Chapter 1

Introduction

1.1 Background and motivation

1.1.1 Emergence of smart active distribution system

Increasing electricity consumption, power quality issues, and rising electricity prices have prompted many utility customers to seek for alternative sources of power. Energy generation and storage systems located at or near the place of use are the most common Distributed Energy Resources (DERs) technologies.

In recent years, the rapid development of various DERs has changed the structure, operating conditions and performance of distribution networks. The traditional passive distribution network with unidirectional power flow is transitioning towards an Active Distribution Network (ADN) with bidirectional power flow network. ADN will need to implement novel control structures and equipment capable of managing bidirectional power flow. Power distribution and utilization efficiency can be improved with Smart Grid (SG) functionalities such as power generation and consumption optimization, volt/var optimization, Demand-Side Management (DSM), energy loss reduction, and renewable energy generation and storage optimization. The term DSM refers to efforts to modify consumer demand patterns through various methods such as financial incentives and/or Time-of-Use (TOU) pricing schemes. According to the U.S. Department of Energy [1] report, the DSM can be defined as *"Changes in electric usage by end-use 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".* Information and Communication Technology (ICT) facilitates Distribution Network Operators (DNOs) to collect and act on statistical data about the behavior of suppliers, prosumers and consumers to improve the economics, efficiency, reliability and sustainability of electricity use.

In addition to the technical and economic aspects, some environmental concerns also encourage changes to the traditional distribution system. Globally, Greenhouse Gas (GHG) emissions have increased by 50 % from 1990 to 2018. The top ten GHG emitting countries contribute about 68.71 % of the world's total GHG emissions. The Figure 1.1 shows that China (26.1 %), the United States (12.67 %), the European Union (7.52 %) and India (7.08 %) are the major contributors to GHG emissions, and electricity/heat and transportation sectors are the main sources of emissions [2].

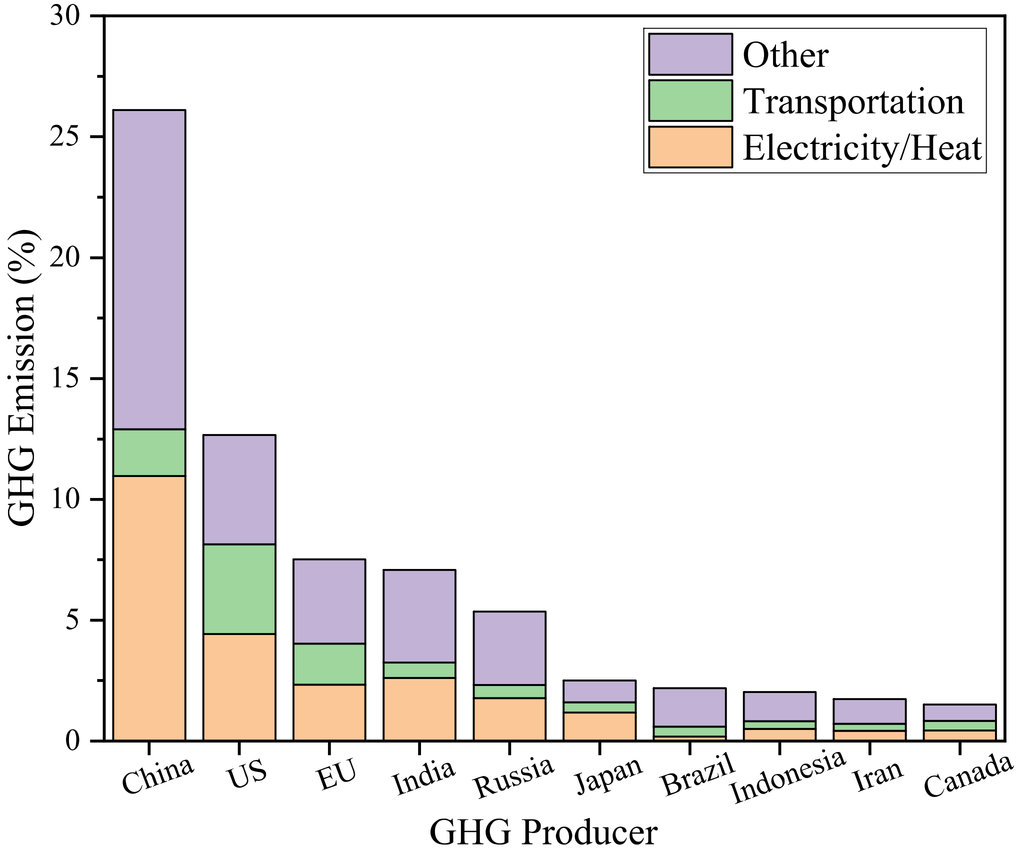

Figure 1.1: Contribution of top ten GHG producers in world's total GHG emissions

Therefore, the power generation and transportation sectors are the focus of interest for reducing GHG emissions. Renewable Energy Sources (RESs) and Electric Vehicles

(EVs) offer the best options for accelerating GHG reduction. The integration of RESs and EVs in distribution systems is a focused area of research in the recent years.

RES integration

RESs have become increasingly popular as a result of rising electricity demand, the fossil fuel depletion and growing concerns over GHG emissions. RESs can be divided into dispatchable sources, such as hydro, geothermal, biomass power, and non-dispatchable or variable sources, such as wind and solar. Dispatchable RESs are ready for production on demand, whereas the power generation of non-dispatchable RESs is dependent on weather conditions and/or time of day. The annual increase in global RESs capacity is shown in the Figure 1.2 [3].

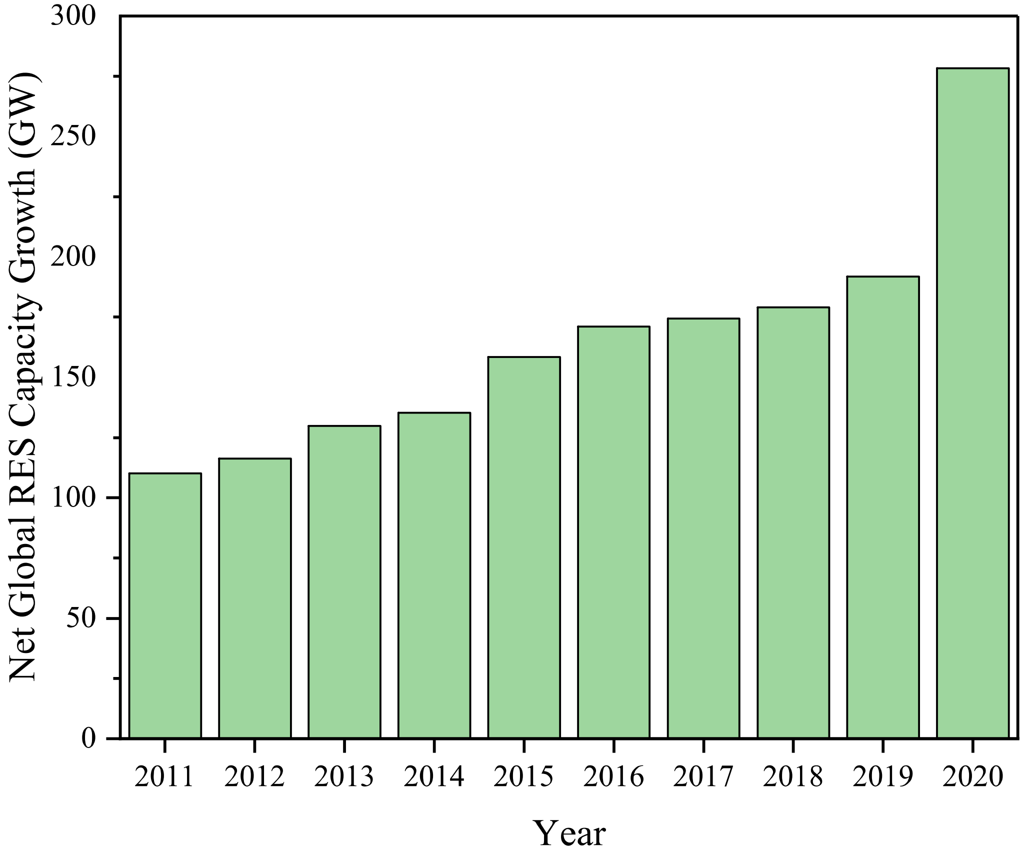

Figure 1.2: Annual increment in global RESs capacity

The RESs capacity increased by 278.3 GW in 2020. The solar and wind power have respectively 48.15 % and 40.82 % share in this increment. The solar and wind power are considered as fastest growing RESs technologies. Figure 1.3 shows that the worldwide cumulative installed capacity of solar and wind-based power generation has increased from 0.65 GW and 17.30 GW to 707.50 GW and 733.28 GW, respectively, over the past two decades [4].

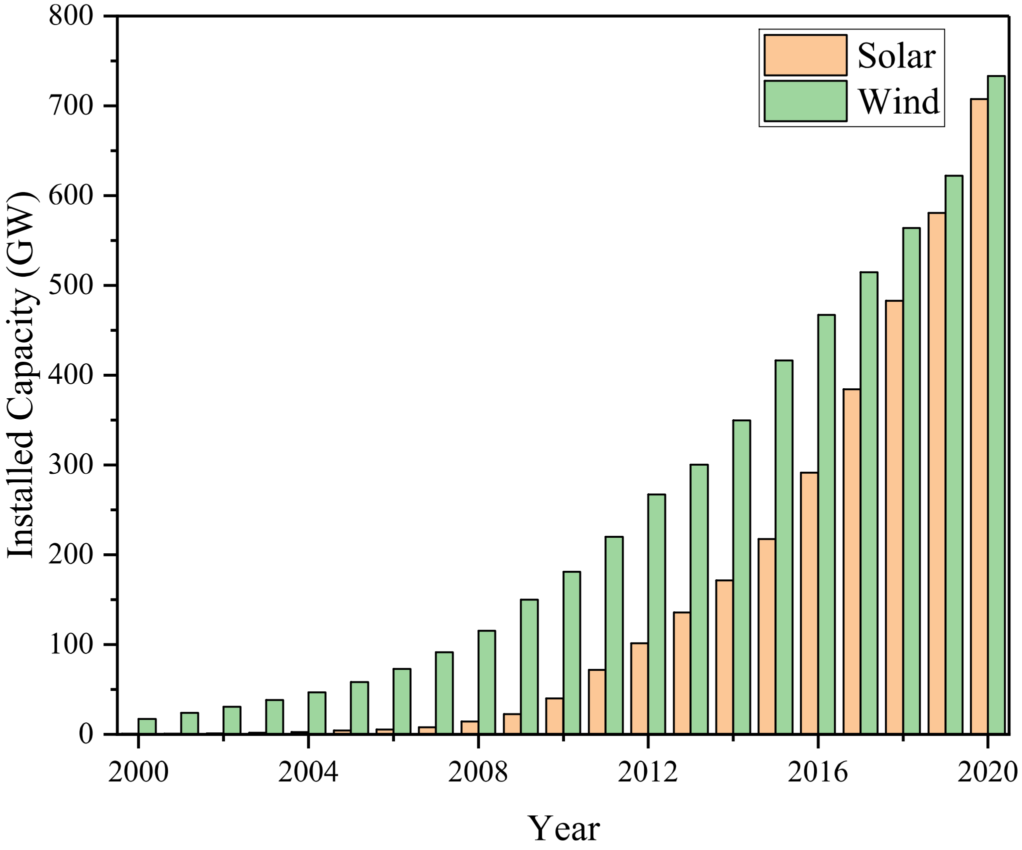

Figure 1.3: Installed solar and wind power generation capacity

Generally, solar and wind power generation can be installed more flexibly than other RESs in terms of location, but they are considered ‘variable energy sources’ because of their intermittent and uncertain nature. Solar Photovoltaic (PV) panels can be installed on the roofs of residential or commercial buildings or on the ground near commercial/industrial loads, whereas Wind Turbines (WT) are quite common in rural and suburban areas. However, adopting RESs can help in achieving various goals, such as reduction in GHG emissions and cost-effective delivery of energy. But the intermittent and uncertain nature of solar and wind power also poses planning and operational challenges for the distribution system [5–9]. Higher levels of RESs penetration require greater use of SG enabled technologies and energy storage systems.

Integration of battery energy storage and electric vehicles

Electrical energy storage can play an important role in energy management by increasing the flexibility of renewable DGs and loads. Widespread deployment of intelligently controlled energy storage devices can improve power quality, distribution reliability and power flow management. Energy storage can be utilized for ancillary services, peak shaving, load flattening and island support etc. [10–14]. Battery Energy Storage Systems (BESSs) can be installed either by DNO as a centralized BESS or by an individual consumer in the form of Distributed BESS (D-BESS) [15]. BESSs can be integrated with rooftop PVs or can be placed standalone to ensure economic service during power congestion. BESSs can effectively damp the variabilities/changes present in PV systems. Therefore, it facilitates the enhancement of PV penetration in the system [16–18]. The BESSs are valuable components for accommodating high penetration of RESs by reducing the negative effects of RESs. The BESS is capable of reducing energy procurement costs, reducing power losses and improving reliability [19–23].

The modern era witnesses the rapid integration of Electric Vehicles/Plug-in Hybrid Electric Vehicles (EVs/PHEVs). The IEA report [24] compares two scenarios in relation to EVs, viz. (1) the “Stated Policies Scenario”, which considered the existing policies of government, and (2) the “Sustainable Development Scenario”, which considers climate goals of Paris agreement. By 2030, the global electric vehicle stock (excluding two/three wheelers) will reach around 140 million vehicles as per the “Stated Policies Scenario” and about 245 million vehicles as per the “Sustainable Development Scenario”. The “Stated Policies Scenario” also suggests that the global electricity demand due to EVs/PHEVs will reach around 550 TWh in 2030, whereas “Sustainable Development Scenario” suggests that the global electricity demand due to EVs/PHEVs will reach around 1000 TWh. Increased penetration of EVs/PHEVs in the distribution system with uncoordinated charging can affect system loading, voltage deviations, network losses and other power quality issues [25, 26]. Coordinated charging is one of the solutions to mitigate the negative impacts of large penetration of EVs/PHEVs in distribution systems [27–29]. On the other hand, EVs/PHEVs are equipped with large battery capacities, which adds to battery energy storage in the system. As per the “Sustainable Development Scenario”, 16000 GWh of energy can be stored in electric vehicle batteries globally in 2030. This storage could actively support the grid via Vehicle-to-Grid (V2G) technology. The applicability of V2G capability depends on the availability of vehicles at the opportune time, prosumer willingness, and the potential to produce revenue for the stakeholders, along with technical limitations such as battery discharge rates and its effects on battery life. The V2G mode of EVs/PHEVs can provide backup support thereby improving the reliability of the system [30–33]. The battery storage capacity of EVs/PHEVs can be used to minimize peak demand in distribution systems [34–36].

The flexibility of BESS and the potential of EVs/PHEVs can be utilized to reduce the variability effect of RESs and improve the economics, reliability and stability of the distribution system through dynamically controlled charging and discharging.

1.1.2 Innovations in energy trading approaches for smart active distribution system

Traditional distribution networks are considered as passive terminations of the grid with unidirectional power flows, intended to supply reliable and efficient power to the end users. The high penetration of DERs, such as DGs, storage systems and DSM, is gradually transforming the unidirectional passive distribution network into a new kind of bidirectional Active Distribution System (ADN). Due to the introduction of ADNs, some inevitable changes are required in the design of the traditional distribution networks and, the operation and energy management models of the traditional Distribution Network Operators (DNOs). Management of Distributed Energy Resources (DERs) necessitates a good ICT infrastructure to ensure the compliance of network constraints along with the energy balance in the network in an optimal manner. Therefore, all the key elements of smart ADN need to be equipped with Intelligent Electronic Devices (IED) and communication infrastructure to enable them to exchange information for coordination and control.

With the above discussed restructuring in terms of ADN, it is possible to trade energy in a competitive environment, and through an electricity market mechanism, energy trading between different energy resources can be established. Transactive energy mechanism has enabled coordination among the producers and active consumers (prosumers) using market-based structures. Transactional energy model refers to a market structure having economic and system control mechanisms, where prosumers, consumers and network operators can trade energy securely at a fair price settlement [37,38]. Electricity markets at distribution level are considered as an efficient way to involve end-users and DERs in energy management. Pool based (centralized) and peer-to-peer based (distributed) markets are two forms of energy market. In a pool-based market, all participants negotiate and contract with an entity that operates and manages the market while peer-to-peer energy markets use bilateral contracts and energy trading between participants [39–41].

However, many opportunities are emerging in energy management of distribution systems due to the increasing penetration of DERs and the active participation of end users equipped with energy storage, local production and smart devices. But managing a large number of consumers, prosumers and energy resources with different needs and objectives is a challenging task for the central controller. In addition, the market participation consisting of small and spatially distributed energy resources faces several challenges, viz. the uncertainties associated with individual end-user's flexibility and RES, potential to influence the retail market, increased complexities in dedicated communication infrastructure, etc. [42]. By aggregating agents, such as consumers, prosumers, producers or any combination thereof, the burden on the central controller can be reduced. Aggregation reduces the distribution network of thousands of nodes to an equivalent network of a few nodes, which enables DNOs to make operational decisions faster. In fact, the aggregator contractually engages various DERs that are cumulatively large enough to participate in the electricity market.

Microgrid operator

ADNs can be divided into smaller parts, such as Microgrids (MGs), to reduce the burden of managing all DERs in a centralized manner. Microgrid can be define as *"a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode"* [43]. In others words, MGs are locally managed entities equipped with communication and control systems, and are capable of coordinating all energy resources and loads in their premises and exchanging power with networks in grid-connected mode. Functionally, MGs can act as an energy-balanced bodies within an ADN as well as a stand-alone power network in small communities and/or remote sites. The MG controller, namely, Microgrid Operator (MGO), has responsibilities similar to as the DNO to manage the DERs within its defined electrical boundaries. MGO acts as a single agent for DNO, which can control the DERs locally and reduces the need for a vertical control center. An efficient Energy Management System (EMS) is an important entity enabling collaboration between MGOs and DNO to improve the reliability, resilience, and stability of the distribution system.

Electric vehicles and energy storage aggregator

Demand Response (DR) programs provide opportunities for EVs to participate in energy management. The charging and discharging profile of EV can be changed as per Time-of-Use (TOU) tariff. However, EV owners can benefit from managing EV demand according to the tariff structure, but due to smaller battery capacity, the bargaining power of individual EVs with their service provider may be negligible. The aggregation of EVs can act as a prosumer with substantial bargaining power. On this basis EV aggregators are emerging as new players in the retail market to actively participate in energy trading and manage the charging/discharging behavior of a large number of EVs. Thus, the EV aggregator, which is an intermediary between the DNO and the EV owners and acts as a single entity, aggregates EVs that may not be considered valuable enough to participate in the electricity market individually [44,45]. In a similar way, BESS aggregators increase the flexibility and market power of D-BESSs. The EV/BESS aggregator provides DNO with an economically efficient mechanism that can be used to reduce variations due to the intermittent nature of RESs. The aggregator can also enter into a service contract with DNO rather than of participating in the energy market to provide ancillary services.

End-user (Demand response) aggregator

In recent years, Demand Response (DR) concepts have been widely used in distribution systems for energy balancing, voltage support, and peak load shaving [46]. Each consumer can take advantage of the TOU tariff and/or monetary incentives by controlling its full or partial load. A DR aggregator or end-user aggregator (EUA) allows the active participation of small end users, such as households, commercial buildings, and small industrial facilities, in energy management by considering consumer preferences. The EUA can contract with end users to gain access to their energy data. With the aim of profit maximization, the aggregator can use its portfolio to optimize the combined energy usage of the end users and provide services, such as ancillary services of peak curtailment or peak leveling, voltage support, voltage regulation etc., to the DNO on behalf of the end users. In fact, EUA can efficiently manage the responses of the end users to their satisfaction, so that the user responses are economically efficient in an automated manner.

1.2 Literature survey

Nowadays, energy management in distribution systems is becoming increasingly popular. Electricity generation and consumption need to be coordinated so that resources are used efficiently, energy costs and energy losses are reduced and emissions targets are met. In the an active distribution system, DERs play vital role in energy management. Contrary to the benefits of DERs, such as real power loss reduction, low carbon emissions, demand curve flatting etc., they also pose some challenges to the distribution system. The intermittent nature of RESs increases uncertainty on the supply side, whereas the uncontrolled charging/discharging of PHEVs and fluctuating load at consumers increase uncertainty on the demand side. In the context of the work present in this thesis, the existing literature can be classified into two categories as follows.

1.2.1 DER: Types, their coordination, and objectives

In recent years, many studies have focused on coordinated optimal scheduling of diverse energy resources to achieve various objectives such as peak shaving, energy cost minimization, voltage profile improvement, ancillary services deployment, power loss minimization, greenhouse gas emission reduction etc. [47–50]. A decision-tree-based algorithm has been proposed by K. Mahmud *et al.* for coordinating EVs, BESS and PV units for peak shaving in residential distribution networks [50]. The term peak shaving is related to reducing the power consumption during peak demand periods. This may be achieved by load shedding or by activating distributed energy resources. RESs (as DGs) are expected to reduce CO_2 emissions and energy losses in the system. The BESSs play important role in accommodating high penetration of RESs [51, 52]. Large battery capacities of EVs/PHEVs enable them to be used for energy storage during their parking time. In smart Parking Lots (PLs), battery storage of EVs/PHEVs can support distribution network by realizing the Grid to Vehicle (G2V) and Vehicle to Grid (V2G) power transfer concepts considering owner's satisfaction parameters [53–56]. EVs can act as Dispatchable Load (DL) as bulk energy storage capability. With an appropriate control and energy dispatch strategy, the energy stored in the batteries of EVs can be used to reduce peak load, increase the stability and resilience of the Distribution Utility (DU), and reduce the adverse effects of intermittent behavior of RESs [57–59]. Considering the objective of reducing cost, network losses and voltage deviation, real-time coordination algorithms for EVs have been developed in the literature [60, 61]. A load stabilization function is used in [62] for reducing the peak to valley difference. In this function, the average load is calculated based on conventional load without considering load of PHEVs and system losses. Similarly, coordination of charging stations for peak shaving and valley filling at distribution level has been used in [63].

Some of the EV researches have focused on customer-side profits, seeking to maximize the profits of the PL operator/aggregator or EV owner. EV aggregators can maximize their revenue either by maximizing revenue of each EV through optimal scheduling [64–66] or by maximizing its profits through market participation taking into account the utility constraints and satisfaction of EV owner [67, 68]. A multi-objective optimization model for maximizing the revenue of a solar PV based grid-connected EV charging station and minimizing battery degradation has been proposed by H. H. Eldeeb *et al.* [69].

Recently, some research works have addressed the integration of RESs and EVs in distribution networks. For instance, a two-stage model for allocating the bus locations to the PLs in a distribution system considering installation cost of PLs, power loss cost, voltage deviation, and network reliability as objectives is presented in [70]. The problem of optimal size and location of DGs and PLs to minimize losses and costs are discussed in ref. [71]. Integrated scheduling of EVs and RESs from micro-grid perspective considering the participation of EVs in Spinning Reserve (SR) and constraints imposed by EV users is presented in [72]. The coordinated energy management of EV, battery swapping stations and interruptible loads in MG based on incentive price mechanism has been developed in [73]. In the studied problem, grid-connected and island mode operation of MG are considered. EVs charging cost minimization and battery swapping stations profit maximization are the objectives considered in grid-connected mode. Whereas, island mode uses energy stored in EVs and battery swapping stations to reduce the operating cost of MG and maximize the utilization of the RESs. The V2G potential of EVs to reduce the voltage deviations due to the variability of solar PV outputs has been investigated by L. Cheng *et al.* [74]. The authors [74] demonstrated that voltage deviations in distribution systems with high PV penetration can be effectively relieved by active power feedback from EVs. PHEVs in V2G and G2V modes, and RESs as DGs have been utilized to minimize energy cost, real power losses and voltage deviations for the IEEE-33 bus system in [75]. Taking into account the participation of PL Operators (PLOs) in the energy, regulation and reserve market at the distribution level, a stochastic energy management model for PLOs profit maximization and DNO cost minimization is presented in ref. [76]. The effect of wind and PV penetration level and location on distribution system and PLO operation has also been investigated in this paper [76]. The role of parking lots in improving the reliability of the distribution system with RESs integration has been investigated in [77]. Probabilistic modeling of the energy available from the PLs in random contingency events has been used in this research [77]. The main objective of this study was to reduce EV cost and improve reliability indices of the system in the context of power supply restoration. In ref. [78], a stochastic framework is presented to examine the impact of wind power and battery degradation costs on the scheduling of EVs with and without V2G mode. Based on the studied framework, it is suggested that under certain conditions V2G operation of EVs is uneconomical considering battery degradation cost.

Similar to EV integration with RESs, incorporation of DR and integrated scheduling of BESS and RESs in the distribution networks has also been investigated in several research works. A day-ahead scheduling of a virtual power plant containing energy storage systems and small scale prosumers has been proposed in [79]. M. Giuntoli *et al.* [79] has considered the objective of maximizing the profit of virtual power plant. An energy management for a MG, which includes PV generation, Micro Turbines (MTs) and BESS, has been proposed in ref. [80]. To examine the benefits of RESs and BESS coordination, an energy management framework considering operating cost minimization and consumer load curtailment index has been developed in [81]. In ref. [82], BESS and DR coordination has been used to minimize the power generation cost and mitigate the effects due to uncertainties in wind power generation. BESS has been used to reduce the ramping event due to fluctuations in the output of PV due to cloud passing [83]. BESS has been used for peak load shaving in ref [20, 84]. In ref. [84], optimal scheduling of BESS has been proposed for peak load shifting in MG. Demand profiles after load leveling for a distribution substations has been compared in ref. [20] for three different sizes of BESS. Considering the intermittent nature of PV generation, an optimal charging/discharging strategy of BESS has been developed to reduce line losses in the distribution network in [85]. In ref. [86], a two-stage scheduling strategy has been proposed for utilization of assets. In the first phase (planning phase) uncertainties in load and RESs generation forecasts has been adopted to plan import/export commitment with the main grid for day-ahead with 1-hour resolution. The objective of the planning phase was to reduce energy imports from the grid. In the second phase (operational phase), four hour ahead with 15 minute resolution scheduling of various assets has been performed to reduce the deviations from commitment. To perform the above said phases, a dynamic AC-OPF has been used considering BESS, RESs, reactive power compensation and spinning reserves. The case study considered in ref. [86] suggests that it is more beneficial to use energy storage only in energy balance whereas, dispatchable DG can be used as spinning reserve. A multi-objective energy management framework has been proposed in ref. [87]. The DR program and BESS have been used to reduce the operating cost of MG and GHG emissions.

The above studies show that the coordination of DGs, BESSs and EVs provides an effective means to mitigate the variabilities in power generation due to RESs and reduce parameters such as cost, active power loss, and voltage deviation. The various DERs and objectives considered in the literature are summarized in the Table 1.1. As shown in the Table 1.1, integrated scheduling of different DERs has been used in the literature to achieve various technical and economic objectives. But most of the literature focuses on a single or two objectives, i.e., energy cost and peak load shaving (or load flattening). A study needs to be carried out to analyze the effects of simultaneous optimization of several conflicting objectives and to investigate the adequacy of solution approaches for such problems.

1.2.2 Energy trading approaches in network-connected multi-microgrid system

Multi-Microgrid (MMG) energy management has been widely investigated in recent years. Both centralized as well as decentralized frameworks have been used in the literature

Table 1.1: Classification of DERs and Objectives

Ref. No.	DERs				Objectives				
	DG	EV/PHEV		BESS	Cost/ Profit	GHG emission	Load Flattening /Peak Shaving	Active power loss	Voltage deviation
		G2V	V2G						
[20]				✓			✓		
[47]	✓	✓			✓		✓		
[48], [54], [72], [76], [78]	✓	✓	✓		✓				
[50]	✓	✓	✓	✓			✓		
[51, 52]	✓			✓					✓
[53], [64], [67, 68]		✓	✓		✓				
[55]		✓					✓		
[59]	✓	✓			✓	✓			
[60, 61]		✓			✓			✓	
[62]		✓			✓		✓		
[63]		✓	✓				✓		
[69], [73]	✓	✓		✓	✓				
[70]	✓	✓	✓		✓			✓	✓
[71]	✓	✓			✓			✓	✓
[74]	✓	✓	✓						✓
[75]	✓	✓	✓	✓	✓			✓	✓
[79], [81, 82]	✓			✓	✓				
[84]	✓			✓			✓		
[85]	✓			✓				✓	
[87]	✓			✓	✓	✓			
✓count	14	14	7	9	12	2	7	5	5

[88–91]. Some researchers have used central controllers for MGs, while some researchers have considered MGOs as separate bodies to optimize their assets independently. Competitive as well as collaborative strategies based on intermediate platforms have been investigated for trading power between MG and Distribution Utility (DU). A non-pricing trading mechanism has been proposed in [92]. In [92], the allocation of the surplus energy of seller-MGs to buyer-MGs is based on the priority index. A coalitional game theory based cooperative scheduling of network-connected MMG system with the aim of reducing average power loss in distribution networks has been presented in [93]. Ref. [94] has also examined coalitional game theory based energy management of MMG without considering energy storage. The proposed framework in [94] allows MGs to buy power from the grid and sell it to other MGs simultaneously. A centralized energy management framework has been proposed to maximize the overall benefit of a group of MGs in [95]. In this proposed framework, MGs can exchange power between them to effectively use RESs. A decentralized bi-level model has been proposed to trade power between MGs and DNO in a networked MMG system in [96]. Each of the MGs and DNO has been considered as an independent entity with the objective of minimizing its operating cost. Although MGs and DNO are in coordinated operation, no mechanism has been proposed in ref. [96] that encourages MGOs to prefer interchange power among themselves instead of DNO. A power-sharing optimization problem to minimize energy cost for grid-connected MMG system has been introduced in [97]. The MGs are classified into priority groups according to their RESs and storage capacity, and treated with lexicographic programming. This model relies on large flow of bi-directional information between the central controller and MGs. Also, the power exchange prices between MGs are prefixed based on grid prices. In [98], the authors have developed a two-tier optimization problem for managing storage and power exchange between MGs and grid. In the first-tier the optimization of user utility function, transmission cost, and load variations is considered whereas, in the second-tier optimization of the generation and transmission cost for MGs has been dealt. A centralized energy management system for grid-connected MMG system has been discussed in [99]. In [99], a entity called common control center optimizes all MGs assets. In the literature, no mechanism has been worked out to promote MGOs to adjust their respective net power demand according to the demands of other MGs. A cooperative model predictive control based EMS for minimizing the cost power exchange with grid in presence of local generation has been developed in [100]. In order to coordinate all MGs, an optimization phase considering guaranteed benefit for all MGs has been included between the initial and final optimization phase at individual MG level [100]. A day-ahead coordinated energy scheduling to minimize the energy cost of the MMG system, consisting of dispatchable DG, energy storage, and EVs, has been investigated in [101]. A central operator controls all the generation and consumption units of MGs. A novel cooperative game theory-based coalitional economic dispatch problem has been formulated in [102] for a distribution system containing MMG. An alternative cooperative energy management framework aiming at minimization of operation cost and power exchange from grid has been studied in [103]. As an centrally optimized multi-objective problem, pricing based model for power exchange among MGs has not been discussed in [103]. In ref. [104], a bi-level energy management model for MMG has been proposed. The *outer level* takes care of power-sharing during the networked operation of MG, and the *inner level* takes care of energy management of isolated MG. A weighted average of marginal prices of the seller and buyer MGs has been used as a price for power exchange between MGs. A Nash bargaining theory-based incentive mechanism for power trading between MGs has been proposed in [105]. This study uses an alternating direction method of multipliers based decentralized approach for scheduling and benefit sharing among traders. A comparison-based analysis of cooperative and non-cooperative game theory-based optimization of BESS in the MMG system proposed in [106] illustrates that the cooperative operation provides lower daily operating cost.

The aforementioned studies show the advantages of coordinated operation of MMG. Each MGO aims to achieve economic benefits by utilizing energy resources in its entity. In the non-coordinated approach, MGOs tend to optimally schedule their assets and exchange power with distribution utility (DU) depending on consumers' demand response, generation availability, and energy tariff of the upstream grid. In cooperative operation, MGs exchange power among themselves for more benefits. Here, in cooperative operation, instead of preferring power exchange with DU, MGOs prefer to exchange power among themselves as much as possible. Each MG may have distinct surplus/deficit energy periods due to non-identical consumer demand pattern and generation availability. They can exchange power among themselves at a settled price for economic profit rather than the price set by the DU. In the existing literature, the coupling constraints are used to coordinate the operation of MGs for power exchange to avail economic benefits. These coupling constraints necessitates joint scheduling of all the MGs . One of the important research gaps in the present scenario is that, a dedicated communication network between the MGOs, and between the MGOs and DU, is mandatory to exchange information in both centralized and decentralized approaches. This also amounts to increase in the complexity of the communication network with increase in number of MGOs. For example, in the case of (n) networked MGs system, each MGO is required to communicate with DU and $(n-1)$ MGOs to select the best pairs to exchange power. Besides the communication requirements, sharing of information/data of MGs is also assumed, which may be sensitive hence may not be shareable.

The interconnection of multiple microgrids in the distribution system provides an opportunity for internal competitive power trading. In recent years many studies have focused towards the energy management of grid connected MMG systems. The authors in ref. [107] present a bi-level optimization model for a hybrid distribution system with network-connected MMG. The Stackelberg game theory based interaction model is used to determine the power exchange between the distribution network and the MGs. However, in the said interaction model consumer DR is not considered and the power exchange price is considered as a predetermined parameter. A bi-level scheduling model for distribution system with MMG has been investigated in the article [108]. In the said model the voltage deviation and power loss minimization are considered as objective functions for the upper level (distribution system level) and MGs cost minimization objective is considered for the lower level. The demand side management of flexible loads and uncertainty associated with RESs are not included in this study. A bi-level price incentive based day-ahead energy management for network-connected MMG system is proposed in the article [109]. A two stage robust optimization model is used to deal with uncertainty. The researchers in ref. [110] investigate a Stackelberg game theory based distributed EMS for smart grid. In so called *multi-leader* (generators) and *multi-follower* (MGs) game model, each player tries to maximize its payoffs. The authors in ref. [111] proposed a bi-level optimization for real-time pricing based energy management of smart grid with multiple MGs. However, power flow constraints, uncertainties in RESs, and DR of end-users are not considered. The authors in [112] proposed a hierarchical EMS for interconnected MGs considering uncertainties in RESs and consumer load. The upper level realizes energy scheduling to determine power exchange between MGs and the main grid, and power exchange within MGs. Lower level decisions are based on chance-constrained model predictive control taking into account various uncertainties. A Model-free Reinforcement Learning (RL) based EMS of network-connected MMG has been developed in [113]. Distribution System Operator (DSO) uses peak-to-average ratio minimization and profit maximization objectives to decide retail price for MGs via a Monte Carlo Simulation (MCS). A competitive *leader* (i.e., central production unit)- *follower* (i.e., energy serving entity for MGs) game theory based EMS is presented in the article [114]. The leader aims to maximize its profit margin at upper level, whereas follower tries to maximize its profit at lower level. A bi-level optimization for maximizing the profit of distribution company at upper level and minimizing the cost of MGs at lower level has been developed in the article [115]. The distribution company determines retail price for individual MG, and MGOs schedule their assets according to the said retail price. A two-stage EMS for MMG considering PCC line capability has been proposed in the article [116]. The upper stage considers the total profit maximization of MMG, whereas the division of earned profit between MGs is considered at the lower stage. The authors in [117] have developed a two-stage decentralized EMS based on Alternating Direction Method of Multipliers (ADMM) to coordinate power exchange between the MGs and the DSO. The uncertainties related to RESs and loads have been addressed using Monte Carlo simulation and robust optimization.

The aforementioned studies suggest that the concept of multiple operating entities such as Distribution Utility (DU), MGOs, and end-users, (multi-agent) based power trading models are widely used in present distribution system. Most of the literature investigates the coordination either between DU and MGOs or between MGO and end users. However, the decisions of all agents DU, MGOs and end-users are interlinked. These agents can affect each other directly or indirectly. The techno-economic aspects may be accomplished more effectively if the energy management framework considers the decisions of all agents together.

1.3 Research gap

Based on the literature review in section 1.2, it has been found that energy management for active distribution systems has been widely studied but still has scope for investigation.

In the context of this thesis, following research gaps have been identified.

- Integrated scheduling of different DERs has been used in the literature to meet various techno-economic objectives, as illustrated in Table 1.1. However, the majority of the research focuses on one or two objectives. An investigation into the consequences of *simultaneous* optimization of several conflicting objectives, as well as the suitability of solution methodologies for such problems, is required.
- Coupling constraints, and sensitive data/information sharing of MGs are taken as prerequisite in the existing literature for coordinated operations of network-connected microgrids. An energy management framework with *decentralized* approach and *limited* information sharing for coordination of MMG is required.
- The envisaged scenario of active participation of end-users as stakeholders with sufficient negotiating power in energy management with the distribution utility and MGs operator has not been investigated. An energy management framework considering active participation of all operating agents, such as DU, MGO, end-users, in an active distribution system must be developed and investigated.

1.4 Objectives and scope of the thesis

The main goal of this research is to develop an energy management framework considering the different perspectives of multiple operating agents in an active distribution system and to analyze different approaches to coordinate all the energy resources owned by different operating agents. To accomplish this goal, the present work is further divided into the following sub-objectives

1. Firstly, the aim is to develop a multi-objective energy management framework that proposes a combined formulation of energy cost, CO_2 emissions, active power loss and load flattening by considering integration of PHEVs (G2V and V2G modes), D-BESSs and DGs. The effectiveness of reformulated energy cost function in the context of eliminating solutions involving excessive charging and discharging of BESSs and PHEVs has also been examined. In addition, a comparative analysis has been carried out between a decentralized multi-agent scheduling and a centralized scheduling with a central controller.

2. The next objective is to develop a framework for price signal based cooperative scheduling of network-connected MGs emphasizing the flexibility and active participation of Parking Lot (PL) operators and Distributed Battery Energy Storage (D-BESS) aggregators. Further an approach incorporating internal pricing scheme within each microgrid is developed.

3. Finally, the objective is to develop an energy management framework incorporating a three-level hierarchical decision approach for an active distribution system with multi-microgrid. The three level in the order of hierarchy are Distribution Utility (DU), Microgrid Operators (MGOs), and End-User Aggregators (EUAs), respectively. In this framework, multiple operating agents, such as DU, MGOs and EUAs, can actively engage in energy management to achieve their respective goals. The impact of risk averse and risk-seeker decisions of MGOs on the operating cost of DU has also been investigated in this model.

1.5 Organization of the thesis

Thesis is organized in the following manner to address the aforementioned objectives.

Chapter 2 presents the preliminary introduction of energy management frameworks of a distribution system with multiple operating agents that will be used in this thesis. The basic concepts of some of the methodologies for developing solution approaches for energy management framework are described in this chapter. This chapter attempts to provide an overview of energy management framework and methods before detailed discussions in subsequent chapters.

Chapter 3 presents the integrated scheduling of PHEVs, D-BESSs and DGs in an active distribution system. In the proposed framework, the optimization problem considers the combined formulation of energy cost, CO_2 emissions, real power loss and load flattening and is effectively solved by ε-constraint method. In this chapter, the reformulation of the energy cost function has also been investigated to eliminate the solutions associated with excessive charging and discharging of BESSs/D-BESSs and PHEVs on scheduling problem by the central controller from the utility's point of view. Finally, the case of the decentralized multi-agent optimization problem has been compared with centralized optimization with a central controller. The decentralized multi-agent scheduling is carried forward in the next chapter for multi microgrid systems with each microgrid consisting of different energy resources and self-governing profit based entities.

Chapter 4 presents a price signal based decentralized approach to maximize economic benefits among network-connected MGs through cooperative scheduling. The Shapley value method has been used for generating fair price signals to encourage MGs to share power among themselves instead of distribution utility. The stochastic Dantzig-Wolfe decomposition (SDWD) has been used to solve the resulting optimization problem in a decentralized manner. MGO trading-status based tariff has been used for active participation of PL operator and D-BESS aggregator. The uncertainties related to load demand and RESs has been modeled using scenario-based methods while the uncertainty associated with PHEVs has been modeled using copula theory-based estimation. This chapter addresses the energy management of the MMG system considering energy trading aspects among the participating MMGs. The next chapter involves DU as an operating agent with multiple MGOs.

Chapter 5 presents a hierarchical decision based multi-objective energy management framework for an active distribution system with multi-microgrid. Multiple operating agents, such as DU, MGOs and EUAs, have been considered in this energy trading arrangement to achieve their respective goals. In this chapter, a game-theoretic dynamic pricing scheme has been used for the interaction of DU-MGOs as well as MGO-EUAs, rather than prefixed pricing scheme. The effects of risk-averse and risk-seeking decision making of MGOs on DU benefits have also been investigated in this chapter.

Chapter 6 summarizes the main findings from this research as well as possible improvements and future work that may follow the work presented in this thesis.