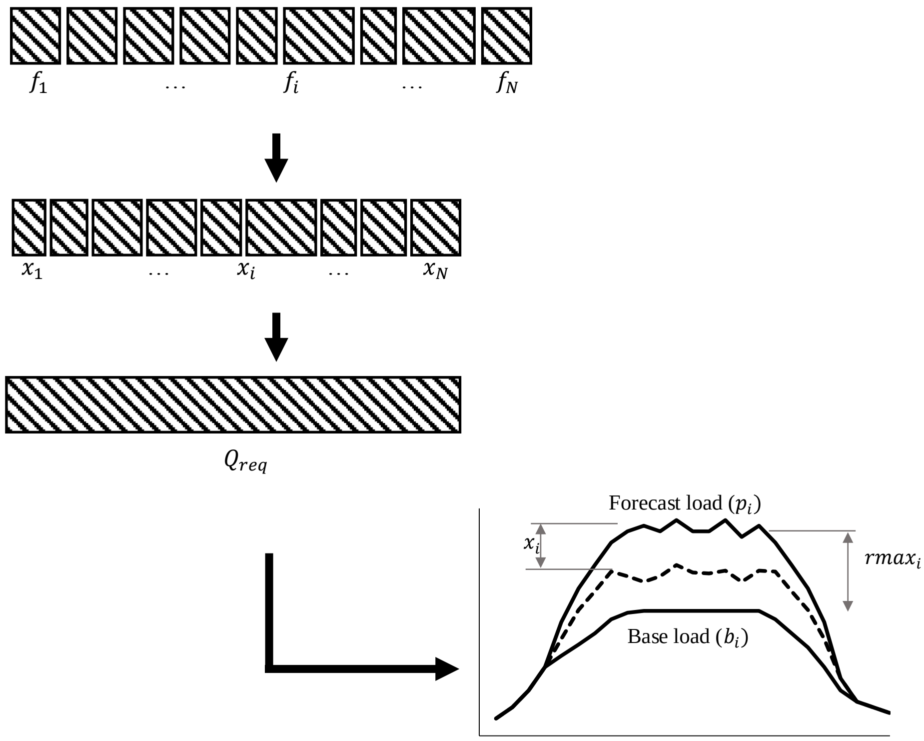

Figure 6.7: Step 3 – optimizing to match the required quota in the power and utility spaces

This optimization problem aims at minimizing the sum of the differences between customers' loss of utility corresponding to fairly allotted power reductions, denoted by $u(f_i)$, and those achieving the quota under an adjusted allocation, denoted by $u(x_i)$. In the objective function, defined by Equation 6.16, the values f_i and x_i correspond to the fair power reduction (resulting from Step 2) and the final power reduction (to be produced by Step 3) for customer i, respectively. This optimization solves for the final power reduction, x_i, which satisfies the demand reduction quota Q_{req}, lies between the baseload b_i and the forecast load p_i, and is at most equal to $rmax_i$, .

$$\min_{(x_1,\ldots,x_n)\in\mathbb{R}^n} \sum_{i=1}^{N} \left(u_i\left(f_i\right) - u_i\left(x_i\right)\right) \tag{6.16}$$

The following four equations define the optimization constraints. Equation 6.17 defines the power demand after reducing the final allocation x_i, $p_i - x_i$, whose value must lie between the baseload b_i and the forecast load p_i. Equation 6.19 indicates that the value of x_i must be positive and either equal to or less than the maximum power reduction $rmax_i$. Equation 6.18 makes sure that x_i does not exceed f_i, as some allocations might have exceeded the $rmax_i$ constraint

Equation 6.20 shows that the total power reduction distributed by this step of the algorithm to the coalition of customers must be equal to the requested quota Q_{req}.

$$b_i < p_i - x_i < p_i \qquad \forall i \in \{1,\ldots,n\} \tag{6.17}$$

$$x_i < f_i \tag{6.18}$$

$$0 < x_i \leq rmax_i \qquad \forall i \in \{1,\ldots,n\} \tag{6.19}$$

$$Q_{req} = \sum_{i=1}^{N} x_i \tag{6.20}$$

This optimization problem is convex and can be solved using convex optimization techniques [331], in a similar manner to the optimization presented in Section 6.5.1.

6.5.2 Evaluation Scenarios

This section includes the evaluation scenario and data chosen to test the proposed algorithm for the loss of utility allocator. Let us assume a smart power grid infrastructure where two-way communication between grid stakeholders is available and smart meters are used. Customers choose electricity pricing plans that best fit their utility function. We consider a DR event that is sent out by a grid operator via an aggregator to a coalition of customers to reduce power use during a specific period of time.

The inputs to the algorithm are typically gathered from four sources, the grid operator, the distribution system operator (DSO), the aggregator and the customer, as follows:

- The grid operator requests a specific quota Q_{req} of power demand reduction from an aggregator based on grid status and the grid area covered by the aggregator. Depending on the requested quota, the aggregator can target one collective of customers or more. For simplicity, only one customer collective is targeted here, where the aggregator requests a power reduction quota of Q_{req} from that collective.

- The DSO collects customers' smart meter data and upon getting customer consent the DSO provides smart meter data to the aggregator which can disaggregate and analyze data to produce customer forecast power demand p_i and baseload demand b_i.

- The aggregator has a range of customer details including customer preferences, availability, pricing plans, history of DR participation, etc. Depending on the specifics of the DR event, the aggregator can use such customer details as inputs or constraints to the proposed algorithm to allocate power demand reduction to the target collective of customers.

- The customer provides the aggregator with information such as preferences of appliance usage, and the maximum power demand reduction allowed $rmax_i$. Initially, this value can be set, for example, to the Wattage of a certain appliance the customer is willing to shed during the DR event, then data can be refined after a number of participations by the customer.

Three utility functions are considered in this evaluation, based on three electricity price plans [332]. For example, for customer i, with a forecast power demand denoted by p_i, the utility function u_i is given by $0.22\, {p_i}^{0.5}$, $0.25\, {p_i}^{0.4}$, or $0.28\, {p_i}^{0.5}$. For the sake of evaluation, we randomly generate data for the baseload b_i, forecast power demand p_i, and maximum demand reduction $rmax_i$, based on realistic data available in references 354–356 for an average single-family household with appliances.

The fair loss of utility allocator was implemented using MATLAB, and the optimization problem was modelled using YALMIP[9] and solved using the IBM ILOG CPLEX Optimizer. An Intel-i5 CPU with a 64-bit Windows 7 and 8GB RAM was used to run the computations.

The evaluation scenario for the algorithm involves an aggregator achieving the requested demand reduction quota Q_{req} by targeting a collective of residential customers

[9] YALMIP is an open-source optimization modelling language that integrates with MATLAB [333].

sharing the same low-voltage distribution network. For simplicity, the algorithm was run for a 1-hour DR event for a collective of 150 customers collectively reducing their aggregate power demand by 150 kW. This evaluation illustrates how the final power demand allocated by the algorithm compared to the forecast, minimum and fair power demands.

6.5.3 Results

The run time of the evaluation scenario (including the computations of the Shapley value using the Mann and Shapley generating function method) was 75.3 seconds. The following three figures illustrate the deviations between the final allocated power demand and the forecast, minimum, and fair power demand, respectively.

The forecast and final power demands of customers in the coalition are shown in Figure 6.8. The solid diagonal line indicates two identical values, whereas the dashed lines denote points on deviations (+/- 10 and 20%). Points below the solid line indicate that all customers will be reducing their power demand. Most power reductions are around 25% of the forecast power, and a few customers reduce up to 53%.

The range of customers' power demand reductions is between 0.5 to 2 kW, where 42 customers each reduce between 0.5 and 1 kW. In practical terms, this can be a customer delaying washing clothes, or having his freezer/fridge cycled by the aggregator. Then, 89 customers each reduce between 1 and 1.5 kW by, e.g., reducing the thermostat of their heat pump, or rescheduling the dishwasher to off-peak periods. The remaining 19 consumers each reduce between 1.5 and 2 kW, perhaps by delaying their cooking or shedding the air conditioner. More power demand reduction can be achieved by controlling water heating and clothes drying.

Figure 6.9 illustrates the minimum power demand[10] resulting from computing the minimum total loss of utility in the first step of the algorithm) versus the final power demand, where the values for 92 customers overlap or are within 1% of the solid line, which indicates that minimum and final demands are quite similar. Nevertheless, 58 customers have more varying results, with 34 of them having differences that range between 1.8 kW less and 0.1 kW more than the final demand, and 24 have differences between 0.1 and 1.5 kW more than the final demand. This indicates that around 39% of the customers in the evaluation scenario have final power demand that differs from

[10]The term minimum power demand is not used to refer to minimum values, as w_i values are not guaranteed to give minimum demand, but is used to to refer to the power demand values computed in the first step during optimizing for the minimum loss of utility.

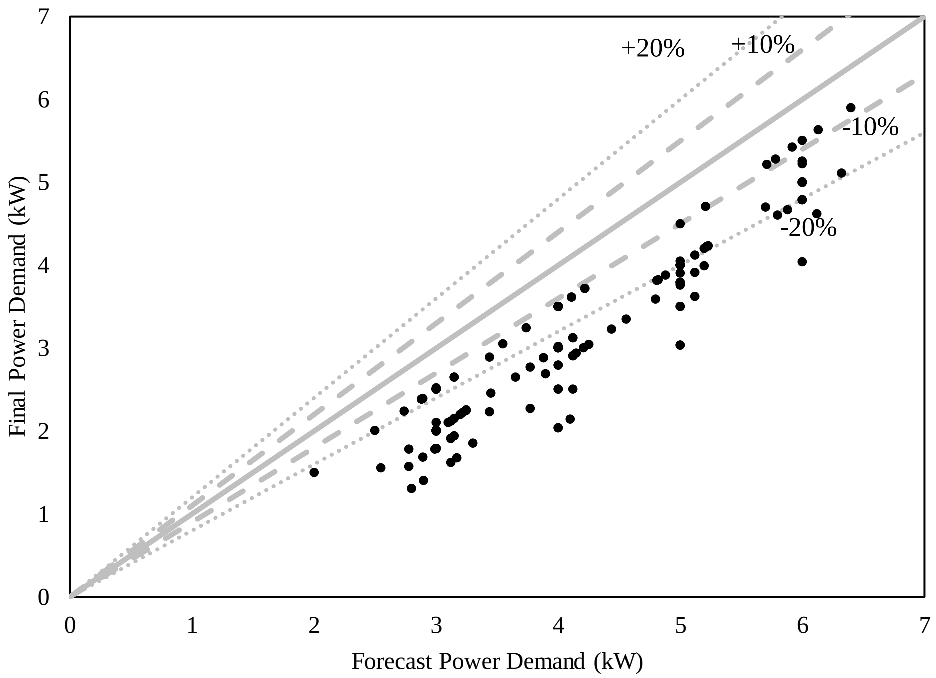

Figure 6.8: The forecast versus final power demand of each consumer in a coalition of 150 consumers

minimum demand.

Figure 6.10 illustrates that the final power demand is less than the fair power demand, which implies greater loss of utility is observed than in the case of using the minimum total loss of utility optimization.

6.5.4 Discussion

The utility that residential customers get from using electricity varies greatly due to a number of factors, e.g. energy practices, household appliances, and customer flexibility. Thus, equally allocating power demand reductions among customers would be regarded as unfair, because utility specifics need to be taken into account while allocating such reductions. As trying to collectively minimize the loss of utility experienced by a collective of customers participating in a DR event achieves a fair distribution but may breach $rmax_i$ constraints, an algorithm is proposed to trade off optimality and try to achieve fairness by taking the utilities of customers into consideration when allocating power demand reduction among the collective.

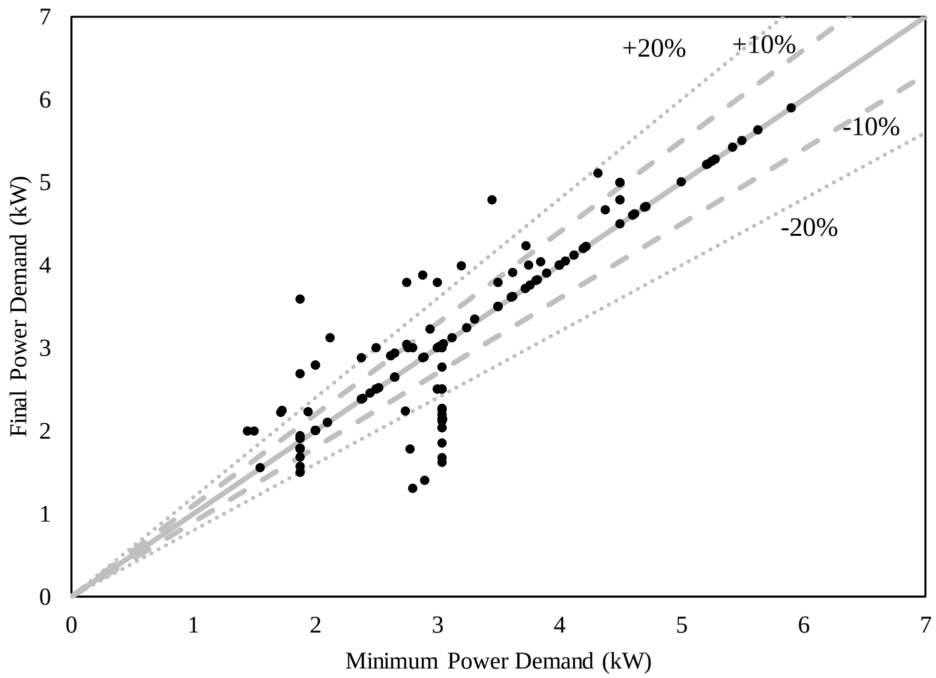

Figure 6.9: The minimum versus final power demand of each consumer in a coalition of 150 consumers

Participating customers may act strategically by changing their actual power use (and thus the maximum power reduction $rmax_i$) over a period of time and thus provide false power demand profiles. Nevertheless, the aggregator can detect cheating customers by matching $rmax_i$ with actual power use data over time. Otherwise, the aggregator can reward customer flexibility by paying each participant in the DR event a fixed fee based on the difference between his baseload b_i and maximum power reduction $rmax_i$; however, this is not addressed here.

In this setting, practical issues prevent problems with coalition stability, as the aggregator considers only the grand coalition of a set of customers participating in a DR event, and deals individually with those customers, not members of subcoalitions. In addition, there is no realistic option for a residential customer to defect from the grand coalition, especially during a single DR event, as grid operators require bulk power reductions. Thus, having a customer directly sell DR resources to the grid operator is only feasible for large customers (e.g. industrial and commercial facilities) or the aggregator.

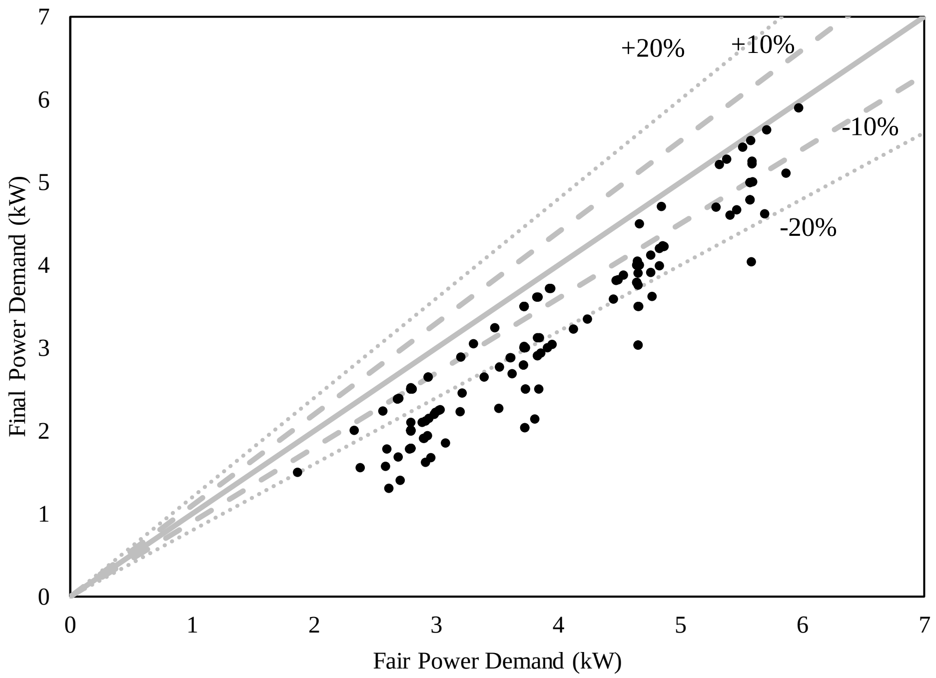

Figure 6.10: The fair versus final power demand of each consumer in a coalition of 150 consumers

To compute fair allocations, the Shapley value is used because it is beneficial in the case of super-additive environments where forming large coalitions has benefits and adding customers does not significantly require additional costs.

At the end of the second step of the algorithm, fairly allocated loss of utility is mapped from the utility space to the power space in order to ensure that the power reduction requested from the coalition is met. Because resulting fair power reductions might not necessarily meet the power reduction quota or respect the maximum power reduction allowed by each customer, a third step is needed in the algorithm to guarantee that constraints are met.

The third step of the algorithm comprises an optimization to determine a new set of final power demand reductions that meets and respects the power reduction quota, customers' maximum allowed power reductions, and constraints of the DR event and the customer coalition. The target of this step is to minimize the total difference between the fair and final loss of utility across all customers. An optimization is used rather than another round of fair allocations in order to avoid adding to the computation time, as fast response time is highly desired for DR applications.

Additionally, comparing the minimum power demand resulting from the first step of the algorithm with the final power demand resulting from this step indicates that around 39% of the customers in the scenario have final power demand that differ from minimum demand, which supports the assumption that the minimum total loss of utility (computed in the first step of the algorithm) does not necessarily yield fair allocation.

6.6 Summary

In this chapter, two mechanisms have been developed to enable fairness in dynamic demand response practices targeting residential collectives, both prosumers or consumers.

The first mechanism – the fair share allocator – uses the Shapley value, which is a solution concept in cooperative game theory, to fairly distribute the collective's revenue from exporting electricity to the grid/market among its prosumers. This mechanism is modelled as a weighted voting game, where prosumers' weights reflect their electricity contribution in achieving the electricity quota to be exported from the collective.

Four methods for computing the Shapley value for weighted voting games have been investigated in terms of their accuracy, computation time and memory use. Two of the methods, namely direct enumeration and the Mann and Shapley generation function method, provide exact results, while the stratified sampling and linear-time approximation methods provide approximate results.

The stratified sampling method provides more accurate results than linear-time approximation for computing the Shapley value in the fair share allocator, while the fastest method in terms of computation time is the linear-time approximation method. Nevertheless, using the Mann and Shapley generating function method with sparse matrices was found to have appropriate computation time up to a collective size of 400 customers.

To put this to scale, for a collective of 400 prosumers, if 200 prosumers have 2 kW solar panels while the remaining 200 have 4 kW of solar panels, and the households export at least 50% of their solar electricity, then the collective exports at least 600 kW of solar electricity in an hour of sunshine. Based on existing and planned virtual power plant projects, this is a realistic amount of electricity for both energy and reserve market power commitments, and also a reasonable size for a prosumer collective.

If the fair share allocator is customized to compensate residential consumers participating in demand response events, if each consumer in a collective of 400 sheds their heat pump, or equivalent demand, during a 1-hour event, then 600 kW are shed, which is reasonable demand response activities in residential areas.

As for allocated memory usage, the linear-time approximation method uses the least memory in the fair share allocator, while that used by the stratified sampling method is realistic. However, the memory usage of the Mann and Shapley generating function method grows rapidly and is thus the main disadvantage of this method.

The second mechanism – the loss of utility allocator – also uses the Shapley value to fairly distribute loss of utility associated with demand response practices among a collective of consumers, as equally allocating power demand reductions among customers may not necessarily be fair. This mechanism trades off optimality, in terms of minimum total loss of utility, with the aim of achieving as much fairness as possible. This mechanism assumes that users want to experience the least loss of utility possible during DR events, as changing their normal demand patterns may cause inconvenience.

The mechanism comprises three steps: (1) computing the minimum total loss of utility that achieves the power demand reduction quota, (2) fairly allocating the minimum total loss of utility among a collective of users, and (3) reallocating new distributions of loss of utility among users if fair allocations of the minimum total loss of utility do not meet the demand reduction quota when mapped back to power and adjusted for maximum participation constraints.

Results of a sample scenario show that 39% of customers were allocated a final power demand that differs from their minimum power demand, thus supporting the assumption that the minimum total loss of utility does not necessarily yield fair allocation.

Those two mechanisms may both be incorporated into the software offerings provided by middle actors to residential collectives, and may be customized to target both prosumer as well as consumer collectives. Such software mechanisms around distributive fairness can help build trust and transparency between stakeholders involved in residential prosumer and consumer collectives.

Chapter 7

Conclusion

This chapter weaves findings from this research with literature findings, and intertwines research findings together, to highlight linkages, identify novelty, and provide future recommendations.

7.1 Overview

Power grids today are becoming more digitized, decentralized and decarbonized, where they are increasingly integrating new information, communication and distributed energy technologies, and becoming smart grids. The traditional power grid model where electricity is generated in centralized plants then transmitted and distributed to end-users is changing, where end-users are uptaking micro-generation to produce their own electricity mainly due to their rising affordability. More recently, groups of households started coming together to form prosumer collectives whose complex socio-technical interactions are requiring more dynamic demand response approaches for managing energy, and creating value for the collective and involved stakeholders.

Smart grid technologies and capabilities have the potential to enable innovative products and services to manage the sophisticated flows of power, data, and money among prosumers in a collective, and between collectives and the grid. Such capabilities include balancing intermittent supply with variable demand across prosumer households, maximizing value creation arising from collective prosumerism (e.g. selling electricity to the grid), and incorporating social notions that are essential in socio-technical contexts (e.g. fairness).

Most electricity system incumbents (i.e. top actors) do not provide dynamic demand response solutions for prosumer collectives. Nonetheless, new businesses (i.e.

middle actors) are leveraging this opportunity to create innovative offerings which enable prosumer collectives to manage and value energy in new ways.

This thesis provides novelty in investigating how smart grid opportunities can be leveraged to improve demand response practices for residential prosumer collectives, by exploring new emerging businesses, their innovative smart grid offerings, how this implicates dynamic demand response, and how to incorporate fairness in such offerings based on its notion from literature and interview findings.

To conduct this investigation, the thesis posed four research questions:

- RQ 1 – What is the current status of energy demand management and what new opportunities exist?
- RQ 2 – How do new opportunities offered by the smart grid support the emergence of residential prosumer collectives?
- RQ 3 – How are middle actors shaping smart grid offerings, and what are the implications for dynamic demand response in residential prosumer collectives?
- RQ 4 – How can fairness be fostered in dynamic demand response for residential collectives?

The first two research questions have been addressed through reviewing literature from academic publications, industry studies, and project reports, on current energy demand management practices, and how smart grid opportunities are generally supporting the rise of residential prosumer collectives. This literature review has identified the lack of enabling solutions from top actors in the electricity system, the rise of new businesses, middle actors, which are developing smart grid offerings for residential prosumer collectives, and the need to consider fairness and demand flexibility aspects in dynamic demand response for such collectives.

The third question investigated how new businesses are shaping smart grid solutions and how this implicates dynamic demand response, by gathering qualitative data from semi-structured interviews with executives from new businesses with current or potential solutions for dynamic demand response for prosumer collectives.

The fourth question explored how to foster fairness in software solutions enabling dynamic demand response for collectives of households, by interpreting the notion of fairness based on literature and interview findings, and using qualitative data (smart meter data, electricity tariffs, etc.) to do so.

7.2 Findings and Discussion

In this section, I discuss the main findings of the research, highlight how they link to the literature, and intertwine findings from the social and technical work streams of this thesis. Section 7.3 lists the points of novelty, where I am contributing to extend the literature, and Section 7.4 presents future recommendations on how this research can be used and by who.

7.2.1 Smart Grids

Based on literature review and further underpinned by research findings, smart grids host various technologies and features, which can significantly evolve current demand response practices to become more dynamic and suitable for the changing energy landscape in general, and the rise of prosumer collectives in particular.

Interview findings have shown that dynamic demand response solutions, being increasingly developed by new businesses for prosumer collectives, offer various benefits to power grids, prosumers and collectives, and the wider society, including:

- Greater resilience for power grid systems and operations, which can enhance grid reliability and stability
- Improved utilization of power grid assets, which can help with the transition towards decentralized power grids and cancel or postpone building large generation power plants
- Enhanced data-driven decision-making in power grids and prosumer collectives, which supports value creation from smart grid data
- Stronger market access and business models for prosumer collectives, which boosts their position to sell or trade electricity, or provide demand response resources
- Greater autonomy for prosumer collectives, where they can rely on energy self-consumption and be more independent of the grid
- Enhanced options for prosumer engagement, choice and control
- Increased use of renewable energy technologies, which contribute to various environmental and societal benefits for the wider society

7.2.2 Prosumers and their Collectives

The literature review and interview findings confirm that the rapid emergence of prosumers and the growing phenomenon of prosumer collectives are both strong trends in the transition of power grids from centralized load-following to decentralized supply-following. Such trends are indicators of how the energy landscape is changing, and how energy end-users' characteristics, activities, and objectives are becoming multi-faceted. Such complex changes are triggering the adoption of interdisciplinary research, as leveraged herein, and the creation of innovative smart grid offerings and new business cases.

Individual Prosumers

Although the concept of prosumerism, which was first introduced in the 1980s and expanded in 2008, revolves around value creation, my findings have concluded that current definitions of *energy prosumer* in the literature focus on energy and who is using it (i.e. whether it is self-consumed or shared with others), rather than value creation around this energy, which limits prosumerism in a way.

Literature review and research findings have shown that an energy prosumer can create value by totally using, totally exporting, or both using and exporting energy, which contrasts with existing definitions describing the prosumer as someone that is primarily exporting surplus energy. Prosumers have various objectives; they may have become prosumers, in the first place, for financial benefits rather than to achieve energy self-sufficiency. Such findings indicate that, in all cases, prosumers add to the electricity mix of the grid, irrespective of who is consuming that electricity, and creating value around energy in new ways (selling electricity, storing energy, etc.). This, in turn, informs the development of smart grid offerings targeting prosumerism, and highlights how they can be shaped to create benefits for prosumers, the grid, and other involved stakeholders.

To make individual prosumerism more encompassing of value creation, I proposed a new definition for an energy prosumer, as follows:

> *An energy prosumer produces energy and can totally or partially consume, sell, store or trade this energy.*

Interview findings have especially highlighted the value creation issue, where some executives think future prosumers may become paid nodes by receiving incentives in return for their location on the grid and the benefits they can help others (grid operators, distribution companies, etc.) achieve. Such findings should ideally trigger middle actors to develop businesses models and innovative offerings for prosumerism in a way that incorporates value creation for and by prosumers.

Literature and interview findings have underlined that macro- and micro-scale economics, policies and regulations play a core role in shaping the constraints of prosumers' objectives. Today, a prosumer may use electricity or store it; tomorrow, they may sell it to the grid or to a consumer. Therefore, when developing smart grid offerings for prosumers, careful consideration should be given to the wider economic and regulatory context where such offerings are to be deployed, to guarantee their acceptance and successful adoption.

Based on interview insights, smart grid offerings enabling dynamic demand response for individual prosumers include battery storage, distributed energy control and optimization, automated demand response, energy disaggregation, dynamic electricity pricing, and online electricity trading.

Prosumer Collectives

Based on literature review, I proposed the following definition to describe a prosumer collective,

> *A prosumer collective comprises a group of consumers producing and/or storing electricity through multi- or focal-site distributed energy resources, and leveraging information and communication technologies to create value for the collective and its external stakeholders.*

I have concluded that this definition is inclusive of the various initiating entities and configurations of prosumer collectives. This term neither links the definition to a "community", because not all collectives are community-based, nor restricts it to a specific grid structure (e.g. micro-grid). In a similar way to the definition I proposed for a prosumer, this definition builds on the concept of value creation, where prosumer collectives can potentially benefit "everyone", which should ideally push the creation of more collective-driven smart grid products and services.

Building on this definition, it is important to reiterate that a prosumer refers to each member of a prosumer collective, regardless of whether this member is individually considered a prosumer. This is especially applicable to focal-site collectives (e.g. Hepburn Wind). Underlining this point may promote the concept of collective prosumerism, by making it easier for households to join a prosumer collective, as they do not necessarily need to have their own distributed energy resources to be part of a collective, but can alternatively support shared energy assets, e.g. technically, or financially.

Furthermore, the proposed definition broadens the opportunities for creating value for a collective. For instance, this definition does not limit value creation in a prosumer collective to exporting surplus energy to external entities, as certain collectives may be essentially financially-driven. In fact, one of the executives pointed out that their company dominantly works with prosumer collectives selling their electricity production to the grid rather than those self-consuming it. Such findings can trigger new businesses to look beyond the energy self-sufficiency issue of prosumer collectives, and address a wider set of objectives for those collectives.

In the interviews, most executives used the words community and micro-grid to refer to what I define as a prosumer collective. I link this back to the early development of prosumer collectives, which were often initiated by grassroots community efforts, and to commercial micro-grids, which integrate various forms of distributed energy resources and operate in island-mode in case of grid emergencies. This indicates that new businesses are working across a range of offerings for prosumer collectives, and are not limited to specific physical configurations.

Based on the literature, drivers of forming prosumer collectives include future proofing and creating relevant actors in a world powered by renewable energy. One of the executives described this meaning, in a way, by saying that their business is "building a leader board of like-minded people who are engaged on something that is mundane like electricity". Interview findings further support this point, where executives see prosumer collectives relevant in a future where the uptake of distributed renewables is rising and where resiliency to climate change impacts is essential. Such findings support middle actors' business cases and their efforts to advance the state of prosumer collectives and associated smart grid offerings, and underpins their role in catalyzing energy transformations.

While the desire to live green by using renewable energy is one of the key drivers of individual and collective prosumerism, interview findings indicate that this desire goes beyond electricity usage to include transportation, public buildings, geographies and community action. One of the executives summarized it by saying that "it is about doing things in a new way". This emphasizes the need to build collaborations around products and services pertaining to energy, in order to create a holistic view of the wider society.

The literature shows evidence that power grids in many countries are becoming smart(er). By using interview findings to relate to this, executives think that enabling technologies for prosumer collectives are available, and expect future collectives to use more real-time technologies and generally become smarter; nonetheless, executives also think that the future is more about cost drivers rather than technology. This triggers the urgency to bring economic analysis into this socio-technical context, especially around developing products and services, as cost is expected to play a key role in driving the future growth of prosumer collectives.

Literature and interview findings highlight the rise in integrating batteries in households, and link it to the fall in battery prices. While the literature focuses on prosumers' benefits arising from using distributed storage, executives highlighted how batteries implicitly benefit distribution companies, by helping mitigate the impacts of intermittent micro-generation on distribution networks. This is one way of emphasizing that value creation from smart grid offerings for prosumer collectives goes beyond individual prosumers and collectives, to benefit top actors (e.g. distribution companies). This also draws attention to the integral role of batteries in dynamic demand response, where they enhance the potential for creating flexible demand, notably in case of intermittent micro-generation.

Based on literature findings and analyzing example prosumer collectives, solar PV, wind turbines, biogas plants, and solar thermal panels are the main technologies being used for distributed generation in prosumer collectives. Yet, in the interviews, executives rarely mentioned solutions around solar thermal panels. In fact, one of the companies has developed a solution to heat water using solar PV rather than solar thermal because of its inefficiencies if poorly insulated. This focus on electricity-generating solar can be attributed to the rise in electrification, e.g. rise in the uptake of heat pumps as a heating/cooling source, rather than non-electricity based heating. In fact, this focus can further support the rise in electrification identified in the literature, especially as the adoption of prosumer collectives grows.

7.2.3 Top Actors

The literature review has shown that the majority of top actors (grid operators, distribution companies, etc.) lack the pace and/or the capacity to innovate dynamic demand response offerings for prosumers and collectives. This was confirmed by interview findings, where executives think that one of the factors triggering their companies to launch was to fill the gaps left by top actors in catering for prosumerism in general. This emphasizes that there is a gap left by top actors, and middle actors are emerging to elevate the capabilities of top actors to develop smart grid offerings that improve demand response practices to cater for the needs of prosumer collectives.

Executives have generally linked the tardiness of most top actors to a lack of knowledge and appropriate pricing mechanisms, slow markets and processes, and caution around revenue generation. This finding can serve as a guidance to top actors, so that once they experience such issues, they should seek support from middle actors to enhance their capabilities in addressing the needs of prosumer collectives.

The executive from the only top actor interviewed, a distribution company, has exemplified the voice of a slow top actor. This executive forecasted that prosumers will grow, whether top actors like it or not, and that top actors have to adapt, which reflects a passive role reacting to change rather than a proactive role catalyzing this change.

7.2.4 Middle Actors

In this thesis, the term “middle actors” is used to refer to businesses facilitating the interactions between rapidly rising bottom actors (i.e. prosumer collectives) and slow-moving top actors (electric utilities, grid operators, etc.). Middle actors developing state-of-the-art smart grid offerings to prosumers and collectives are emerging so rapidly that very limited literature exists on this topic.

Interview findings have demonstrated that middle actors have mostly emerged to fill the gap left by those top actors failing to meet the needs of prosumers and collectives while maintaining reliable and stable power grids. Middle actors mainly add value by developing offerings, mostly software-based, for prosumer collectives to maximize energy self-consumption, maintain grid reliability, create value from smart grid data, and enable flexibility management.

Based on their dates of establishment, middle actors have mostly launched their businesses during the past few years. In seeking to find well-established businesses with new offerings for prosumers and collectives – so as to interview their executives – very few companies have been found to fit this category. This was further underlined by interview findings, which have shown that very few innovative solutions are being built by well-established companies with existing offerings for traditional demand response.

With regards to evolving their solutions, interview findings have shown that some companies evolve vertically, by adding new features to their solutions and enhancing their existing offerings, while others try to diversify their offerings horizontally by expanding their geographies, markets, and technologies. This finding can guide the growth of businesses developing dynamic demand response solutions, by providing various options for enhancing their offerings and presence.

7.2.5 Dynamic Demand Response Solutions

Based on literature review, I identified five categories of solutions with potential for enabling dynamic demand response for prosumer collectives, as follows: (1) virtual power plant, (2) technology for optimized resource use, (3) dynamic electricity pricing, (4) peer-to-peer transactions within a community, and (5) aggregation.

Based on the interviews, I identified four categories of solutions, namely (1) virtual power plant, (2) automated demand response, (3) dynamic electricity pricing, and (4) online electricity trading, as described below. Those four categories have been distinguished based on terminology used by interviewees, the way they categorize their companies' offerings, and considerations around what is included under each category of solutions (e.g. aggregation is being currently considered as part of virtual power plant operations).

- Virtual Power Plant – Monitor and control various micro-generation, storage and flexible load devices (e.g. solar PV inverters, battery management systems, and load controllers) based on the demand flexibility plans of households, grid conditions, external conditions (e.g. temperature and humidity), and market conditions around energy trading in order to optimize power flows or trade energy.

- Automated Demand Response – Monitor and control various household appliances and storage devices (e.g. smart thermostats and home batteries) based on a preprogrammed demand reduction plan, demand response event specifics, and grid conditions in order to automatically change demand during an event (also applies to consumer households).

- Online Electricity Trading – Provide online trading services that allow prosumers to sell their electricity to consumers on the same distribution network or to the power grid, and enable consumers to shop for their energy.

- Dynamic Electricity Pricing – Provide retailing services, where electricity is sold at wholesale electricity market prices or dynamic tariffs (e.g. expected cost-to-service tariffs) in addition to fixed retailer costs, to consumers who want to benefit from cheaper rates at off-peak hours and prosumers who want to store cheap electricity in their batteries.

Solutions around virtual power plants and dynamic electricity pricing have been identified in both the literature and interview findings. Aggregation has been identified in the interviews as part of virtual power plant operations, and is thus not currently considered a separate category of solutions.

Based on the interviews, technologies for optimized resource use primarily achieve automated demand response. As for peer-to-peer transactions within a community, this categorization is very specific, and thus not descriptive enough for electricity trades in prosumer collectives. Therefore, building on interview insights, the term online electricity trading has been chosen instead, to provide a broader description, which can be within the collective or between the collective and external entities.

Those various categories of dynamic demand response solutions are all leveraging smart grid technologies and features, in one way or another, to evolve the demand response concept, enhance its practices, and make it accommodating for prosumerism and collectivism. This, in turn, helps address the overarching research aim of this thesis, around how new opportunities made possible by the smart grid can be used to improve the status of demand response for prosumer collectives, while benefiting end-users and power grids. Demand response is evolving and branching into a number of dynamic demand response offerings, which are motivated by a range of drivers and are creating various benefits.

7.2.6 Demand Flexibility

Interview findings have shown that companies interpret the word "flexibility" in various ways that go beyond demand flexibility, and thus two streams of smart grid solutions relating to flexibility have been identified, solutions (1) incentivizing flexibility (using dynamic pricing, etc.), and others (2) enabling flexibility (using smart controls, etc.). Dynamic demand response approaches are thus expanding beyond demand flexibility, to address a wider range of interpretations for flexibility.

In the literature review, I pointed out that the current definition of demand response needs to be stretched to accommodate energy transformations at the demand-side of the grid, and proposed the term "dynamic demand response" to describe the new approaches being developed for managing energy in prosumer collectives. Nevertheless, most executives used the term "flexibility management" to refer to the new and improved version of demand response that relates to enabling flexible demand.

In the literature, demand response and distributed storage are generally identified as two separate ways of creating demand flexibility. Interview findings, however, have reflected that distributed storage is an integral part of smart grid offerings. Thus, dynamic demand response includes distributed storage at its core.

7.2.7 Fairness

The literature review has underlined that failure to develop fairness and equity in prosumer collectives may result in a lack of their social acceptance, and that exploring procedural and distributive fairness in such collectives can help in understanding and evaluating their processes and outcomes.

Investigating the example prosumer collectives, presented in Section 3.3.6, has specifically identified the importance of tackling issues such as fair distribution of fees, benefits and flexibility, in order to support the growth and acceptance of prosumer collectives.

Very little literature exists around fairness for prosumer collectives and in dynamic demand response settings, where fairness is often poorly formulated and/or explained, and only comprises part of research investigations.

The concept of "fairness" has been discussed with company executives, and findings show that it is a very important aspect that is highly valued by companies, and is integrated in different forms in their solutions. The responses have generally indicated that companies see fairness as an issue that needs to be holistically addressed across involved stakeholders, rather than be focused on a specific feature in a product or service. Considering social concepts, such as fairness, in such smart grid solutions is thus happening, and it is recommended to be holistically addressed rather than be implemented in silo features.

Fairness for some companies is implemented by providing transparency through dynamic electricity prices which reflect wholesale electricity spot prices. For other companies, fairness lies in providing market access to prosumer collectives, in a similar way to traditional generators, to sell their electricity to the grid or large-scale consumers, or in enabling trading among prosumers and consumers in a collective. Executives also see fairness being implemented via providing freedom for both prosumers and consumers to choose who to sell and buy electricity to and from, respectively, which is actually being offered by a few online trading platforms. Reflecting on this, it is important to clarify that choice in this case is just in terms of transactions rather than actual physical electrons moving from a prosumer to a consumer.

By linking those findings to the literature, such forms of fairness yield procedural justice in enhancing the outcome of decision-making processes made by bottom actors, where aspects like transparent access to information, the right to participate, and freedom of choice are supported.

As for fairness in the form of distributive justice, some executives see their companies delivering fairness by empowering prosumers and collectives to partition energy assets and associated financial benefits with big electric utilities, e.g. by exporting their electricity to the market and create a market share for themselves, instead of the dominance of big utilities. Other companies focus on fairly distributing benefits among stakeholders involved in prosumer collectives. As for battery system providers, they see their batteries contributing to fairness in the case of low feed-in tariffs, as they help prosumers fairly distribute the value of their investment instead of having to opt-in to revenue from low tariffs.

The two software algorithms developed in the technical stream have built on the perceptions induced from the interviews about what fairness means for middle actors. The first algorithm, the *fair share allocator*, can help a prosumer collective selling its electricity to share its income fairly among its prosumers. This algorithm can be modified to suit consumers and distribute compensation among those collaborating to reduce demand during a demand response event. The second algorithm, the *loss of utility allocator*, can help households collectively reducing demand by assigning fair allocations of loss of utility, associated with demand response, among those households. This algorithm can be modified to distribute loss of utility among prosumers (equipped with separate units of micro-generation) contributing to electricity exported by a collective.

Both algorithms can be integrated into software solutions provided by emerging businesses to top actors, to create fairness-driven offerings that attract both prosumers and consumers and promote collective action. Those algorithms approximate fair shares, using the Shapley value, for a collective comprising up to 400 households with high accuracy, while using appropriate time and memory resources.

7.2.8 Business Models and Regulations

Although business models of middle actors and associated regulatory frameworks enabling prosumer and collectives have been briefly touched upon throughout this thesis, delving into details pertaining to both topics was not intended to be part of this research. Interviews have been conducted with companies operating across different jurisdictions and regulatory contexts, and no specific countries or markets were discussed in details. Interviewees have not been directly asked neither about the details of their business models nor about regulatory contexts impacting their offerings.

Nevertheless, interview findings have highlighted situations where regulations have impacted both prosumerism and collectivism. For example, the drop in feed-in tariffs in 2011 in Germany has motivated prosumers to use batteries to increase their self-consumption from their rooftop solar panels and save money on buying electricity from the grid, rather than earn reduced money from selling electricity to the grid. In Germany, network providers pay entities (e.g. middle actors) to take excess energy from the grid in order to stabilize it, and such middle actors may use this money to cover the expenses needed by the prosumers they serve to achieve 100% energy self-sufficiency.

I concluded that middle actors are basically moving away from the traditional corporate model of electric utilities, and adopting new business models for value creation. The majority of middle actors today rely on a business-to-business model, where they provide solutions to top actors, which then serve bottom actors. This finding overlaps with the literature review, which indicated that although most top actors are not up to speed with adequately offering innovative solutions to collectives, those top actors that are up to speed are doing so in collaboration with middle actors.

Interviews have shown that only a few companies rely on a business-to-customer model in which they directly serve bottom actors. This may be due to the nature of products and services provided by those middle actors. However, this may stem from the absence of proactive top actors, which create opportunities for middle actors to shadow the role of top actors, especially in deregulated markets promoting competition, while providing innovative offerings as well.

7.3 Novelty

The literature studying the transition to more decentralized energy systems mainly takes a technocratic approach around how and where to integrate distributed energy resources into existing infrastructure while maintaining grid reliability. Social studies on decentralized energy systems focus on their influence on end-user behaviour and their spatio-temporal diffusion, while socio-technical literature on the same topic is limited. The ways in which socially-conscious technology solutions can be shaped to support the integration of distributed energy resources is often overlooked, while the actors developing such solutions are under-investigated.

This research provides novelty by interweaving social and technical knowledge from literature to develop new interpretations for the complex interactions arising in residential prosumer collectives and the innovation leveraged in dynamic demand response, and to create new socio-technical knowledge around those interpretations.

This research extends the literature by:

- Investigating the role of new businesses (middle actors) in facilitating the interactions between electricity system incumbents (top actors) and residential prosumer collectives (bottom actors), and the value they create

- Exploring how advanced technologies in information, communication, and distributed energy are disrupting traditional demand response and creating a new wave of dynamic demand response offerings

- Identifying four categories of dynamic demand response solutions: virtual power plants, automated demand response, online electricity trading, and dynamic electricity pricing

- Extending the socio-technical literature around what fairness means for middle actors, and how fairness is reflected in smart grid offerings for prosumer collectives

- Proposing a definition for a prosumer collective, and a new definition for an energy prosumer, where both definitions revolve around value creation rather than specifics of physical configurations or objectives

- Approximating the Shapley value, which determines the unique and fair share of each player in a coalition, based on their average marginal contribution, with high accuracy and reasonable time and memory resources for a collective comprising 400 players

- Developing a software algorithm which approximates the fair distribution of a collective's revenue (from selling electricity) among its prosumers

- Developing a software algorithm which trades off minimum total loss of utility, experienced by a collective of households in a dynamic demand response event, with fairness in allocating loss of utility among those households

7.4 Future Work

Interview findings have shown that the future of energy demand management is forecast to focus on flexibility management, power quality enhancement and developing decentralized power grids, while residential prosumer collectives are expected to integrate more battery storage and real-time intelligent technologies, and be both physical and virtual.

As for the challenges facing the development of prosumers and collectives, they are expected to revolve around creating flexibility, coordinating between involved stakeholders, developing scalable business models and adequate regulatory frameworks, and managing social risks. Based on those findings, I conclude that future research around dynamic demand response for prosumer collectives needs to focus on four topics, as follows:

- Creating effective coordination between stakeholders involved in prosumer collectives, to holistically tackle the multi-faceted problems facing collectives that go beyond socio-technical energy research (e.g. economic topics)
- Developing scalable business models for those regulatory contexts supporting the emergence of prosumers and collectives, while mitigating associated social risks
- Investigating virtual prosumer collectives to identify their benefits and challenges
- Creating regulatory frameworks that support the growth of prosumer collectives in contexts lacking support for collective prosumerism and associated interactions

My findings can inform the decision-making of middle actors around innovating socio-technical products and services enabling energy management for prosumer collectives. Such findings can trigger further research by interdisciplinary teams, or shape product roadmaps for new businesses developing user-centric offerings for dynamic demand response in residential prosumer collectives.

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Appendix A

Demand Response Mechanisms

This appendix includes demand response mechanisms based on their objectives at three power grid levels [22]: (1) system operation, (2) generation, transmission, and distribution, and (3) retail, for industrial, commercial and residential customers. Tables A.1–A.9 include each objective and its explanation, example mechanisms and their characteristics, and example programs.

Table A.1: Providing power capacity

Objective – Capacity provision
Overview – The GO uses DR resources to provide power capacity to the grid in case of a system-wide peak load. This DR mechanism aims to (1) reduce the generation capacity requirements of the power grid, (2) reduce the dependence on generation expansions to meet future peak demand, (3) ensure a medium to long term balance between electricity supply and demand, and (4) cut the costs required to meet forecast demand [37, 100, 334].
Mechanism explained – In this DR mechanism, auctions take place, where bidders (i.e. DRP participants) commit to reduce demand during a future peak (e.g. a peak occuring in the window of three years ahead [335]) in exchange for incentives [22].
Response speed – Few minutes - few hours [22].
Response duration – Few minutes - several hours [22].
Correlation with renewables – Low (or inverse in the case of renewables, which can act as a competitor to DRP participants by introducing additional power supply instead of reducing power demand) [22, 335].
Example program – The capacity provision market, called Reliability Pricing Model, implemented by the Pennsylvania-New Jersey-Maryland Interconnection (PJM) [335], a world leader in grid operations and competitive wholesale markets in the US [336], is an example program targeting large-scale customers [337].

Table A.2: Enhancing system reliability

Objective – System reliability enhancement

Overview – The GO uses DR resources to enhance power systems reliability, by maintaining and improving the balance between electricity supply and demand in case of system contingencies (e.g. the occurrence of a blackout where power plants fail to cover demand loads) [38]. Due to the flexibility, fast response and lower costs of deploying DR over operating electricity generation units, it is preferred by GOs for enhancing system reliability. [22]. In such mechanisms, the GO sends DR requests to DR administrators willing to change electricity use, based on agreed constraints, and DR administrators are compensated in return [22].

Example mechanisms

- Direct load control
- Interruptible load
- Frequency regulation
- Frequency-controlled load shedding
- Ancillary service market participation

Mechanism explained – In direct load control, the GO controls certain loads at the consumer's premises, especially small flexible loads that can be easily aggregated (e.g. heaters, air conditioners, refrigerators, and water heaters) [338]. Such direct controls, which are sent by the GO via a special direct load control device installed at the consumer's side, can take different forms, e.g. load cycling, load limiting, or operation point control [339].

Response speed – Few seconds - few hours [22, 101].

Response duration – Few minutes - several hours [92, 340].

Correlation with renewables – Low - high [22].

Example program – Hydro Quebec, which oversees all power grid operations and services in Quebec, has an interruptible load program available to its large scale customers who can reduce at least 3000 kW of load upon request [341].

Table A.3: Enhancing market efficiency

Objective – Market efficiency enhancement
Overview – Where system reliability and fast response times are not major concerns, the GO uses DR to provide flexible energy consumption and more economic system operation [247]. This DR mechanism helps maintain efficient electricity spot prices, guarantees long-term demand flexibility, and is suitable for loads able to withstand long curtailment periods [22].
Example mechanism – Demand bidding/buyback.
Mechanism explained – This DR mechanism is triggered by price signals, where the GO provides incentives to DRP participants whose demand reduction bids in the electricity market can reduce spot prices [342].
Response speed – Few minutes - few hours [22].
Response duration – Several hours [22].
Correlation with renewables – Medium [22].
Example program – The DR program implemented by the National Electricity Market of Singapore enables consumers to receive incentives when they reduce loads by at least 100 kW per half hour, directly or indirectly (i.e. via an aggregator) [343]. Typical loads include non-critical production equipment and HVAC systems. Consumers can alternatively use on-site backup generators, instead of electricity coming from the grid, to enable load flexibility [343].

Table A.4: Balancing generation with load

Objective – Load Shaping
Overview – In order to have more controllability and dispatchability over generation resources, especially intermittent renewable ones, electricity generators leverage demand flexibility enabled by DR, where demand is changed to match available supply, to meet their supply obligations towards demand loads [35, 102]. This mechanism is still uncommon, as generation entities do not frequently deal directly with loads [22]. Additionally, there remains a need to enhance the flexibility of demand loads to optimally match intermittent generation, by integrating advanced energy storage and control systems [35, 102]. Thus, this mechanism is yet to undergo improvements enabled by the new technologies continuously being rolled out in the power grid.
Response speed – Few minutes - few hours [104].
Response duration – Few minutes - few hours [104].
Correlation with renewables – Very high [35, 102].
Example program – In Japan, a power producer and supplier (PPS) only manages generation facilities, without network transmission or distribution ownership, and provides electricity directly to any large-scale consumer buying at least 50 kW of electricity. A PPS contracts directly with customers, and sends them DR requests to reshape the load if generation imbalance occurs [22, 103].

Table A.5: Managing congestion at the transmission level

Objective – Congestion management
Overview – Increasing electricity demand, especially in areas with weak network connections and an aging grid infrastructure, causes congestions in grid transmission. To avoid such congestions, the transmission operator uses DR as a proven solution to congestion mitigation, instead of investing in infrastructure upgrades [105, 106]. Through an auction mechanism, DRP participants in a zone with a congestion problem offer demand flexibility to transmission operators in return for incentives [344]. Note that this concept is similar to capacity provision; however, DR implemented by congestion management solely targets transmission network congestions.
Response speed – Few hours - several hours [107].
Response duration – Few hours [107].
Correlation with renewables – Medium [22].
Example program – The distribution Load Relief Program developed by Con Edison, one of the largest US energy companies operating in metropolitan New York, offers incentives to customers who reduce demand upon request. In this program, which has a 2-hour or less notification period, customers receive payments for the load they actually reduce in addition to a fixed monthly payment based on the energy they pledged to reduce. For example, in network locations with a higher priority for DR, a customer receives \$15 per kW per month and \$1 for each kWh reduced during a DR event. All other customers receive \$6 per kW per month and \$1 for each kWh reduced during a DR event. A customer able to reduce at least 50 kW can apply directly to Con Edison; otherwise, participation is via an aggregator [107]. The Commercial System Relief Program, also developed by Con Edison, has a 21 hour notification period and offers customers \$10 per kW per month and \$1 for each kWh reduced during a DR event [107].

Table A.6: Enhancing system reliability at the distribution level

Objective – System reliability enhancement
Overview – Ripple control is a common form of direct load control used by distributors to enhance system reliability by reducing peak loads through operating night storage heaters and hot water cylinders during off-peak hours [101, 108]. This DR mechanism is commonly used in the UK, Germany, South Africa, Australia, and New Zealand. It involves superimposing a higher frequency signal using a ripple injection device, over the standard frequency signal. This higher frequency signal is received by a ripple receiver at the customers side, and as a result, the meter relay switches off during peak hours then back on again during off-peak hours [101, 108, 109].
Response speed – Few seconds [108].
Response duration – Few hours - several hours [108].
Correlation with renewables – Low - high [22].
Example program – Ripple control was introduced in New Zealand in 1949 [109] and has been in operation since then as the main DR tool used by distributors. As a result of ripple control, a 5-10% reduction in peak demand, corresponding to 30-60 MW, can be reached [101].

Table A.7: Enhancing electricity procurement at the retail level

Objective – Procurement enhancement

Overview – The electricity retailer may encounter a deficit in supplying power to its loads, due to sudden changes in load patterns or an error in forecasting demand. In this case, the retailer would need to buy electricity from spot markets with highly fluctuating prices, which may negatively impact its revenues. To avoid losses, retailers use DR to change demand patterns, and thus minimize the costs of electricity procurement [56, 113, 114].

Example mechanisms

- Incentive-based interruptible load
- Price-based interruptible load

Mechanism explained – Interruptible load is load available for automatic demand reduction using frequency controlled relays [101]. In exchange for demand reduction, customers with large loads typically receive incentives in the form of pro rata or fixed payments (incentive-based DR) ([115], and those with smaller loads receive discounted prices (i.e. price-based DR) [345].

Response speed – Few seconds - few minutes [101, 346].

Response duration – Few minutes - few hours [101, 346].

Correlation with renewables – Low [22].

Example program – The DemandSMART Interruptible load program in New Zealand is an example program which rewards commercial and industrial businesses with incentives in return for providing interruptible loads, e.g. refrigeration compressors, HVAC systems, and electric furnaces. The program runs in weekdays, between 7 am and 8 pm, where customers receive 2 hours advance notice for DR events that typically last 24 hours. This program is provided by EnerNOC, a leading provider of energy management software, in partnership with Genesis Energy, which offers electricity generation and retailing services in NZ. EnerNOC automatically aggregates interruptible loads for customers [347, 348].

Table A.8: Providing power capacity at the retail level

Objective – Capacity provision
Overview – In certain markets, an electricity retailer needs to secure a specific level of power capacity based on the peak loads it serves, and if it surpasses this level, penalties are imposed. To optimally manage power capacity, retailers use DR to reduce peaks (i.e. the capacity level needing to be secured), and to guarantee that this level is not surpassed to avoid penalties [22, 110].
Response speed – Few minutes - few hours [111, 337].
Response duration – Few minutes - few hours [111, 337].
Correlation with renewables – Low [22].
Example program – The capacity market developed by PJM allows curtailment service providers (i.e. aggregators) to bid DR capacity on behalf of retail customers who receive incentives in exchange for reducing demand [112, 337].

Table A.9: Shaping demand load at the retail level

Objective – Load shaping
Overview – This DR mechanism can be used by retailers to leverage consumers' demand flexibility in order to shape retailers' load [22, 349, 350], with the objective of increasing its profits [351]. The triggers of this mechanism are either dynamic price signals or incentives, where consumers' loads are shifted from on-peak to off-peak periods with cheaper prices or to certain periods as requested by the retailer. The use of this mechanism is scarce as DR has a limited ability to maintain load increases [22]; however, innovative approaches are underway to optimally shape demand profiles especially with the proliferation of distributed local generation and storage technologies [350, 352].
Response speed – Few minutes - few hours [104].
Response duration – Few minutes - few hours [104].
Correlation with renewables – Very high [35].
Example program – Although DR can help a retailer reshape their load to cut down on required generation capacity and cost, it inherits risks which can affect the retailer's profitability [353]. Few studies have been conducted on this type of DR mechanism; one study has shown that a retailer using DR to shape their load can reduce cost volatility by more than 7%, peak costs by more than 14%, and expenditures by 3.5% [351].

Appendix B

Interview Questions

Story of Company – To learn about the company and the participant

- Can you please introduce yourself and tell us about your background?
- Can you tell us the story of the company and what it does?
- What are your responsibilities within the company?

Value to Society – To learn about the values provided by the company

- What are the products and/or services provided by the company?
- What are the values of the company?

Enabling Prosumer Collectives – To understand how company solutions enable demand flexibility and fairness, and learn about prosumer collectives the company is involved with

- How do the solutions provided by the company enable energy demand flexibility?
- Are these solutions currently used by any individual prosumers?
- If yes, can you tell us more about this?
- If no, are there future plans to target prosumers?
- Are these solutions currently used by any residential prosumer collectives?
- If yes, can you tell us more about this?
- If no, are there future plans for involvement in prosumer collectives?

- What incentives do end-users receive for using the solutions you provide?
- Do these solutions provide fairness (e.g. fair billing or pricing, fair distribution of incentives, fair allocation of demand flexibility)?
- If yes, how?
- If no, how do you see them providing fairness?
- Can you tell us more about some of the feedback you receive from your customers?

Future Vision – To understand how company solutions are evolving and learn about the future challenges facing energy demand management and prosumer collectives

- What can be improved in the current solutions you provide?
- How do you see the solutions provided by the company evolving?
- How do you see the future of energy demand management in general?
- How do you see the future of residential prosumer collectives?
- What do you think the main challenges will be in providing energy management solutions for prosumer collectives?

Appendix C

Ethics Approval

Reporting Sheet for use ONLY for proposals considered at departmental level

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Form Updated: May 2016

UNIVERSITY OF OTAGO HUMAN ETHICS COMMITTEE APPLICATION FORM: CATEGORY B

(Departmental Approval)

Please ensure you are using the latest application form available from: http://www.otago.ac.nz/council/committees/committees/HumanEthicsCommittees.html

1. **University of Otago staff member responsible for project:** *Dr. Janet Stephenson*

2. **Department/School:** *Centre for Sustainability*

3. **Contact details of staff member responsible:** *janet.stephenson@otago.ac.nz*

4. **Title of project:** *Business Involvement in Energy Management for Prosumer Communities*

5. **Indicate type of project and names of other investigators and students**:

Staff Research		**Names**	
Student Research	Y	**Names**	Salma Bakr
Level of Study (e.g. PhD, Masters, Hons)			PhD
External Research/ Collaboration	Y	**Names**	Dr. Rebecca Ford
Institute/Company			

6. **When will recruitment and data collection commence?**

Recruitment and data collection will commence from 1 August 2016.

When will data collection be completed?

Data collection will be completed by 10 November 2016.

7. Brief description in lay terms of the aim of the project, and outline of the research questions that will be answered (approx. 200 words)**:**

The transition from centralized power grids to more decentralized microgrids, which integrate distributed energy generation and storage, is changing where and how electricity is produced, consumed, and managed. Energy consumers are becoming prosumers who can locally produce energy to meet their demand, and importantly, can sell, store or trade their surplus energy. Globally, prosumers are interacting with others in their vicinity, selling or sharing surplus energy with each other, and forming prosumer collectives. However most renewable generation (e.g. solar PV and micro-wind) used by prosumer collectives provide intermittent energy supply. In order to optimise the use of locally generated energy within prosumer collectives' microgrids, and to optimally manage the relationship with the wider energy system, there is a need for demand flexibility in prosumer communities.

In this project, we aim to investigate how demand flexibility can be achieved in residential prosumer communities, and how prosumers can be rewarded for being flexible. Additionally, we are interested in learning more about how to allocate demand flexibility and prosumer rewards in a fair way that encourages prosumers to have flexible energy demand.

We will conduct interviews with a number of companies with an existing or potential role in enabling energy demand to be managed in flexible ways. We aim to learn more about the companies, their solutions, and their values. Additionally, we aim to understand how their solutions enable energy demand management and achieve fairness in distributing flexibility and incentives. Finally, we aim to get an insight into the prospect plans of the companies, energy demand management in general, and their perspectives on the future challenges facing prosumer communities.

8. Brief description of the method. Include a description of who the participants are, how the participants will be recruited, and what they will be asked to do and how the data will be used and stored:-

The participants will be members (e.g. founders, chief executives, senior employees) of companies with existing or potential products or services in five areas that can enable demand flexibility and associated incentives: dynamic electricity pricing, technologies for optimized resource use, peer-to-peer transactions within a community, virtual power plants, and aggregators.

Between 5 and 10 businesses will be recruited based on their existing or potential role in developing products or services for flexibly managing energy demand in prosumer communities, and in order to represent the five areas listed above.

Each participant will be asked to have an interview in person where possible, or an individual phone/Skype interview if a face to face interview is not possible. Each participant will be asked to answer questions about their company, and its solutions and values; the ways in which the company's solutions can enable energy demand flexibility and fairness; and their personal views on how they see the future unfolding for the solutions they provide, energy demand management and prosumer communities.

All interviews will be recorded in audio format, with explicit permission provided by participants. Before starting the interview, participants will be asked to sign a consent form for in-person interviews, or agree to the terms laid out in the consent form for phone/Skype interviews.

Personal data will be stored securely such that only staff members involved in the project will be able to gain access to it. Any personal information will be destroyed immediately at the end of the project, except that, as required by the University's research policy, any raw data on which the results of the project depend will be retained in secure storage for at least five years, after which it will be destroyed. Where data is used in communications and publications, every attempt will be made to preserve the participants' anonymity.

9. Disclose and discuss any potential problems: (For example: medical/legal problems, issues with disclosure, conflict of interest, safety of the researcher, etc)

We are not aware of any potential problems. All respondents are invited to participate in advance and will be able to withdraw from the research at any point without any disadvantage to themselves.

An information sheet and consent form will be sent to each participant prior to the interview. A draft letter that will explain the nature of the project, the participants' commitments and ability to withdraw is attached to this application

***Applicant's Signature:**

Name (please print): Janet Stephenson

Reporting Sheet for use ONLY for proposals considered at departmental level

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Date: 9 July 2016

**The signatory should be the staff member detailed at Question 1.*

Signature of **Head of Department*:*

Name of HOD (please print): Caroline Orchiston (Deputy Director, Centre for Sustainability)under delegated authority from HOD Geog.

Date: *26.7.16*

**Where the Head of Department is also the Applicant, then an appropriate senior staff member must sign on behalf of the Department or School.

Departmental approval: *I have read this application and believe it to be valid research and ethically sound. I approve the research design. The research proposed in this application is compatible with the University of Otago policies and I give my approval and consent for the application to be forwarded to the University of Otago Human Ethics Committee (to be reported to the next meeting).*

ACTION TAKEN

[X] Approved by HOD [ ] Approved by Departmental Ethics Committee

[ ] Referred to UO Human Ethics Committee

IMPORTANT NOTE: As soon as this proposal has been considered and approved at departmental level, the completed form, together with copies of any Information Sheet, Consent Form, recruitment advertisement for participants, and survey or questionnaire should be forwarded to the Manager, Academic Committees or the Academic Committees Administrator, Academic Committees, Rooms G22, or G26, Ground Floor, Clocktower Building, or scanned and emailed to either gary.witte@otago.ac.nz. or jane.hinkley@otago.ac.nz

[Reference Number: *as allocated upon approval by the Human Ethics Committee*]
[*Date*]

UNIVERSITY of OTAGO
Te Whare Wānanga o Otāgo
NEW ZEALAND

Business Involvement in Energy Management for Prosumer Communities

INFORMATION SHEET FOR PARTICIPANTS

Thank you for showing an interest in this project. Please read this information sheet carefully before deciding whether or not to participate. If you decide to participate we thank you. If you decide not to take part there will be no disadvantage to you and we thank you for considering our request.

What is the aim of this project?

We are interested in how new businesses are emerging to improve the management of electricity generated by prosumers (households that both produce and consumer electricity). In particular, we are interested in how new business models are seeking to cater for prosumer communities, where residents in a neighbourhood may seek to collectively manage their surplus electricity so as to optimise its use.

What types of participants are being sought?

We are interested in talking with members (e.g. founders, chief executives, senior employees) of companies with existing or potential products or services that can enable solutions that help achieve flexibility in energy demand and fair allocation of benefits.

What will participants be asked to do?

Should you agree to take part in the project, you will be asked to participate in a face-to-face or phone/Skype interview. You will be asked questions about your company, its solutions and values; the ways in which your company's solutions can enable end-users to use energy in flexible ways and be rewarded accordingly; your thoughts on how such solutions disseminate fairness in allocating flexibility and rewards to end-users; any residential prosumer communities you are, or may be, involved with; and your personal views on how you see the future unfolding for the solutions your company provides, energy demand management and prosumer communities.

Please be aware that you may decide not to take part in the project without any disadvantage to yourself at any time.

What data or information will be collected and what use will be made of it?

The results of the interviews will be used to write up some case studies outlining the market players enabling flexible energy demand in residential prosumer communities. Where data from the interviews is used, every attempt will be made to preserve the company and participants' anonymity.

Data will be stored securely such that only researchers involved in the project will be able to gain access to it. At the end of the project any personal information will be destroyed immediately except that, as required by the University's research policy, any raw data on which the results of the project depend will be retained in secure storage for at least five years.

What data or information will be collected and what use will be made of it?

You may withdraw from participation in the project at any time and without any disadvantage to yourself.

What if participants have any question?

If you have any questions about our project, either now or in the future, please feel free to contact:-

Salma Bakr, PhD Candidate Centre for Sustainability University of Otago Email: salma.bakr@postgrad.otago.ac.nz Phone: +64212941112	Dr. Janet Stephenson Centre for Sustainability University of Otago Email: *janet.stephenson@otago.ac.nz*

This study has been approved by the Department stated above. However, if you have any concerns about the ethical conduct of the research you may contact the University of Otago Human Ethics Committee through the Human Ethics Committee Administrator (ph 03 479-8256). Any issues you raise will be treated in confidence and investigated and you will be informed of the outcome.

Business Involvement in Energy Management for Prosumer Communities

CONSENT FORM FOR PARTICIPANTS

I have read the Information Sheet concerning this project and understand what it is about. All my questions have been answered to my satisfaction. I understand that I am free to request further information at any stage.

I know that:-

1. My participation in the project is entirely voluntary;

2. I am free to withdraw from the project at any time without any disadvantage;

3. Personal identifying information will be destroyed at the conclusion of the project but any raw data on which the results of the project depend will be retained in secure storage for at least five years;

4. The results of the project may be published and will be available in the University of Otago Library (Dunedin, New Zealand) but every attempt will be made to preserve my anonymity.

I agree to take part in this project and confirm that I am over 18 years of age.

....

(Signature of participant) (Date)

....

(Printed Name)

Appendix D

Publications and Presentations

The following sections include my PhD publications and presentations to date. Publications in progress are not included.

Publications

- S. Bakr, S. Cranefield, Using the Shapley Value for Fair Consumer Compensation in Energy Demand Response Programs: Comparing Algorithms, in: Proceedings of the IEEE International Conference on Green Computing and Communications (GreenCom), 2015

- S. Bakr, S. Cranefield, R. Ford, A Fair and Profit-Optimal Consumer Compensation Structure for Load Curtailment Programs in Smart Grids, in: Proceedings of the International Workshop on Demand Response, Co-located with the ACM e-Energy Conference, 2014

- S. Bakr, S. Cranefield, Optimizing Shiftable Appliance Schedules Across Residential Neighbourhoods for Lower Energy Costs and Fair Billing, in: Proceedings of the Second Australasian Workshop on Collaborative Agents - Research and Development (CARE 2013), volume 1098, CEUR Workshop Proceedings, 2013, pp. 45–52

Presentations

- IEEE International Conference on Green Computing and Communications 2015, Sydney, Australia – Using the Shapley Value for Fair Consumer Compensation in Energy Demand Response Programs: Comparing Algorithms

- Groningen Energy Summer School 2014, Groningen, Netherlands – Smart Community-Level Energy Management for the Residential Sector
- International Workshop on Demand Response 2014, Cambridge, United Kingdom – A Fair and Profit-Optimal Consumer Compensation Structure for Load Curtailment Programs in Smart Grids
- National Energy Research Institute Conference 2014, Wellington, New Zealand – Optimizing Shiftable Appliance Schedules Across Residential Neighbourhoods for Lower Energy Costs and Fair Billing
- Second Australasian Workshop on Collaborative Agents 2013, Dunedin, New Zealand – Optimizing Shiftable Appliance Schedules Across Residential Neighbourhoods for Lower Energy Costs and Fair Billing
- Otago Energy Research Center Symposium 2013, Dunedin, New Zealand – Optimizing Household Appliances for Lower Energy Costs and Fair Billing