

Coordinated Operation of Distributed Energy Resources in Renewables Based Microgrids under Uncertainties

by

Walied Alharbi

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2013

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

In recent years, the share of renewable energy sources (RESs) has been increasing in the electricity generation mix with a mandate to reduce greenhouse gas emissions that are released from burning fossil fuels. Indeed, a large share of electricity from renewable resources is required to de-carbonize the electricity sector. With the evolution of smart grids and microgrids, effective and efficient penetration of renewable generation such as wind and solar can possibly be attained. However, the intermittent nature of wind and solar generation makes microgrid operation and planning a complex problem and there is a need for a flexible grid to cope with the variability and uncertainty in their generation profiles. This research focuses on the coordination of distributed energy resources, such as energy storage systems (ESSs) and demand response (DR) to present an efficient solution towards improving the flexibility of microgrids, and supporting high levels of renewables generation.

The overall goal of this research is to examine the influence of coordinated operation of ESS and DR on microgrid operations in the presence of high penetration levels of renewable generation. Deterministic and stochastic short-term operational planning models are developed to analyze the effects of coordinating ESS and DR, vis-à-vis their independent operation, on microgrids with high renewable generation. Special focus is on operation costs, scheduling and dispatching of controllable distributed generators, and levels of renewable generation. A set of valid probabilistic scenarios is considered for the uncertainties of load, and intermittency in wind and solar generation sources.

The numerical results considering a benchmark microgrid indicate that coordinated operation of ESS and DR is beneficial in terms of operation costs, vis-à-vis their independent presence in the microgrid, when there is sufficient renewable generation. The coordinated operation reduces the risk in scheduling and increases the flexibility of the microgrid in supporting high levels of renewable generation.

Acknowledgments

First and foremost, all praise and thanks are due to almighty Allah for enlightening my path and directing me to each and every goal I accomplish.

I would like to express my sincere gratitude to Professor Kankar Bhattacharya for his supervision, continuous guidance, helpful support, and encouragement throughout the period of my MASc studies at the University of Waterloo.

I am also grateful to Professor Ramadan El-Shatshat and Professor Tarek El-Fouly for serving as members of my thesis committee. Their valuable comments and support are highly appreciated.

Further, I am thankful to the Saudi Arabian Ministry of Higher Education represented by Majmaah University for their financial support. My appreciation and thanks are also extended to the Saudi Arabian Culture Bureau in Canada for their continuous assistance throughout the course of my studies at the University of Waterloo.

I wish to express my sincere thanks to my parents and my siblings for believing in me, praying for me, and supporting my academic career although it meant being away from them.

Special thanks are extended to two of my dearest friends: Abdulaziz Almutairi and Abdullah Bin Humayd for their sincerity, support, and encouragement during my academic journey.

Last but not least, I would like to thank all my friends in Waterloo, who have enriched my life and made it enjoyable.

Dedication

To the soul of my grandfather,

To my parents

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NOMENCLATURE

Sets and Indices

do	Demand variation downward
J, j	Set of indexes of generating units
K, k	Set of indexes of the time periods
N	Number of power intervals
S, s	Set of indexes of scenarios
up	Demand variation upward

Parameters

μ	Upper bound for if-condition linearization
B_{UP}, B_{DOWN}	Maximum upward/downward variation, %
C_{curt}	Curtailment cost for the wasted renewable energy, \$/kWh
C^{max}	Maximum allowable energy stored in ESS
C^{min}	Minimum allowable energy stored in ESS
CM_j	The crew start-up and maintenance costs of unit j
CSC_j	Cold start-up cost of unit j
C_{SH}	Transaction cost for demand shifting, \$/kWh
C_{st}, C_E	Initial/final stored energy of ESS
CST_j	Cold start-up time of unit j
D_j	Number of periods of unit j that must be initially online due to its minimum down time
D_{j0}	Number of periods of unit j is offline prior to the first period of the time span
d_k	Time duration of each period
D_{Tj}	Minimum down-time for unit j , hour
G_j	Number of periods unit j initially online due to its minimum up time
HSC_j	Hot start-up cost of unit j
P_{ES}^{max}	Maximum allowable charge/discharge limit
P_j^{max}	Capacity of unit j , kW
P_j^{min}	Minimum power output of unit j , kW
$P_{k,s}^D$	Demand with DR in period k considering scenario s , kW
$P_{k,s}^{PV}$	Power output of solar generation in period k and scenario s , kW
$P_{k,s}^W$	Power output of wind generation in period k and scenario s , kW
RD_j	Ramp-down limit for unit j , kW
$R_{k,s}$	Spinning reserve requirement in period k and scenario s , kW
RU_j	Ramp-up limit for unit j , kW
$S_{l,j}$	Slope of block ℓ of the piecewise linear production cost function of unit j
SU_j	Start-up ramp limit for unit j , kW
T	Number of periods of the time span
$T_{l,j}$	Upper limit of block ℓ of the piecewise linear production cost function of unit j
U_{j0}	Number of periods of unit j is online prior to the first period of the time span

UT_j	Minimum up-time for unit j , hour
V_{j0}	Initial commitment state of unit j
η_c, η_d	Charge / discharge efficiency of ESS
λ_s	Probability of occurrence of scenario s
<i>Variables</i>	
ETC	Expected total cost of the microgrid (\$)
$\Delta P_{k,s}^{UP}$	Demand increase in period k and scenario s , kW
$\Delta P_{k,s}^{Down}$	Demand decrease in period k and scenario s , kW
$C_{k,s}$	Energy stored in ESS until period k considering scenario s , kWh
C_k^{Grid}	Main grid electricity price in period k
$H_{l,j,k,s}$	Power generated in block ℓ of the piecewise linear production cost function of unit j , in period k considering scenario s , kW
$P_{j,k,s}$	Output power of committed unit j in period k considering scenario s , kW
$P_{k,s}^{CH}$	Charging power of ESS in period k considering scenario s , kW
$P_{k,s}^{Curt}$	Power curtailment from RE sources, in period k and scenario s , kW
$P_{k,s}^{DCH}$	Discharging power of ESS in period k considering scenario s , kW
$P_{k,s}^{DEM}$	Variable demand with DR in period k and scenario s , kW
$P_{k,s}^{EXP}$	Power exported to the main grid in period k and scenario s , kW
$P_{k,s}^{IMP}$	Power imported from the main grid in period k and scenario s , kW
$V_{j,k}$	Binary variable is equal to 1 if unit j is online in period k and 0 otherwise
$V_{k,s}^{CH}$	Binary variable; = 1 if ESS charging in period k and scenario s ; = 0 otherwise
$V_{k,s}^{Curt}$	Binary variable; = 1 if power curtailed in period k and scenario s ; = 0 otherwise
$V_{k,s}^{DCH}$	Binary variable; = 1 if ESS discharging in period k and scenario s ; = 0 otherwise

Chapter 1

Introduction

1.1 Motivation

In recent years, the share of renewable energy sources (RESs) has been increasing in the electricity generation mix with a mandate to reduce greenhouse gas emissions that are released from burning fossil fuels. Indeed, a large share of electricity from renewable resources is required to de-carbonize the electricity sector. With the evolution of smart grids and microgrids, effective and efficient penetration of renewable generation such as wind and solar can possibly be attained [1]. Microgrids are defined as medium or small power systems, either isolated and relying only on their local generation, or connected to the external grid to supplement their supply requirements; comprising distributed energy resources (DERs); and controllable and non-controllable loads [2]. The intermittent nature of wind and solar generation raises operational problems and challenges in microgrids, and to assure continuity of electricity service, other microgrid elements must be able to rapidly respond to shortages arising in these variable generation sources [2]. This concept of flexibility can be defined as the ability of the microgrid to rapidly modify generation or demand in response to shortages and/or excess of renewable generation, so as to maintain the balance. As renewable penetration increases, maintaining this balance becomes a challenging task because of the increase of variability and uncertainty in supply of electricity, which can lead to increase in electricity cost, eventually. The flexible resources and the needs for flexibility in a microgrid are shown in Figure 1. These resources can contribute to alleviate the operational challenges that arise from the variability and uncertainty of RESs.

The requirement for instantaneous power balance is the main challenge in microgrid operations. Energy storage systems (ESSs) help, but may not be enough to compensate for the highly unpredictable fluctuation of wind and solar generation outputs. Demand response (DR), which seeks to adopt the demand profile in response to supply conditions, can open the possibility of high penetration of renewable generation. Indeed, implementation of effective DR can reduce the gap between supply and demand to a significant extent [1]. However, DR may reduce storage utilization and therefore ESS cannot be fully utilized. This is due to the fact that ESS operations involve charging and discharging losses that depend on the cycle efficiency of the storage device, which is not the case with DR, and hence the latter is preferred [3]. The research question that arises here is

whether the coordinated operation of DR and ESS in microgrids can result in further benefits in terms of cost reduction or increased penetration of renewables.

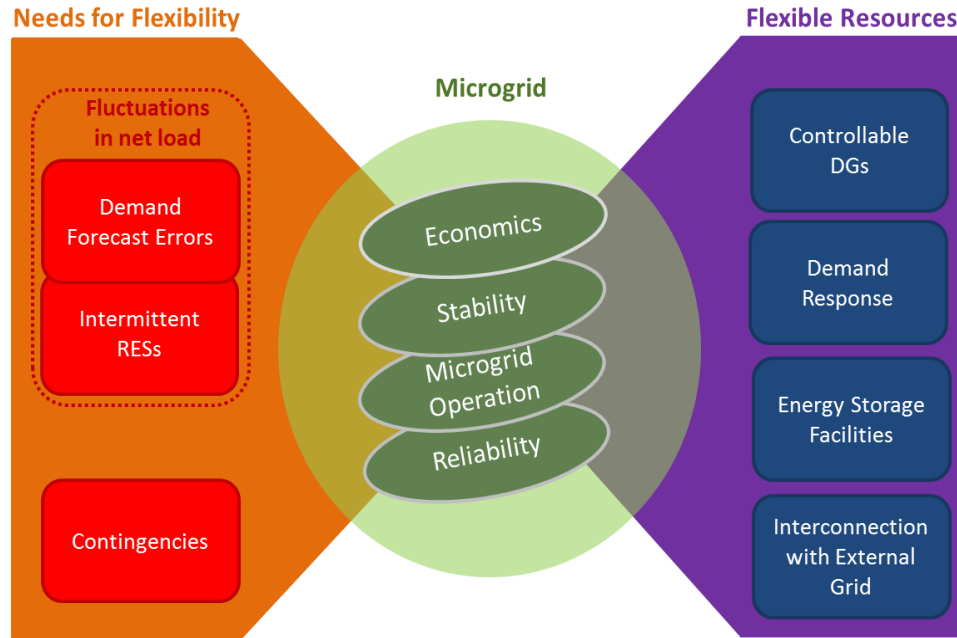


Figure 1-1 Flexibility and resource needs in a microgrid

The way renewable energy impacts Unit Commitment (UC) decisions in microgrids is another major challenge. UC can be treated as a deterministic problem with low renewable penetration levels. However, with high renewable penetration levels, a significant stochastic element is added to the microgrid operation since renewable generation, such as wind and solar, cannot be controlled nor accurately forecasted, and therefore a large reserve capacity needs to be provided by conventional generators. As a result, the emission reduction associated with renewable resources will not be as significant as expected [1]. The issue of UC schedules and real-time dispatch of a microgrid with controllable distributed generators (DGs) is also more complicated in the presence of wind and solar generation. To address these challenges, it is necessary to manage and handle the uncertainty associated with these variable generation sources. It has become clearer than ever that a flexible microgrid is vital. In this research, meeting the aggregate power balance (demand-supply balance) constraint is the main concern, while other constraints imposed by the microgrid distribution system are ignored and left for future work.

1.2 Research Objectives

This research focuses on studying the influence of coordinated operation of ESS and DR on microgrid operations; special focus is on operation costs, scheduling and dispatching of controllable DGs, and levels of renewable generation. The specific objectives of this research are as follows:

- Develop mathematical optimization models that include ESS and DR to solve the short-term operational planning problem in a microgrid considering different modes of operation.
- Develop stochastic short-term operational planning models that include ESS and DR, for grid connected and isolated microgrids, to address uncertainties of load, and intermittency in wind and solar generation resources.
- Examine the influence of coordinated operation of ESS and DR, vis-à-vis their independent presence in microgrids with high penetration of renewables, considering deterministic and stochastic operational frameworks.
- Investigate the impact of coordinated operation of ESS and DR on the maximum possible level of penetration of renewable generation in remote microgrids considering both deterministic and stochastic operational frameworks.

1.3 Thesis Outline

The thesis is organized as follows: Chapter 2 discusses the UC problem and presents a literature review on a microgrid and its operational aspects, ESS, and DR. This chapter also presents a brief overview on uncertainty management in power systems operations.

Chapter 3 presents short-term operational planning models for isolated and grid connected microgrids with ESS and DR included, and with specified wind and solar generation profiles. The models can be used to examine the effects of coordination of ESS and DR on microgrids with high renewable generation. The developed models are solved using mixed-integer linear programming (MILP), and the analysis provides insight into their effects on operation costs, and scheduling and dispatching of controllable DGs. The potential for accommodating higher levels of renewable generation in remote microgrids is also discussed.

Chapter 4 presents stochastic short-term operation planning models with ESS and DR for grid connected and isolated microgrids. The developed models include the uncertainties of load, and intermittency in wind and solar generation sources to track the stochastic behavior of load, wind and solar generation. This chapter examines the advantages of coordinated operation of ESS and DR, vis-à-vis their independent operation in microgrids with high penetration of renewables, in the presence

of uncertainty. The impact of coordinated operation of ESS and DR on the maximum possible level of penetration of renewable generation in remote microgrids, considering stochastic models and reserve requirements is also investigated. The thesis summary, conclusions and suggested future work are presented in Chapter 5.

Chapter 2

Background and Literature Review

2.1 Introduction

In Chapter 1, the motivations and objectives of the research work are discussed and presented. In this chapter, a literature survey pertaining to few topics related to this research is presented. The chapter reviews unit commitment problem, and a microgrid and its operational aspects. Flexible resources such as ESS and DR are also reviewed and presented. The last part of this chapter presents some practices techniques for handling uncertainties of load, wind, and solar power forecasting errors.

2.2 Unit Commitment

In power systems, the determination of start-up and shutdown decisions of power generators is known as Unit Commitment (UC), which involves minimizing the total operation cost subject to various generation and system operational constraints, over a specific time span [4]. It also determines the power dispatch of the committed units to meet the system demand and spinning reserve requirements. However, Economic Dispatch (ED) is used to allocate the system demand among generating units, over a shorter time span, i.e., five minutes ahead. ED does not affect the UC solution, but instead updates the power dispatched settings of the committed units by considering an updated system condition, while taking into account more constraints such as transmission capacity and power flow.

Significant attention has been paid over the years to develop computationally efficient algorithms to solve the UC problem. As a consequence, numerous solution techniques have been developed, for instance, Lagrangian relaxation (LR) [5], MILP [6], and evolution inspired approaches [7]. A recent extensive literature survey and general background of research and developments in UC problem can be found in [8]. LR is the most widely used technique due to its capability of solving large-scale problems. Nevertheless, the main drawback of this technique is that heuristic procedures are required to find feasible solutions, which may result in suboptimal solutions; this is because of the non-convexities of the UC problem. In contrast, the MILP based methods guarantee convergence to the optimal solution while providing a flexible and accurate modeling framework. Besides, information on the proximity to the optimal solution is available during the search of the problem tree. An efficient and widely used MILP solution method is the branch and bound along with its variations, which is used in the research presented in this thesis. By using the branch and bound

method, the original MILP problem is split into a sequence of linear programming problems by relaxing the inter conditions and including additional constraints [9]. The MILP formulation of UC problem is briefly described and presented below [10, 11]:

2.2.1 Objective Function

The objective of the operator while solving the UC problem is to minimize the total system operation cost (TC), over a horizon operation time, as given below:

$$TC = \sum_{k \in K} \sum_{j \in J} (C_j(P_{j,k}) + SU_{j,k} + SD_{j,k}) \quad (2.1)$$

In (2.1), $C_j(P_{j,k})$ is the production cost of a generator, which is represented by a polynomial function, typically quadratic, and can be written as [11]:

$$C_j(P_{j,k}) = a_j v_{j,k} + b_j p_{j,k} + c_j p_{j,k}^2 \quad (2.2)$$

As reported in [11], a general quadratic cost function can be accurately approximated using a set of piecewise blocks, and the analytical form of this linear approximation is represented by (2.3) – (2.9) [11]:

$$C_j(P_{j,k}) = A_j v_{j,k} + \sum_{\ell=1}^{NL_j} S_{\ell,j} \times H_{\ell,j,k} \quad \forall j,k \quad (2.3)$$

$$P_{j,k} = \sum_{\ell=1}^{NL_j} H_{\ell,j,k} + P_j^{\min} v_{j,k}, \quad \forall j,k \quad (2.4)$$

$$H_{1,j,k} \leq T_{1j} - P_j^{\min}, \quad \forall j,k \quad (2.5)$$

$$H_{\ell,j,k} \leq T_{\ell j} - T_{(\ell-1)j} \quad \forall j,k, \forall \ell = 2 \cdots (NL_j - 1) \quad (2.6)$$

$$H_{NL_j,j,k} \leq P_j^{\max} - T_{(NL_j-1)j}, \quad \forall j,k \quad (2.7)$$

$$H_{\ell,j,k} \geq 0, \quad \forall j,k, \forall \ell = 1 \cdots NL_j \quad (2.8)$$

$$A_j = a_j + b_j P_j^{\min} + c_j (P_j^{\min})^2 \quad (2.9)$$

In (2.1), $SU_{j,k}$ is the start-up cost of a generator and typical modeled as exponential start-up cost function, as given by (2.10) [4].

$$SU_{j,k} = CMC_j + CSC_j \left(1 - e^{-DT_{j,k}/CST_j} \right) \quad \forall j,k \quad (2.10)$$

The start-up cost can be simplified using a piecewise function with two states: either equal to the hot or cold start-up cost, depending on the cold start-up time (CST_j) of generator j . That is, if the unit is in the OFF-state for a number of hours greater than CST_j , then the start-up cost is equal to the cold start-up cost. Otherwise, it is equal to the hot start-up cost.

$$SU_{j,k} = \begin{cases} hc_j, & \text{if } DT_j < CST_j \\ cc_j, & \text{if } DT_j \geq CST_j \end{cases}, \quad \forall j, k \quad (2.11)$$

The mixed-integer linear formulation for the above equations is given by (2.10) – (2.12) [11]:

$$SU_{j,k} \geq hc_j \cdot (v_{j,k} - v_{j,k-1}), \quad \forall j, k \quad (2.12)$$

$$SU_{j,k} \geq cc_j \cdot (v_{j,k} - \sum_{i=1}^{CST_j} v_{j,k-i}), \quad \forall j, k \quad (2.13)$$

$$SU_{j,k} \geq 0, \quad \forall j, k \quad (2.14)$$

The last term of (2.1) denotes the shut-down cost of a generator, which is not significant with respect to other costs, and therefore it is ignored and assumed to be zero in this work.

2.2.2 Constraints

Demand-Supply Balance: ensures that enough generation capacity has been scheduled at a certain hour so that the system demand is met at that hour.

$$\sum_{j \in J} P_{j,k} = P_k^D \quad (2.15)$$

Adequacy constraint: ensures that the net available capacity from all committed generators meets the system demand and spinning reserve allocations.

$$\sum_{j \in J} (P_j^{max} \cdot v_{j,k} - P_{j,k}) \geq R_k \quad (2.16)$$

Generation Limits: ensures that the output power of a generator at a period k is within its minimum and maximum power limits.

$$P_j^{min} v_{j,k} \leq P_{j,k} \leq P_j^{max} v_{j,k}, \quad \forall j, k \quad (2.17)$$

Ramp Rate Limits: These ensure that the inter-hour generation changes are within the generator ramping-up and down limits.

$$P_{j,k} - P_{j,k-1} \leq UR_j, \quad \forall j, k \quad (2.18)$$

$$P_{j,k-1} - P_{j,k} \leq DR_j, \quad \forall j, k \quad (2.19)$$

Logic Constraint: ensures that the transitions of the generator states from 0 to 1 and *vice versa* are coordinated with the startup and shutdown unit decisions.

$$Ust_{j,k} + Usd_{j,k} = v_{j,k} - v_{j,k-1} \quad (2.20)$$

Where $Ust_{j,k}$ and $Usd_{j,k}$ are start-up and shut down decision variables of generator j , respectively.

Positive Variables: ensure that the following variables are positive.

$$H_{\ell,j,k} \geq 0, \forall j, k, \forall \ell = 1 \cdots M \quad (2.21)$$

$$SU_{j,k} \geq 0, \forall j, k \quad (2.22)$$

Minimum Up-time Constraints: Constraints (2.23) – (2.26) ensure that when a generator is committed, it has to remain in the ON-state for a definable minimum number of hours before it can be turned off [11].

$$\sum_{k=1}^{U_j} [1 - v_{j,k}] = 0, \quad \forall j \in J \quad (2.23)$$

$$\sum_{n=k}^{k+UT_j-1} v_{j,n} \geq UT_j [v_{j,k} - v_{j,k-1}], \quad \forall j \in J, \quad \forall k = U_j + 1 \cdots \beta - UT_j + 1 \quad (2.24)$$

$$\sum_{n=k}^{\beta} \{v_{j,n} - [v_{j,k} - v_{j,k-1}]\} \geq 0, \quad \forall j \in J, \quad \forall k = \beta - UT_j + 2 \cdots \beta \quad (2.25)$$

$$U_j = \text{Min} \{ \beta, [UT_j - U_j^0] V_j^0 \} \quad (2.26)$$

Minimum Down-time Constraints: Constraints (2.27) – (2.30) ensure that when a generator is de-committed, it has to remain in the OFF-state for a definable minimum number of hours before it can be turned on again [11].

$$\sum_{k=1}^{D_j} v_{j,k} = 0, \quad \forall j \in J \quad (2.27)$$

$$\sum_{n=k}^{k+DT_j-1} [1 - v_{j,n}] \geq DT_j [v_{j,k-1} - v_{j,k}], \quad \forall j \in J, \quad \forall k = D_j + 1 \cdots \beta - DT_j + 1 \quad (2.28)$$

$$\sum_{n=k}^{\beta} \{1 - v_{j,n} - [v_{j,k-1} - v_{j,k}]\} \geq 0, \quad \forall j \in J, \quad \forall k = \beta - DT_j + 2 \cdots \beta \quad (2.29)$$

$$D_j = \text{Min} \{ \beta, [DT_j - D_j^0] [1 - V_j^0] \} \quad (2.30)$$

2.3 Microgrids

To establish a green and smart distribution system, considerable efforts have been concentrated on the installation of distributed energy resources (DERs) in recent years. DERs refer to DGs, ESS, DR, and Plug-In Electric Vehicles [2]. DGs include dispatchable generators such as micro-turbines, and non-dispatchable generators, for instance, wind and solar generation. The integration of DERs to utility grids presents major challenges to power system operators. To obtain a reliable and stable use of DERs and distinguish between a large power network and a group of DERs located next to each other, which can be seen as a single generator or loads, the concept of *Microgrids* has been introduced in the distribution network [12]. Microgrids can be considered as vital components in the smart grid environment, which is being developed to improve reliability, power quality, and facilitate integration of DERs. These are defined as medium or small power systems comprising DERs and controllable and uncontrollable loads; either isolated and meeting their own demand needs, or connected to the external grid to supplement their supply requirements. Microgrids are connected to a distribution grid at a single point known as the Point of Common Coupling (PCC).

Each microgrid has an Energy Management System (EMS) which is responsible for the optimization of its operation as well as the maximization of the microgrid's welfare. EMS performs forecasting analysis for load and renewable generation, schedules the output power of controllable DGs, and determines the amount of power should draw from the main grid by using market prices of electricity and gas and probably grid reliability and security concerns [13, 14]. In other words, EMS optimizes its local production capabilities, while taking into account microgrid's stability and security during transition conditions between different modes of operation.

Microgrids are considered to be efficient and resilient since they not only allow for a high penetration level of RESs, but also their ability to operate in isolated mode when faults occur in the main grid [12]. However, the implementation of microgrids encounters a number of challenges. For instance, maintaining demand supply balance in the presence of RESs is a complex task because of generation intermittencies, load mismatches, and voltage instabilities [15, 16].

Recently, several microgrids have been implemented all over the world, and hence real data and operation issues of microgrids are reported. A microgrid with a peak load of 3 MW has been implemented in Santa Rita Jail, in Dublin, California, wherein RESs supply more than 2 MW of peak load [17, 18]. Some of the notable microgrid test systems and remote microgrids in Canada is presented and discussed in [19], wherein the Canadian smart microgrid research network, NSMG-Net

is included. Over 10 research institutions, 24 technology related companies, and 8 utilities are involved in NSMG-Net [20], and part of which is the microgrid implemented in British Columbia Institute of Technology campus, which includes RESs, ESS, and combined heat and power micro-turbines [21]. This microgrid also includes an EMS along with all communication infrastructures for optimizing its operation.

2.3.1 Operational Aspects and Resource Scheduling of Microgrids

Energy resource scheduling in a microgrid is essentially different from that of a large power network due to its size, power exchange with the main grid, and charging/discharging constraints of ESS [22]. Microgrids are also expected to accommodate high penetration levels of renewables as compared to large power systems, and hence have to deal with major uncertainties arising from variable generation and demand. DERs, such as DGs, ESS, and DR, need to coordinate their operation in a microgrid so as to provide a reliable service. In recent years, considerable efforts have been made to address the generation scheduling problem of a microgrid. Two operational objectives have been emphasized upon, minimizing the total operation cost of the microgrid including the operating cost of local generators and the cost of the power drawn from the main grid, or maximizing the revenue of the microgrid when exchanging power with the main grid [13, 14, 16]. Some other objectives considered, are, maximizing the use of RESs, and minimizing emissions [14, 23].

The operation of microgrids in grid connected mode is studied in [13], where demand side bidding is considered while maximizing the profit from the power exchanged with the main grid, and minimizing the operation cost. The priority list method is used to solve the day-ahead UC problem, and economic dispatch is performed using sequential quadratic programming. However, the paper does not consider the presence of ESS, nor the isolated mode operation of microgrids, or the effects of uncertainty due to forecast errors. A multi-agent system for real time operation of a microgrid in both isolated and grid connected modes is simulated using the real-time digital simulator (RTDS) [14]. A two-stage generation scheduling- day-ahead and real time, is considered. Load shifting is carried out before the day-ahead scheduling, while load curtailing is executed in real-time.

An economic dispatch model is proposed in [24], for cost and emissions reduction in combined-heat-and-power based microgrids. The model is solved using differential evolution method. A penalty factor is considered as a cost of emissions, and hence a single objective optimization is used, rather than multiple objectives. The work presented in [24] does not address the isolated mode operation of microgrids, nor takes into account the presence of RESs such as wind and solar

generation. Moreover, the proposed differential evolution method is meta-heuristic and cannot guarantee an optimal solution.

The scheduling of power generation in a microgrid considering isolated and grid connected modes is studied in [25], considering two demand profiles; one where generation is insufficient to meet the demand, and the other with excess renewable generation. However, the work does not consider the presence of ESS or DR, and the main grid electricity price is assumed to be fixed for each hour, and therefore there was no exchange power with the main grid. Ahn et al. [26] presents the optimal power dispatch problem of DGs in a microgrid, in which an ED model is developed to account for active power reserves in isolated operation mode, while interconnected microgrids are able to maintain stable operation by sharing power among different areas. The sharing of power is mainly limited by the capacity of feeders connecting different areas. The energy-related issues pertaining to remote communities in northern Ontario are discussed in [27], wherein the available RE technologies, their potential and the viable alternatives for such locations are considered. Six possible RE integration scenarios are examined for different penetration levels in the Kasabonika Lake First Nation, Ontario.

Cont et al. [28] presents an optimization procedure that enables optimal dispatch of DGs and ESS in a MV islanded microgrid with multiple objectives of minimizing the operating cost and emissions. The proposed multi-objective optimal power flow (OPF) problem is solved using a niching evolutionary algorithm that is capable of finding multiple optima and the objective function's variation in their neighborhood. Nevertheless, the work does not consider DR, and uncertainty handling techniques are not integrated into the developed models.

2.3.2 Energy Storage Systems

The integration of ESSs into power systems and more specifically into microgrids relaxes the paradigm that generation must match the demand and system losses at all times, and thus increases the flexibility of microgrid operations. ESSs are devices that either store or deliver energy depending on whether the system encounters surplus or shortage of energy. It is usually coordinated with RE technologies in the context of smart grids to time shift RE from off-peak generation to on-peak times. An overview of ESS benefits related to each user is shown in Table 2-1.

Table 2-1 Energy Storage Systems Benefits by Users

Users	Benefits
Distribution system operator	• Voltage support • Distribution loss reduction • Capacity support • Deferral of distribution investment
Transmissions system operator	• Reduction of transmission congestion • Deferral of transmission investment
Independent system operators	• Regulation and fast regulation • Spinning and non-spinning reserve • Black start and price arbitrage
Electricity end users	• Power quality • Reliability improvement • Reduction of time of use and demand charges

The day-ahead operation of a microgrid with ESS has been addressed in the literature, where several UC formulations have been proposed. Optimal energy management in a microgrid considering the impact of ESS is studied in [29], where advanced dynamic programming method is proposed to solve the UC with ESS, considering the minimization of fuel costs and gas emissions.

A new method for optimal sizing of ESS in a microgrid, using cost-benefit analysis is presented in [16], wherein an MILP formulation is used for the UC problem with spinning reserve. Two operational modes of the microgrid are considered: isolated and grid connected modes, and their results show that the optimal size of the ESS differs for each mode. Ross et al. [30] presents a knowledge-based expert system (KBES) with an hourly discrete scheduling algorithm for an isolated microgrid. KBES is developed to optimize the scheduling of the microgrid by minimizing the use of dump loads through the use of ESS, and therefore reducing operation cost and emissions.

2.3 Demand Response

The concept of DR or demand side management refers to modifying the load demand to increase consumers' satisfaction and simultaneously producing desired changes in the load shape of the electric utility [31]. Two categories of DR programs can be distinguished [32]: direct and indirect also referred to as price-based DR. The classification of DR depends on whether the alteration of the demand is a utility decision or a choice of customers. Direct DR programs reduce the need for investment in peaking generation capacity, and are used when system reliability is being jeopardized. Since direct DR impacts customers' comfort, incentives are offered to encourage them to participate which thereby allow the utility to take control over a portion of their load. Examples of direct DR programs worth mentioning are the Direct Load Control (DLC) and Interruptible Load (IL) [33]. On the other hand, customers can also take decision through indirect DR programs to adjust their initial demand levels depending on price changes and hence referred to price-based DR. Time-of-Use and Real Time pricing schemes are examples of indirect DR program [34, 35].

A tariff calculation framework for IL on an hourly basis is proposed in [33], wherein the most suitable interruptible tariff is determined using an optimization model that uses an OPF with ramping rate constraints. The objective function of the OPF is modified to include financial returns for the utility, which involve interaction between utility and customers. The study shows that transmission congestion because of operational constraints is almost completely mitigated by using IL; the expected increase of economic social welfare for the market is also reported. In [36], two approaches for load shifting, direct control and customer demand elasticity, are considered for conducting DR studies in an isolated system with high wind integration. A two-step process is used: a UC model without DR defines prices for which variations in demand are calculated, and then the final operation schedule and costs are obtained by minimization of the total cost from DR variations. It is reported that, with the consideration of DR, less controllable units are committed since the impact of wind variations are mitigated, which reduces the operation cost.

A UC approach with responsive demand is proposed in [37], wherein different DR programs and DLC are analyzed to create a DR program priority list for independent system operator. The proposed model studies economic and environmental impacts of DR programs, which consists of generating optimal incentives for different DR programs and then feedback from customers is received to repeat a cost-emission based UC resolution. The participation of customers in DR

programs is improved in this work, and hence encourage an optimal responsiveness and prevent DR from affecting the system.

2.4 Uncertainty Management in Power Systems Operations

Two main types of uncertainties exist in power system operations: outage of generation units and departure from forecasts. The outage of generation units can lead to a supply shortage in the system, which is usually met from operating reserves that includes spinning and non-spinning reserves. Spinning reserve is connected to the system and is the unused capacity from the available and committed DG units, while fast-start units not connected to the system and interruptible loads provide the non-spinning reserves. In case of a microgrid, the disconnection from the main grid is considered as a major outage since the microgrid will be operated in isolated mode and has to supply its demand from the reserves using only its local resources. Departure from the forecasts that include uncertain load, area interchange and generation occurs often and integration of RESs adds more uncertainties in operations. Wind and solar generation are dependent on wind speed and solar irradiance, respectively, which are difficult to predict with high accuracy. In microgrids, the effect of uncertainties associated with wind and solar generation are more significant due to their high penetration levels.

In recent years, considerable efforts have been made on handling uncertainty in power systems operations. In most of the literature, two approaches for managing uncertainty in the UC problem are reported: reserve requirement and stochastic optimization models. An additional reserve is included in [16], to take into account uncertainties in load, wind and solar power forecasting errors. The additional reserve requirement is determined from the forecasting errors, for instance, the root mean square error (RMSE) of the time series, which is used to forecast wind speed, represents wind speed forecasting error. A new approach to quantifying the reserve requirement in a power system with high wind penetration is proposed in [38] where outage rates of generators, and wind power and load forecasting errors are considered. The reserve requirement at each hour is related to the reliability of the system over a year using the developed methodology. The average risk of having load curtailment during each hour, which is also kept the same for all hours throughout the year, is used to allocate the reserve. It is noted that when wind penetration increases, the required reserve must be increased in order to ensure system reliability.

In order to optimize spinning reserve requirement in the UC problem, an approach is proposed in [39], using a cost-benefit analysis. Optimal spinning reserve is defined as the quantity where the cost of providing an extra MW of reserve equivalents the benefits of providing the extra

MW. The reduction in the expected cost of interruptions measures the benefit of the reserve. The authors extend the proposed method in [40], wherein a significant wind penetration is considered. The presented method decouples the reserve requirement from the UC problem in order to overcome the difficulties of incorporating the stochastic behavior of renewable generation and load, and accounting the unreliable equipment through the calculation of loss of load probability (LOLP) and expected energy not served (EENS). However, preprocessing the spinning reserve requirement prior to solving the UC problem is considered as a drawback in this method, which may result in suboptimal solutions. To overcome this drawback, a multi-step probabilistic method is proposed in [23], wherein the UC and reserve estimation problems are solved simultaneously.

A two-stage stochastic programming to solve the UC problem is proposed in [41], wherein UC variables are considered as stage one decisions, while power output and reserve requirements as stage two decisions. Only unit outage events and load uncertainty are considered, while renewable generation is not addressed in this study. In [42], a three stage stochastic programming with rolling planning is proposed, which is part of the Wind Power Integration in Liberalized Electricity Markets (WILMAR) model [43]. The model contains two parts: a scenario tree tool and a scheduling model. The scenario tree tool generates the scenarios, while the scheduling model solves the UC problem. A new 24-hour ahead schedule is carried out every day at noon with a horizon of 36 hours using a rolling planning model. Every 3 hours, the scheduling process is repeated taking into consideration the 24-hour ahead schedule. The inter-day scheduling includes both the UC decisions, and levels of the power output. The forecast is assumed to be perfect in the first stage, and hence using “hear-and-now” approach when taking its decisions. While, the other two stages take decisions through “wait-and-see” approach, due to the fact that uncertainties have not been realized yet, and may vary through future planning periods.

Stochastic UC formulations lead to a better representation of the uncertainties with respect to deterministic UC formulations. Yet they still suffer from the dimensionality curse and hence their solution can be computationally intractable even with scenario reduction techniques [44]. Instead, multi-scenario linear optimization models, considered as the equivalent deterministic models of the stochastic programs, can be used to represent two-stage linear stochastic programs. The objective function of a multi-scenario linear optimization model when solving the UC problem is the summation of the product of the operation cost of each scenario and its corresponding probability. In the meanwhile, original deterministic single-scenario model’s constraints are repeated for each

scenario in the multi-scenarios optimization model. In [45], the UC problem is formulated as multi-scenario linear optimization problem. The authors consider the uncertainties associated with load, solar and wind power, and plug-in vehicles. Particle swarm optimization is used to solve this operational problem. Likewise, the uncertainties are taken into account in the UC problem in [23], using a multi-scenario optimization model. Various uncertainties are combined to an aggregated uncertainty distribution in this study, and hence the number of scenarios is reduced. The proposed problem is formulated as MILP and solved using CPLEX solver in the General Algebraic Modeling System (GAMS) environment [46]. For managing uncertainties, the multi-scenario stochastic optimization and additional reserve requirements will be combined and applied in this thesis. Further details will be presented in Section 4.2.

2.5 Summary

This chapter discussed the UC problem and presented brief review of literature on the operational aspects of a microgrid. These studies reflect the importance of resource scheduling in microgrids, and illustrate the role played by flexible resources, such as ESS and DR. The work carried out in the area of microgrid operations mostly examines ESS, not considering the coordination of ESS and DR. Moreover, the studies performed so far do not consider the potential of accommodating high levels of RESs in a remote microgrid. Maintaining a reliable and secure operation of the microgrid is a challenging problem when considering high and uncertainty levels of renewable generation, and more specifically in the remote microgrid.

Chapter 3

Short-Term Operation of Microgrids with ESS and DR

3.1 Introduction

In the previous chapter, operational aspects of microgrids and flexible resources such as DR and ESS are reviewed and it is concluded that there is a vital need to accommodate more such resources in microgrids to handle the stochastic and intermittent behavior of wind and solar power generation. This chapter presents a mathematical model for short-term operational planning of a microgrid that includes ESS and DR. This model can be used to analyze the effects of the coordination of ESS and DR on microgrid systems with high renewable generation. The proposed model and the accompanying analysis provide insight into the effects on operation costs, levels of renewable generation, and power import/export from the main grid. The main objectives of this chapter are to:

- a. Develop short-term operational planning models of a microgrid with ESS and DR, considering both isolated and grid connected modes of operation.
- b. Examine the advantages of coordinated operation of ESS and DR, vis-à-vis their independent presence in microgrid systems with high penetration of renewables.
- c. Investigate the impact of the coordination of ESS and DR on the level of penetration of renewable generation in remote microgrids.

3.2 Mathematical Models

The hourly variations of wind and solar generation are considered exogenous inputs for the proposed 24-hour ahead energy resource scheduling models for operation of a microgrid with ESS and DR. Two different models, one for grid connected and the other for isolated mode of operation of the microgrid, are presented.

3.2.1 Model-1: Isolated Mode Operation of a Microgrid

The mathematical model is formulated with the objective of minimizing the total cost (TC) over a period of 24 hours, as given below:

$$\begin{aligned}
TC = & \sum_{k \in K} \sum_{j \in J} (C_j(P_{j,k}) + SU_{j,k}) + \sum_{k \in K} C_{ES} \cdot (V_k^{CH} + V_k^{DCH}) + \sum_{k \in K} (P_k^{Curt} \times C_{Curt}) \\
& + \sum_{k \in K} (\Delta P_k^{UP} \times C_{DR})
\end{aligned} \tag{3.1}$$

The first term in (3.1) represents the operating cost of generators, which include the linearized fuel cost and start-up cost of a unit j , as represented and discussed in Chapter 2. The second term denotes the operating cost of ESS. The cost of renewable power curtailment, when renewable generation exceeds the demand at a certain hour is represented by the third term. For instance, in the case where ESS and DR are not introduced into the model, the excess renewable power has to be curtailed, so as to maintain the balance. A transaction cost for shifting the demand is introduced in the fourth term, which represents the nuisance to consumers.

Demand-Supply Balance: This constraint ensures that the total generation meets the forecasted demand of period k , and also includes wind and PV generation, ESS, DR, and renewable power curtailment.

$$\sum_{j \in J} P_{j,k} + P_k^W + P_k^{PV} + P_k^{DCH} = P_k^{DEM} + P_k^{CH} + P_k^{Curt} \tag{3.2}$$

The variable demand P_k^{DEM} represents the resulting demand at an hour k , after demand shifting has taken place, and can be more or less than the original demand P_k^D , as defined in (3.3) [36]:

$$P_k^{DEM} = P_k^D + \Delta P_k^{UP} - \Delta P_k^{Down} \tag{3.3}$$

The load shifting operation and decisions are assumed to be determined and controlled by the microgrid operator, not the electricity end users. It is assumed that the operator has information on the electrical devices (appliances) connected to its system, with an activated delayed option, such that the demand could be shifted to other hours. In order not to shift the customers' activities to the other day, the demand variation must be balanced within the 24 hours [36], as given below:

$$\sum_{k \in K} \Delta P_k^{UP} = \sum_{k \in K} \Delta P_k^{Down} \tag{3.4}$$

The maximum demand that can be shifted from one hour to another is limited as given below [36]:

$$\begin{pmatrix} B_{do} \\ B_{up} \end{pmatrix} \cdot P_k^D \geq \begin{pmatrix} \Delta P_k^{Down} \\ \Delta P_k^{UP} \end{pmatrix} \geq 0 \tag{3.5}$$

Spinning Reserve Constraint: This constraint ensures that the net available capacity, from all committed generators and ESS, meets the system spinning reserve requirements at period k .

$$\sum_{j \in J} (P_j^{max} \cdot V_{j,k} - P_{j,k}) + \eta_d [C_k - C_{min}] \geq R_k \quad (3.6)$$

In addition, each controllable unit is subject to its own operating constraints, such as ramp-up/ramp-down constraints, minimum-up and down time constraints, generation output limits, positive constraints, logical and initial constraints, which are presented earlier in Chapter 2.

Energy Storage Systems: An ESS, such as a vanadium redox flow (VRB) battery, is considered as a special controllable unit that has the ability to absorb energy. The ESS should satisfy the following constraints [15, 16]:

$$\text{Discharge power limit: } P_k^{DCH} \leq P_{ES}^{max} \cdot V_k^{DCH} \quad (3.7)$$

$$\text{Charging power limit: } P_k^{CH} \leq P_{ES}^{max} \cdot V_k^{CH} \quad (3.8)$$

$$\text{Discharging equation: } C(k+1) = C(k) - d_k \cdot P_k^{DCH} / \eta_d \quad (3.9)$$

$$\text{Charging equation: } C(k+1) = C(k) + d_k \cdot P_k^{CH} \cdot \eta_c \quad (3.10)$$

$$\text{Starting / Ending limit: } C(0) = C_S; C(K) = C_E \quad (3.11)$$

$$\text{Stored Energy limit: } C_{min} \leq C(k) \leq C_{max} \quad (3.12)$$

$$\text{Charging / discharging coordination: } V_k^{DCH} + V_k^{CH} \leq 1 \quad (3.13)$$

Power Curtailment: In order to ensure system security, power curtailment is invoked when there is excess of renewable generation, as given below:

$$P_k^D - P_k^W - P_k^{PV} - \sum_{j \in J} (P_j^{min} \cdot V_{j,k}) \leq \mu(1 - V_k^{Curt}) \quad (3.14)$$

$$-P_k^D + P_k^W + P_k^{PV} + \sum_{j \in J} (P_j^{min} \cdot V_{j,k}) \leq \mu \cdot V_k^{Curt} \quad (3.15)$$

$$P_k^{Curt} \leq \mu \cdot V_k^{Curt} \quad (3.16)$$

The above constraints (3.14-3.16) ensure that at least one controllable unit with enough capacity will be available to provide the required spinning reserve when renewable generation exceeds the system load.

3.2.2 Model-2: Grid Connected Mode Operation of a Microgrid

The mathematical formulation of grid-connected mode operation is similar to the isolated mode except for the objective function, demand supply balance and spinning reserve constraints. The objective function is to minimize the total cost (TC) of the microgrid operation using its local generation resources and buying/selling power from / to the main grid.

$$TC = \sum_{k \in K} \sum_{j \in J} (C_j(P_{j,k}) + SU_{j,k}) + \sum_{k \in K} C_{ES} \cdot (V_k^{CH} + V_k^{DCH}) + \sum_{k \in K} (\Delta P_k^{UP} \times C_{DR}) \\ + \sum_{k \in K} (P_k^{IMP} \times C_k^{GRID}) - \sum_{k \in K} (P_k^{EXP} \times C_k^{GRID}) \quad (3.17)$$

The last two terms of (3.17) are the cost for importing and exporting power from / to the main grid, respectively.

Demand-Supply Balance: This constraint ensures that the total generation meets the forecasted demand of period k , and includes wind and PV generation, ESS, DR, power import and export from/to the main grid, and renewable power curtailment.

$$\sum_{j \in J} P_{j,k} + P_k^W + P_k^{PV} + P_k^{DCH} + P_k^{IMP} = P_k^{DEM} + P_k^{CH} + P_k^{EXP} \quad (3.18)$$

Spinning Reserve Constraint: The total maximum available output power, from all committed generators, ESS and the main grid, meets the system spinning reserve at period k .

$$\sum_{j \in J} (P_j^{max} \cdot V_{j,k} - P_{j,k}) + (P_{grid}^{max} \cdot V_k^{IMP} - P_k^{IMP}) \geq R_k \quad (3.19)$$

In addition, the grid export and import constraints are given below:

$$0 \leq P_k^{EXP} \leq P_{grid}^{max} \cdot V_k^{EXP} \quad (3.20)$$

$$0 \leq P_k^{IMP} \leq P_{grid}^{max} \cdot V_k^{IMP} \quad (3.21)$$

In order not to receive and send power from/to the main grid at the same hour k , the following constraint is included into the model.

$$V_k^{IMP} + V_k^{EXP} \leq 1 \quad (3.22)$$

3.3 System under Study

A microgrid benchmark is considered [47], which consists of twelve controllable DGs, a wind turbine (WT), a PV system, and ESS. The total installed capacity in the microgrid system is 4 MW, with a renewable penetration level of 49%. The installed capacity of controllable DGs, WT and PV systems are 2.04 MW, 0.52 MW (4x0.14 MWp) and 1.44 MW (4x 0.36 MWp), respectively. Details of the average hourly wind speed profile, parameters of WT, the irradiance shapes, and parameters of PV can be found in [47]. Data of controllable DGs is given in Table 3-1. The 24 hour load profile for the microgrid that includes commercial, residential, and industrial loads [13] is shown in Figure 3-1 along with the wind and solar generation profiles. The microgrid operator is assumed to have the ownership and operation of the ESS. As per [48], the average operating cost of the ESS is estimated to be 0.54 \$/kWh, considering two operating cycles per day, 1,200 \$/kWh of investment cost, at 8% annual rate of return, and for a life span of 3000 cycles. The ESS considered for this microgrid is a single-layer VRB whose technical characteristics are given in [30]. For ESS, P_{ES}^{max} is 150kW; C^{max} is 900 kWh; C_S and C_E are 0.5 p.u, charging and discharging efficiencies are 0.85 [30]. Data of pollution contaminants of different generators is given in Table A in Appendix A [49].

One third of the load is assumed to be critical. In the islanded mode, the spinning reserve requirement for each hour is considered to be 10% of the critical load of an hour, while in the grid connected mode, 10% of the entire load is considered for the spinning reserve. Since the load profile includes industrial, commercial, and residential loads, the shiftable demand is assumed to be 15% of the total demand. The load shifting cost of customers is assumed to be 2 \$/kWh, which is high due to its impact on customers' comfort. The price of curtailment is set at 18 \$/kWh, which is chosen to be significantly higher than other considered costs, to ensure that power curtailment is not a preferable option. The main grid electricity price is derived from [16], as shown in Figure 3-2. The value of the constant μ used in the linearized equations (3.14–3.16) is considered to be 10,000.

Table 3-1 Data of controllable DGs [47]

Parameters	DG1	DG2	DG3	DG4	DG5	DG6	DG7	DG8	DG9	DG10	DG11	DG12
Pmax (kW)	410	410	270	270	140	140	90	90	65	65	45	45
Pmin (kW)	100	100	50	50	25	25	20	20	15	15	10	10
a (cts/h)	65	60	45	41	40	38	38	35	30	24	18	15
b (cts/kWh)	15.20	15.30	16.60	16.50	18.50	18.76	26.70	26.90	29.71	29.92	26.20	26.79
c (cts/kW2h×10−4)	5.2	6.1	21	21.11	42	53	8	12	9	13	24	31
Min Up (h)	5	5	3	3	2	2	2	2	1	1	1	1
Min Down (h)	5	5	3	3	2	2	2	2	1	1	1	1
Hot start cost (cts)	550	500	450	460	800	750	360	350	280	285	200	205
Cold start cost (cts)	1100	1000	900	920	1600	1500	720	700	560	570	400	410
Cold start time (h)	3	3	2	2	1	1	1	1	0	0	0	0
Initial status (h)	5	5	3	3	2	-2	-2	-2	-1	-1	-1	-1

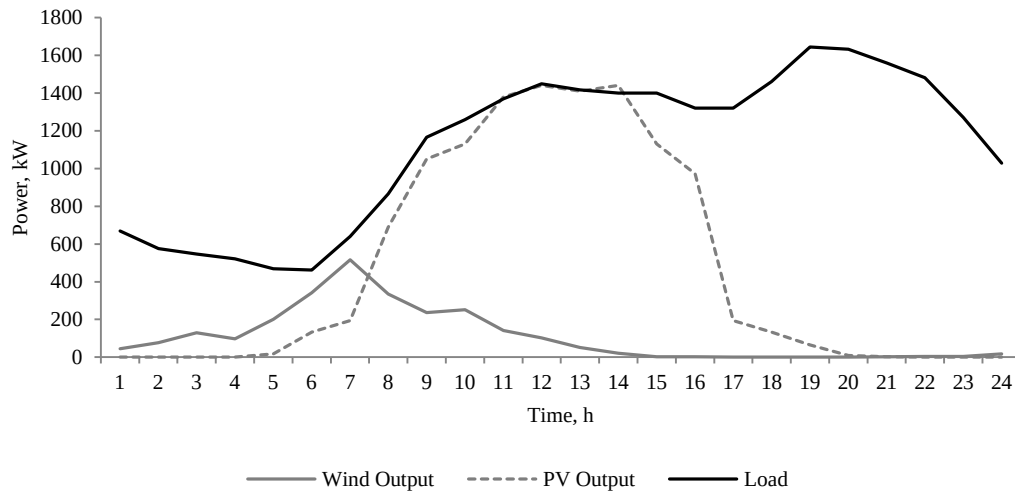


Figure 3-1 Load, wind, and PV outputs profiles for the microgrid system

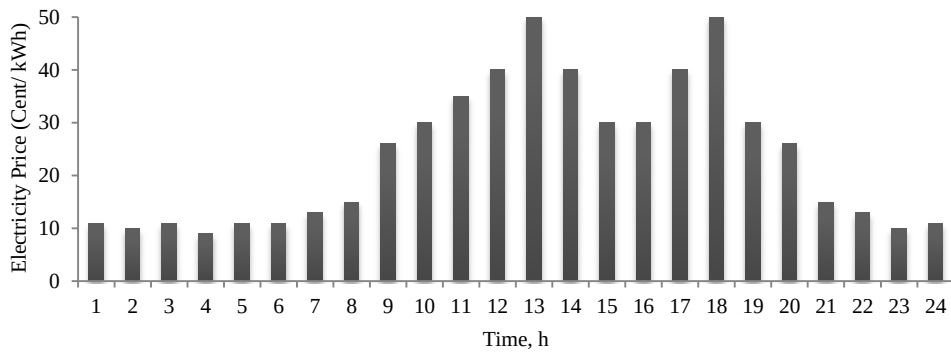


Figure 3-2 Main grid electricity price of every hour

3.4 Analysis and Results

The objective of the microgrid operator is to minimize the total cost by optimizing the DER schedules, which includes controllable and uncontrollable DGs, ESS and DR. When the power produced by the local sources is greater than the system load, the operator can use ESS, DR, or both, to mitigate the mismatch between the supply and demand, and *vice versa*. However, their optimal selection depends on system condition. For instance, if the ESS is not fully charged, then the excess power, most of which from renewables, can be stored into the ESS. On the other hand, if the ESS is fully charged, then the DR comes into effect. Furthermore, both ESS and DR can be also utilized simultaneous when the ESS is fully charged and there is still excess power, the DR can be activated to accommodate the remaining power. This occurs at times when renewable power is high and/or the output power from controllable units is lowest. In grid connected mode, in addition to ESS and DR, the main grid comes into effect, by importing or exporting power when needed. In order not to endanger system security in the isolated mode, at least one controllable unit with enough capacity will be available when there is excess of renewable generation, mainly in the case where ESS is not introduced into the model. In that interval, the maximum available power of this controllable unit takes care of the critical load.

3.4.1 Coordination of Renewable Generation, Controllable DGs, ESS and DR

This subsection discusses the effects of wind and solar generation variations on operation costs, scheduling and dispatching of controllable DGs, and power import/export from the main grid. It also shows how to accommodate more flexible resources into the microgrid system to mitigate demand-supply unbalances arising from the intermittent nature of these variable generations. To study the effects of hourly variations of wind and solar generation on the 24-hour ahead energy resource scheduling of microgrids, four study cases are examined, which are as follows:

- Case-1: Microgrids, No ESS or DR
- Case-2: Microgrids with DR only
- Case-3: Microgrids with ESS only
- Case-4: Microgrids with a combination of ESS and DR

The results of each case for isolated mode operation of the microgrid are presented in Table 3-2. In Case1, when the renewable generation exceeds the system load, the excess power is curtailed. Additional power curtailment takes place to commit at least one controllable unit with enough

capacity to provide the required spinning reserve. On the other hand, no RE curtailments take place in Case-4 since the combination of ESS and DR mitigates this curtailed energy, by optimally charging/discharging the ESS, and/or altering the microgrid load curve. It is to be noted that the operating cost and emissions are reduced as more flexibility, in terms of DR and ESS, is introduced into the microgrid. The fourth case is considered to have the lowest total cost compared with other cases considered.

Table 3-2 Cost components and emissions for isolated microgrid operation

Case	Operating Cost (\$)	RE Curtailment Cost (\$)	DR cost (\$)	Total Cost (\$)	Emissions (lb/kWh)
1	2,364	17,139	0	19,503	2,413
2	2,165	687	1,828	4,680	2,258
3	2,222	201	0	2,423	2,309
4	2,167	0	181	2,348	2,269

A sensitivity analysis is carried out to assess the impact of variation of the parameters of flexible resources, for example, the capacity and the cycle efficiency of ESS. Three different capacities of ESS are considered: 600, 900, and 1,200 kWh. Besides, different cycle efficiencies with a nominal fixed capacity of ESS of 900 kWh are examined to study their effects on microgrid operation costs. As shown in Table 3-3, with increasing the ESS capacity, the operating cost decreases; however, the sizing of ESS has to be selected carefully since the operation cost savings rapidly saturate with increasing storage capacity, while investment costs increase further. The optimal sizing of ESS that achieves optimal cost savings is beyond the scope of this thesis. It can be observed from Table 3-3 that there is still curtailed RE in the system even though the storage capacity is increased. This is because the maximum charge/discharge power of the ESS is considered to be the same in the presented cases, and the only difference is the storage capacity. However, this consideration may not be realistic or practical, but it is used to compare the effects of different capacities of ESS on microgrid operations. From the comparison presented in Table 3-3, the benefits of combining DR with ESS can be realized. That is, DR can be activated to accommodate the remaining excess renewable energy when ESS reaches its maximum charge power, as in our presented cases. Table 3-4 shows the effects of different cycle efficiencies of ESS on microgrid operations, and it is observed that the operating cost decreases with raising the cycle efficiency of ESS. It is to be noted

that the storage capacity, where there is excess renewable generation, influences the operating cost of the microgrid more significantly than the cycle efficiency.

Table 3-3 Cost comparison of different capacities of ESS for isolated microgrid

Capacity of ESS (kWh)	Total operating cost (\$)	RE curtailment cost (\$)	Total cost (\$)
600	2,200	2,618	4,818
900 (nominal)	2,222	201	2,423
1200	2,195	201	2,396

Table 3-4 Cost comparison of different cycle efficiencies of ESS for isolated microgrid

Cycle efficiency with ESS of 900 kWh capacity	Total operating cost (\$)	RE curtailment cost (\$)	Total cost (\$)
0.75	2,241	201	2,442
0.85 (nominal)	2,222	201	2,423
0.95	2,149	201	2,350

Figure 3-3 presents the 24-hour ahead energy scheduling for the isolated microgrid with DR and ESS. When there is excess generation, for example, during periods 7-14, the ESS is utilized to absorb this excess, and if there is still excess power, DR is activated to accommodate the remaining excess power, as at hours 8 and 11. However, it is not shown clearly in the figure due to the fact that the remaining excess amount is relatively small; this impact will be shown clearly in Section 3.4.2. During periods 6-14, all controllable units are de-committed, and the required spinning reserve is provided by the ESS. If ESS is not considered in the spinning reserve, at least one controllable unit is operated at its minimum power in order to provide the required spinning reserve. During time periods 19-23, the ESS and DR are activated, so as not to commit high cost controllable units.

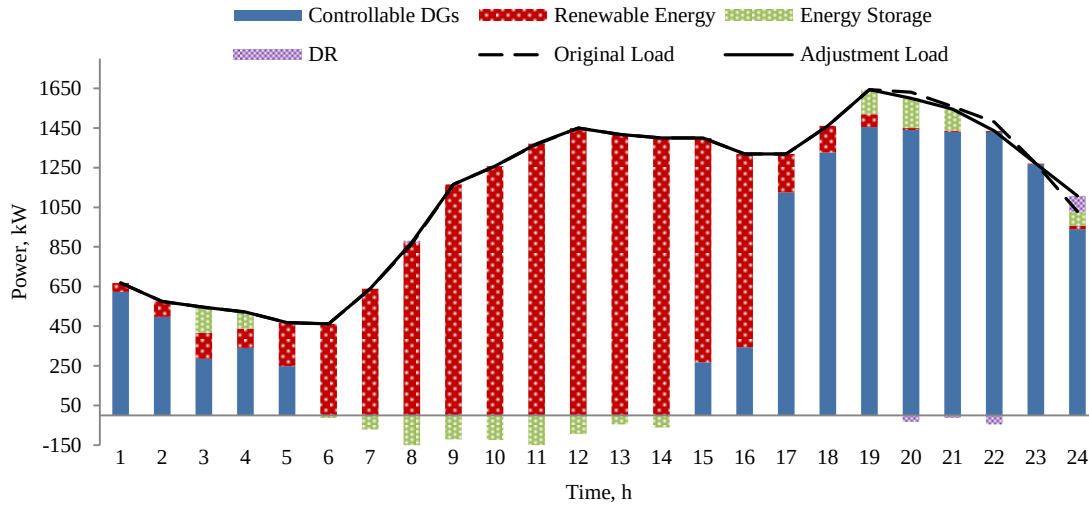


Figure 3-3 The 24-hour energy scheduling for isolated microgrid with DR and ESS

Table 3-5 presents the results of each case for the grid connected mode operation of the microgrid. It is observed from Table 3-5 that the total cost is the lowest in Case-4, with respect to other considered cases. It can also be noted that the total cost for grid connected mode of operation is much lower than that in isolated mode of operation. This is due to the fact that exchanging power with the main grid helps reduce the overall cost of the microgrid. Furthermore, the RE curtailment cost introduced in the objective of the isolated mode operation is significantly higher, and hence leads to increase in the total cost of operation in isolated mode. In order to examine the effects of load shifting in the grid connected mode, the corresponding price is assumed to be in the mean range of the electricity market price, which is 0.13 \$/ kWh.

Table 3-5 Cost components for the grid connected microgrid

Case	Operating cost (\$)	Export revenue (\$)	Import cost (\$)	DR cost (\$)	Total cost (\$)
1	2,480	2,849	765	0	396
2	2,323	2,843	829	74	383
3	2,459	2,811	704	0	352
4	2,331	2,811	772	47	339

The 24-hour ahead energy scheduling for grid connected mode of the microgrid with DR and ESS is presented in Figure 3-4. During time periods 1-7, the electricity price from the main grid is lower than the operating cost of controllable units, and therefore the required power to supply the demand is purchased from the main grid; there is no need to have controllable units committed at these periods since the required spinning reserve is provided by the main grid and/or the ESS. When there is excess renewable energy during periods 8-16, the excess power is utilized optimally by exporting it to the main grid, charging the ESS, and/or inducing DR. For instance, at hour 8, the ESS accommodates the excess power because the market price is not high enough at this hour to export it to the main grid. During periods 21-24, the market price is lower and therefore significant part of the loads served by power purchased from the main grid.

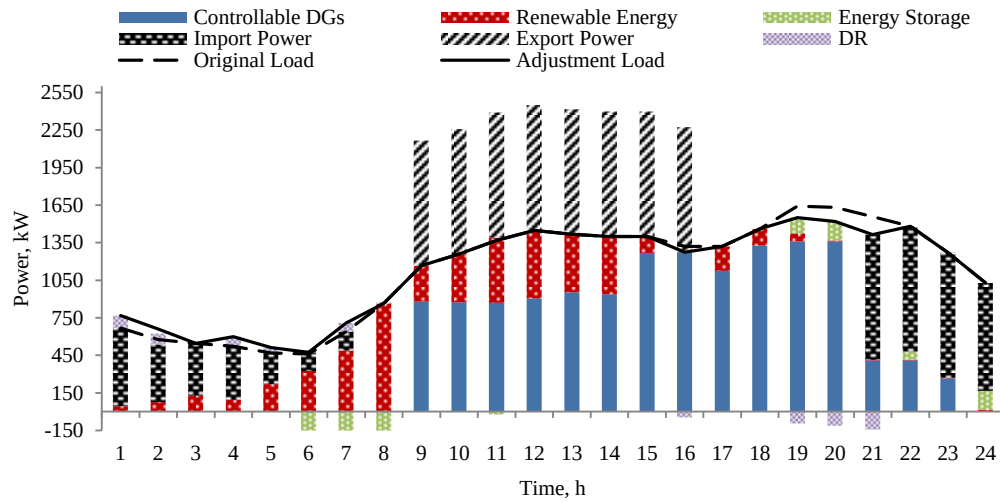


Figure 3-4 The 24-hour energy scheduling for grid connected microgrid with DR and ESS

3.4.2 ESS and DR in a Remote Microgrid for High Penetration of Renewables

This subsection investigates the potential for accommodating high penetration levels of renewables by taking the advantages of combined operation of ESS and DR. Renewable penetration is defined as the percentage of total installed capacity of renewables with respect to total system installed capacity. In order to examine the impacts of accommodating high levels of renewables, four case studies with different levels of renewable penetration are analyzed. It is to be noted that in this subsection only analysis of remote microgrid is considered.

A. Case-1: No ESS or DR

In this case, when the generation from renewables exceeds the microgrid load, the excess power is curtailed. Additional power curtailment can take place to commit at least one controllable unit with enough capacity to provide the required spinning reserve. The total cost and curtailed energy for different penetration levels of renewables are shown in Figures 3-5, and 3-6, respectively. Even though the operating cost reduces when renewable energy penetration increases the total cost increases because of the RE curtailment cost introduced into the model. Since no ESS or DR is present in this case, the renewable penetration has to be limited to a level at which there would be no power curtailment, and therefore it is not possible to increase their penetration, as shown in Figure 3-6.

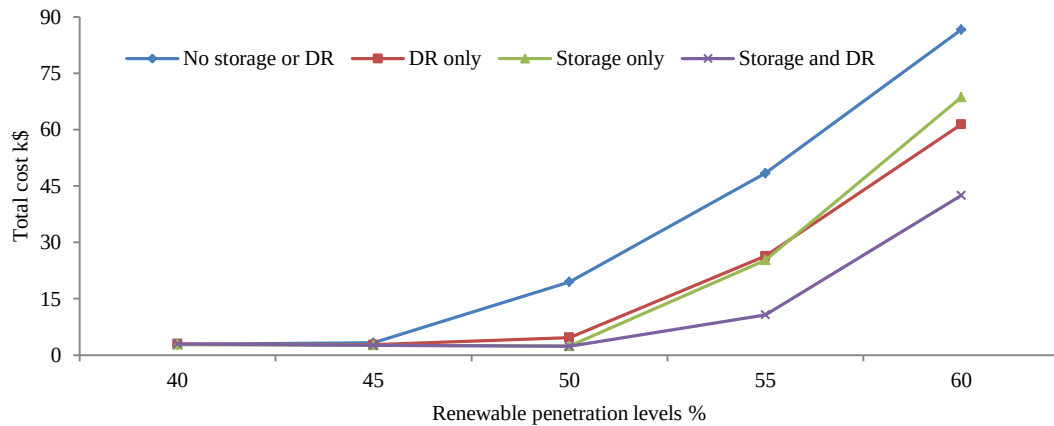


Figure 3-5 Comparison of total cost for different renewable penetration levels

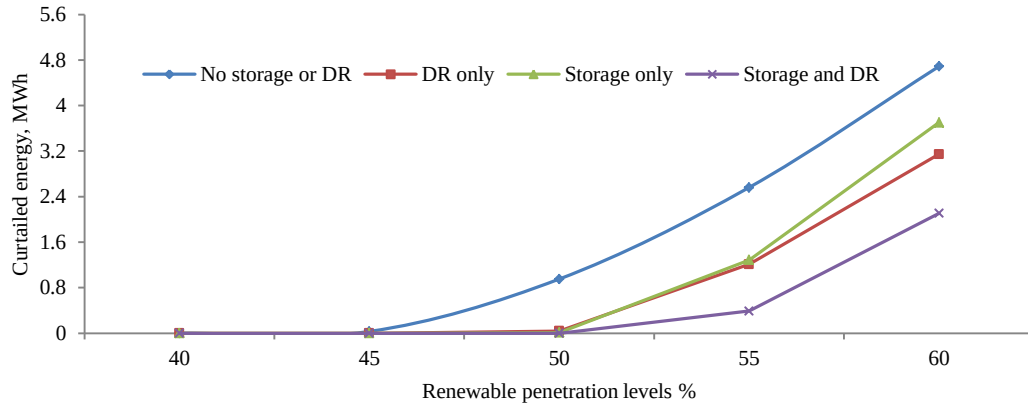


Figure 3-6 Comparison of curtailed energy for different renewable penetration levels

B. Case-2: With DR only

When DR options are considered in microgrid operations, the operator can alter the microgrid load profile to cope with the variation of renewable generation, by shifting the flexible component of the demand. The deferrable demand is selected at times when renewable generation is high and/or the output power of the controllable units is low. When renewable penetration increases, the shifted demand is higher and the RE curtailed energy reduces. In order to remunerate consumers for shifting their loads, a transaction cost is introduced in the model which encourages consumers to defer their demand without causing any inconvenience for them. The penetration level of renewables can be increased when DR is integrated into the microgrid. By altering the load curve to be as close as possible to the renewable power curve, the benefits of renewables are maximized, i.e., operating cost and wasted energy are minimized.

C. Case-3: With ESS only

The ESS acts either as a negative or an additional load, which means the aggregated output power from controllable units and renewable generation, will not match the load, most of the time. When the aggregate output power is greater than the load, the ESS is in charging mode and stores energy for use at a later time. This happens at times when the renewable power is high and/or the output power of the controllable units is lowest. The ESS acts as a negative load when renewable generation is low and/or the output power of controllable units is highest. When ESS is considered, the curtailed energy for different renewable penetration is low compared to the base case where ESS is not introduced, and therefore ESS has the potential to support high levels of renewable penetration. However, there is still

curtailed energy in the system, because there are no other loads in the system to accommodate the excess power when the ESS is fully charged.

D. Case-4: With a Combination of ESS and DR

This case considers both ESS and DR in the microgrid, which means that their potential benefits are combined in this case. This mix reduces the risk in the scheduling problem, and increases the flexibility of the microgrid. It is to be noted that this case results in the lowest cost with respect to other considered cases. The operating cost, the RE curtailment cost and DR cost for the remote microgrid with 60% renewables are presented in Table 3-6. The power output and state of charge (SOC) of the ESS are shown in Figures 3-8 and 3-10 for 50% and 60% RE penetration, respectively, while Figures 3-7 and 3-9 show DR scheduling for 50% and 60% RE penetration, respectively. It is observed that the amount of demand that is shifted is higher when renewable penetration is high. This is due to the fact that the ESS would be fully charged and DR is activated to accommodate the remaining excess power. This combination of DR and ESS in microgrids presents an efficient solution towards improving the flexibility of smart microgrids, and for supporting high penetration levels of renewables.

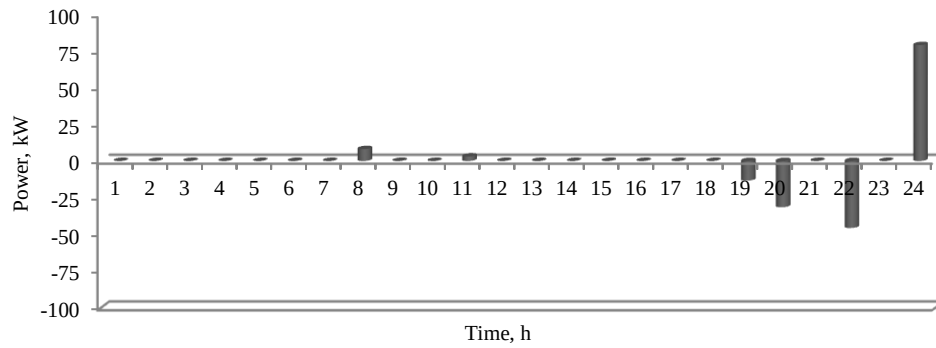


Figure 3-7 DR scheduling for 50% RE penetration

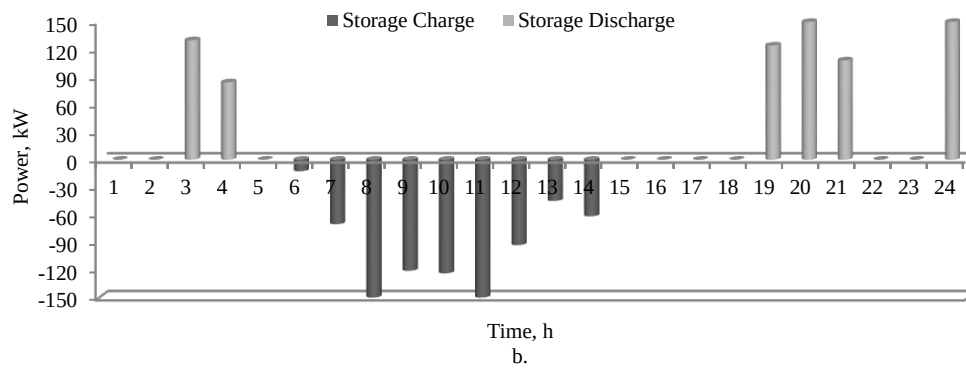
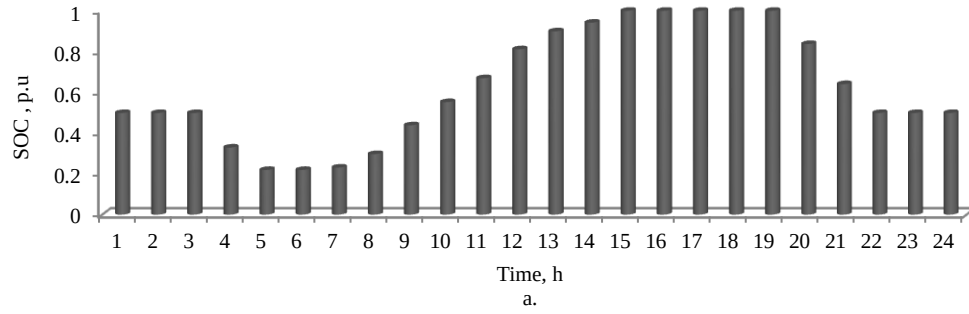


Figure 3-8 a. State of charge (SOC) for ESS and b. ESS charge/ discharge for 50% RE penetration

Table 3-6 Cost components for remote microgrid with 60% renewables

Case	Operating Cost (\$)	RE Curtailment Cost (\$)	DR cost (\$)	Total Cost (\$)	Emissions (lb/kWh)
1	2,240	84,392	0	86,632	2,284
2	1,942	56,645	2,833	61,420	2,005
3	2,062	66,625	0	68,687	2,159
4	1,747	37,931	2,867	42,545	1,829

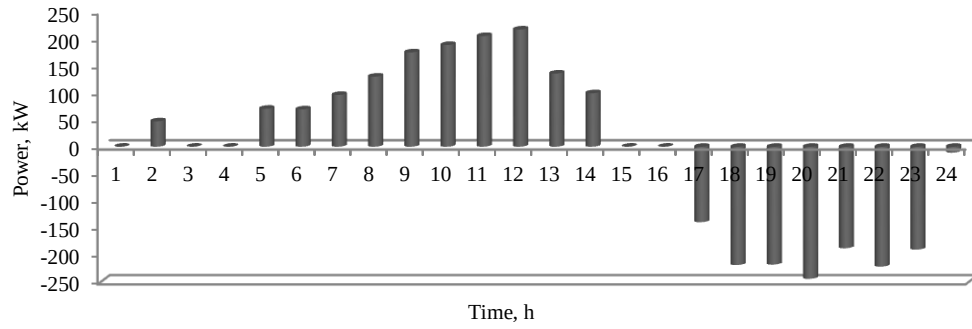
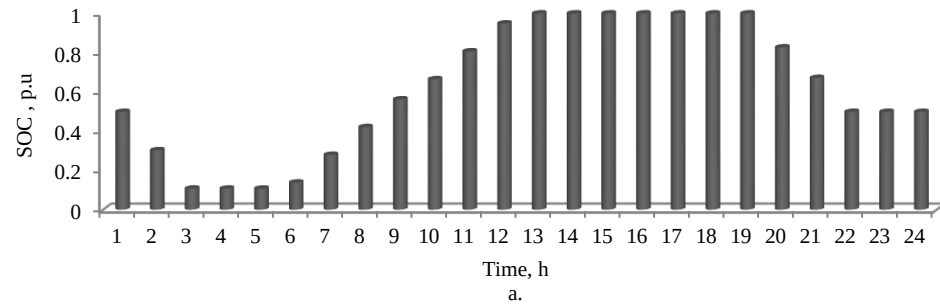
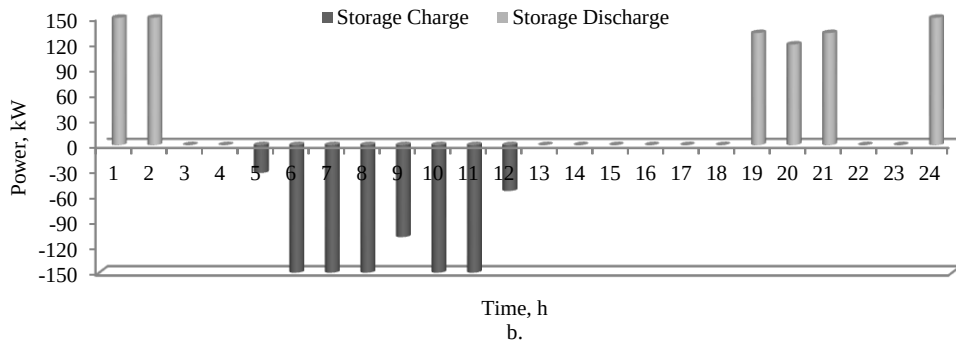


Figure 3-9 DR scheduling for 60% RE penetration



a.



b.

Figure 3-10 a. State of charge (SOC) for ESS and b. ESS charge/ discharge for 60% RE penetration

3.5 Summary

This chapter presents two optimization models to address the 24 hour ahead energy scheduling problem in a microgrid with ESS and DR. Details of the short term operational planning models of the microgrid with ESS and DR included, considering isolated and grid connected modes are presented. The developed models are applied to a microgrid benchmark considering four case studies in order to assess the effects of wind turbine and PV system operation on microgrid systems with and without ESS and DR. The simulation results indicate that the operation of ESS and DR can be effectively and efficiently coordinated to mitigate the demand supply balance issues, and therefore reducing the operating costs and emissions. It can also be concluded that having many options, such as ESS, DR, and/or the main grid, to consider when solving energy scheduling problem, help to reduce further the total cost of the microgrid. The impact of accommodating higher levels of renewable generation on the operation of the remote microgrid is also presented and discussed.

Chapter 4

Stochastic Short-Term Operation of Microgrids with ESS and DR

4.1 Introduction

In the previous chapter, deterministic short-term operational planning models of the microgrid with ESS and DR are developed, for isolated and grid connected modes. The deterministic models can be used to analyze the effects of the fluctuation of wind and solar generation on microgrid operations. However, when it comes to handling uncertainties of variable generations and load, a stochastic model that includes the uncertainties of load, and intermittency in wind and solar generation sources is needed to track their stochastic behaviors. This chapter presents multi-scenario stochastic short-term operational planning models of the microgrid, for isolated and grid connected modes, to examine the uncertainty effects on microgrid operations with and without ESS and DR. The work considers reserve requirements and a set of valid probabilistic scenarios for the uncertainties of load, solar and wind energy. The main objectives of this chapter are as follows:

- Develop stochastic short-term operational planning models that include ESS and DR, for grid connected and isolated modes of microgrids, to address uncertainties of load, and wind and solar generation.
- Examine the advantages of coordinated operation of ESS and DR in the presence of uncertainty, vis-à-vis their independent presence in microgrid systems with high renewables, and study their effects on scheduling and dispatching of controllable DGs as well.
- Investigate the impact of coordinated operation of ESS and DR on the maximum possible level of penetration of renewable generation in a remote microgrid considering stochastic models and reserve requirements.

4.2 Uncertainty Techniques

Numerous methods are reported in the literature to take into account uncertainties in load, wind and solar power forecasting errors, as discussed in Section 2.4. The approaches used in [16], and [45] to handle uncertainties are adopted in this work: inclusion of reserve requirements and multi-scenario stochastic optimization models. As reported in [41], combining both approaches leads to superior UC policies and better representation of the uncertainties. The additional reserve requirements are determined from the forecasting errors of load and renewable generation, which are represented in this research as a factor error of load demand, and wind and solar power outputs. In stochastic

optimization models, it is difficult to consider all continuous states for the uncertainties, and therefore, for simplicity, a set of representative discrete states are extracted. A normal discrete probability distribution of the forecasting errors of load (δ_D), wind (δ_W) and solar power (δ_{PV}) are represented as follows [45]:

$$\begin{aligned}\delta_D = \{ (e_D^1, \rho_D^1), (e_D^2, \rho_D^2), \dots, (e_D^n, \rho_D^n) \} \\ \rho_D^1 + \rho_D^2 \dots + \rho_D^n = 1\end{aligned}\tag{4.1}$$

$$\begin{aligned}\delta_W = \{ (e_W^1, \rho_W^1), (e_W^2, \rho_W^2), \dots, (e_W^n, \rho_W^n) \} \\ \rho_W^1 + \rho_W^2 \dots + \rho_W^n = 1\end{aligned}\tag{4.2}$$

$$\begin{aligned}\delta_{PV} = \{ (e_{PV}^1, \rho_{PV}^1), (e_{PV}^2, \rho_{PV}^2), \dots, (e_{PV}^n, \rho_{PV}^n) \} \\ \rho_{PV}^1 + \rho_{PV}^2 \dots + \rho_{PV}^n = 1\end{aligned}\tag{4.3}$$

Where e is the error of the considered state in the forecasting error probability distribution function, ρ is the corresponding probability of that state, and n is the number of states in the discrete set. The above discrete sets are used to create a set of possible scenarios (S) as given by (4.4), representing the possible deviations from the load, wind, and solar power forecasted values. A set of scenario is created using a two stage scenario tree which branches only at the first time period and ignores the remaining periods. Thereafter, the extracted scenarios and their corresponding probabilities are included in operations model formulation.

$$\begin{aligned}S = \delta_D \times \delta_W \times \delta_{PV} \\ \sum_{s \in S} \rho_D \rho_W \rho_{PV} = 1\end{aligned}\tag{4.4}$$

4.3 Mathematical Models

This section presents the microgrid operational planning model formulations in a stochastic framework, which include ESS and DR, for isolated and grid connected modes. A wider spectrum of uncertainties in the problem is incorporated in the developed models, which are formulated as multi-scenario mixed-integer linear programming models.

4.3.1 Model-1: Isolated Mode Operation of a Microgrid

In the isolated mode, the objective function is to minimize the expected total cost (ETC) over a period of 24 hours, as given below:

$$ETC = \sum_s \lambda_s \left[\sum_{k \in K} \sum_{j \in J} (C_j(P_{j,k,s}) + SU_{j,k}) + \sum_{k \in K} C_{ES} \cdot (V_{k,s}^{CH} + V_{k,s}^{DCH}) + \sum_{k \in K} (P_{k,s}^{Curt} \times C_{Curt}) + \sum_{k \in K} (\Delta P_{k,s}^{UP} \times C_{DR}) \right] \quad (4.5)$$

The expected operating cost of generators is represented by the first term of (4.5), as elaborated in Section 3.2. The second term represents the expected operating cost of the ESS. The expected cost of renewable power curtailment is denoted by the third term, while the last term of (4.5) represents the expected cost of the demand shifting.

Demand-Supply Balance: The total generation, which includes wind and PV generation, ESS, DR, and renewable power curtailment, meets the forecasted demand of period k , as presented in (4.6). The variable demand $P_{k,s}^{DEM}$ represents the resulting demand at an hour k and scenario s , after demand shifting has taken place, and can be more or less than the original demand $P_{k,s}^D$, as defined in (4.7):

$$\sum_{j \in J} P_{j,k,s} + P_{k,s}^W + P_{k,s}^{PV} + P_{k,s}^{DCH} = P_{k,s}^{DEM} + P_{k,s}^{CH} + P_{k,s}^{Curt} \quad \forall s \in S \quad (4.6)$$

$$P_{k,s}^{DEM} = P_{k,s}^D + \Delta P_{k,s}^{UP} - \Delta P_{k,s}^{Down} \quad \forall s \in S \quad (4.7)$$

The demand variation must be balanced within the 24 hour operation horizon in order not to shift the customers' activities to the next day, as given in (4.8), and the maximum demand that can be deferred from one hour to another is given by (4.9):

$$\sum_{k \in K} \Delta P_{k,s}^{UP} = \sum_{k \in K} \Delta P_{k,s}^{Down} \quad \forall s \in S \quad (4.8)$$

$$\begin{pmatrix} B_{do} \\ B_{up} \end{pmatrix} \cdot P_{k,s}^D \geq \begin{pmatrix} \Delta P_{k,s}^{Down} \\ \Delta P_{k,s}^{UP} \end{pmatrix} \geq 0 \quad \forall s \in S \quad (4.9)$$

Spinning Reserve Constraint: This constraint ensures that the net available capacity, from all committed generators and ESS, meets the system spinning reserve requirements at period k and scenario s .

$$\sum_{j \in J} (P_j^{max} \cdot V_{j,k} - P_{j,k,s}) + \eta_d [C_{k,s} - C_{min}] \geq R_{k,s} \quad \forall s \in S \quad (4.10)$$

The spinning reserve constraint can be re-formulated to take into consideration additional reserve requirements for handling uncertainties, as given below:

$$\sum_{j \in J} (P_j^{max} \cdot V_{j,k} - P_{j,k,s}) + \eta_d [C_{k,s} - C_{min}] \geq R_{k,s} + \gamma_D \cdot P_{k,s}^D + \gamma_W \cdot P_{k,s}^W + \gamma_{PV} \cdot P_{k,s}^{PV} \quad (4.11)$$

In addition, each controllable generator is subject to its own operating constraints, as described earlier in Chapter 2.

Energy Storage Systems: The following equations represent the operational constraints of the ESS [15, 16]:

Power charge and discharge limits

$$P_{k,s}^{DCH} \leq P_{ES}^{max} \cdot V_{k,s}^{DCH} \quad \forall s \in S \quad (4.12)$$

$$P_{k,s}^{CH} \leq P_{ES}^{max} \cdot V_{k,s}^{CH} \quad \forall s \in S \quad (4.13)$$

Discharging and charging dynamic:

$$C_{k+1,s} = C_{k,s} - d_k \cdot P_{k,s}^{DCH} / \eta_d \quad \forall s \in S \quad (4.14)$$

$$C_{k+1,s} = C_{k,s} + d_k \cdot P_{k,s}^{CH} \cdot \eta_c \quad \forall s \in S \quad (4.15)$$

ESS operational end points and energy storage limit:

$$C_{0,s} = C_S ; C_{K,s} = C_E \quad \forall s \in S \quad (4.16)$$

$$C_{min} \leq C_{k,s} \leq C_{max} \quad \forall s \in S \quad (4.17)$$

Coordination of charging and discharging operation:

$$V_{k,s}^{DCH} + V_{k,s}^{CH} \leq 1 \quad \forall s \in S \quad (4.18)$$

Power Curtailment: This is invoked when there is excess of renewable generation in order to ensure system security. Equations (4.19)–(4.21) ensure that at least one controllable DG unit with enough capacity will be available to provide the required spinning reserve when renewable generation exceeds the microgrid load.

$$P_{k,s}^D - P_{k,s}^W - P_{k,s}^{PV} - \sum_{j \in J} (P_j^{min} \cdot V_{j,k}) \leq \mu(1 - V_{k,s}^{Curt}) \quad \forall s \in S \quad (4.19)$$

$$-P_{k,s}^D + P_{k,s}^W + P_{k,s}^{PV} + \sum_{j \in J} (P_j^{min} \cdot V_{j,k}) \leq \mu \cdot V_{k,s}^{Curt} \quad \forall s \in S \quad (4.20)$$

$$P_{k,s}^{Curt} \leq \mu \cdot V_{k,s}^{Curt} \quad \forall s \in S \quad (4.21)$$

4.3.2 Grid Connected Operation of a Microgrid

The objective function, in the grid connected mode, is to minimize the *ETC* of the microgrid, as stated below:

$$ETC = \sum_s \lambda_s \left[\sum_{k \in K} \sum_{j \in J} (C_j(P_{j,k,s}) + SU_{j,k}) + \sum_{k \in K} C_{ES} \cdot (V_{k,s}^{CH} + V_{k,s}^{DCH}) + \sum_{k \in K} (\Delta P_{k,s}^{UP} \times C_{DR}) \right. \\ \left. + \sum_{k \in K} (P_{k,s}^{IMP} \times C_k^{GRID}) - \sum_{k \in K} (P_{k,s}^{EXP} \times C_k^{GRID}) \right] \quad (4.22)$$

The expected cost of importing and exporting power from / to the main grid is represented by the second and last terms of (4.22), respectively.

Demand-Supply Balance: This constraint is modified from (4.6) to include export and import of power:

$$\sum_{j \in J} P_{j,k,s} + P_{k,s}^W + P_{k,s}^{PV} + P_{k,s}^{DCH} + P_{k,s}^{IMP} = P_{k,s}^{DEM} + P_{k,s}^{CH} + P_{k,s}^{EXP} \quad \forall s \in S \quad (4.23)$$

Spinning Reserve Constraint: This constraint is modified from (4.10) to include the additional power import possibility from the main grid, if required:

$$\sum_{j \in J} (P_j^{max} \cdot V_{j,k} - P_{j,k,s}) + (P_{grid}^{max} \cdot V_{k,s}^{IMP} - P_{k,s}^{IMP}) + \eta_d [C_{k,s} - C_{min}] \geq R_{k,s} \quad \forall s \in S \quad (4.24)$$

Constraint (4.20) is modified to include additional reserve requirements for handling uncertainties, formulated as follows:

$$\begin{aligned} \sum_{j \in J} (P_j^{max} \cdot V_{j,k} - P_{j,k,s}) + (P_{grid}^{max} \cdot V_{k,s}^{IMP} - P_{k,s}^{IMP}) + \eta_d [C_{k,s} - C_{min}] \\ \geq R_{k,s} + \gamma_D \cdot P_{k,s}^D + \gamma_W \cdot P_{k,s}^W + \gamma_{PV} \cdot P_{k,s}^{PV} \quad \forall s \in S \end{aligned} \quad (4.25)$$

The grid export and import constraints are given by (4.26) and (4.27), and in order not to receive and send power from/ to the main grid at the same hour k , the constraint (4.28) is included in the model.

$$0 \leq P_{k,s}^{EXP} \leq P_{grid}^{max} \times V_{k,s}^{EXP} \quad \forall s \in S \quad (4.26)$$

$$0 \leq P_{k,s}^{IMP} \leq P_{grid}^{max} \times V_{k,s}^{IMP} \quad \forall s \in S \quad (4.27)$$

$$V_{k,s}^{IMP} + V_{k,s}^{EXP} \leq 1 \quad \forall s \in S \quad (4.28)$$

The remaining model constraints are similar to the isolated mode operation of the microgrid.

4.4 System under Study

The microgrid system presented in Section 3.3 is considered for the analysis reported in this chapter. For representation of uncertainty, a normal 5-state discrete probability distribution of the forecasting errors of load, wind and solar power is considered, as given in Table 4-1. Hence, a total of 125 scenarios are generated using a two-stage scenario tree. A detailed table pertaining to the generated 125 scenarios and their probabilities is given in Appendix B. The forecasting error factors applicable to the spinning reserve constraint are adopted from [16] as follows: $\gamma_D = 0.03$, $\gamma_W = 0.13$, and $\gamma_{PV} = 0.09$.

Table 4-1 The discrete probability distribution of the forecasting errors

Wind		Solar		Load	
$\epsilon, \%$	$P(\epsilon)$	$\epsilon, \%$	$P(\epsilon)$	$\epsilon, \%$	$P(\epsilon)$
-2.5	0.10	-2	0.05	-2.5	0.05
-1	0.15	-1.5	0.15	-1	0.15
0	0.50	0	0.60	0	0.60
+1	0.15	+1.5	0.15	+2	0.15
+2.5	0.10	+2	0.05	+3	0.05

4.5 Results and Analysis

The microgrid operator aims to serve the total demand of the microgrid using its local resources in the isolated mode, with the objective of minimizing the *ETC*. While, in grid connected mode, the operator aims to serve the total demand of the microgrid using its local production and buying/selling power from/to the main grid, with the same objective of minimizing the *ETC*. In each mode of operation of the microgrid, 125 scenarios of the load and renewable power generation, as discussed in Section 4.3, are applied for the presented case studies. It is to be noted that the proposed 24-hour ahead operations planning model will provide one commitment schedule, and 125 power generation schedules. In other words, the same controllable DG units will be committed for all scenarios, but will generate different levels of power because of the variations in net demand, from one scenario to the other. Nevertheless, the constraints of the microgrid system and controllable DG units should be met by the provided solution. The following subsection presents the effects of coordinated operation of ESS and DR on the microgrid operation, vis-à-vis their independent presence in microgrid systems with high renewables, considering the proposed stochastic model with and without additional reserve requirements.

4.5.1 Uncertainties of Load and Renewable Generation

To examine the effects of coordinated operation of ESS and DR on the 24-hour ahead operations plan of the microgrid, in the presence of uncertainty, four case studies are considered for each mode of operation, as described earlier in Section 3.4.

Table 4-2 presents the numerical results of each case for isolated mode operation of the microgrid, without additional reserve requirements, *i.e.* considering constraint (4.6) and with additional reserve when (4.6) is replaced by (4.7). The *ETC* is the lowest in Case-4 which involves optimal coordination of ESS and DR. A comparison is carried out between the *ETC* with and without additional reserve requirements; it can be observed from Figure 4-1 that the *ETC* of each case with additional reserve requirements is higher than that without additional reserve requirements (*i.e.* when the required spinning reserve is only 10% of the critical load). However, in Case 3 and 4, the difference in the *ETC* with and without additional reserve requirements is relatively small since ESS is considered in the spinning reserve constraint, and thus provides the additional required reserve.

Table 4-2 Expected cost components and emissions in isolated microgrid

Case	Expected operating cost (\$)	Expected RE Curtailment cost (\$)	Expected DR cost (\$)	<i>ETC</i> (\$)	Expected emissions (lb/kWh)
1	2,395 (+59)	17,185 (+5,759)	0	19,580 (+5,818)	2,419 (+49)
2	2,189 (+60)	724 (+2,430)	1,854 (+345)	4,767 (+2,835)	2,277 (+13)
3	2,279 (+6)	505 (+10)	0	2,784 (+16)	2,338 (+2)
4	2,170 (-2)	0	287 (+19)	2,457 (+17)	2,270 (-1)

*Numbers in parenthesis indicate that the increased/decreased cost and emissions when additional reserve requirements are considered.

It is noticed from Table 4-2 that RE curtailment increases with additional reserve requirements. That is, additional RE curtailment takes place in order to free a portion of the controllable units' capacity to provide the additional required reserve. However, in Case-4, no RE curtailments takes place even with additional reserve requirements, indicating a high degree of flexibility when ESS and DR operations are coordinated. As reported in the literature, combining the stochastic model and reserve requirements leads to superior UC policies and better representation of the uncertainties, but the *ETC* of the microgrid or RE curtailment levels significantly increases. Yet, coordinating ESS and DR operations presents an efficient solution to combine additional spinning

reserve and uncertainties from intermittent renewable generation and load simultaneously without affecting the levels of RE curtailment or the operating cost of the microgrid.

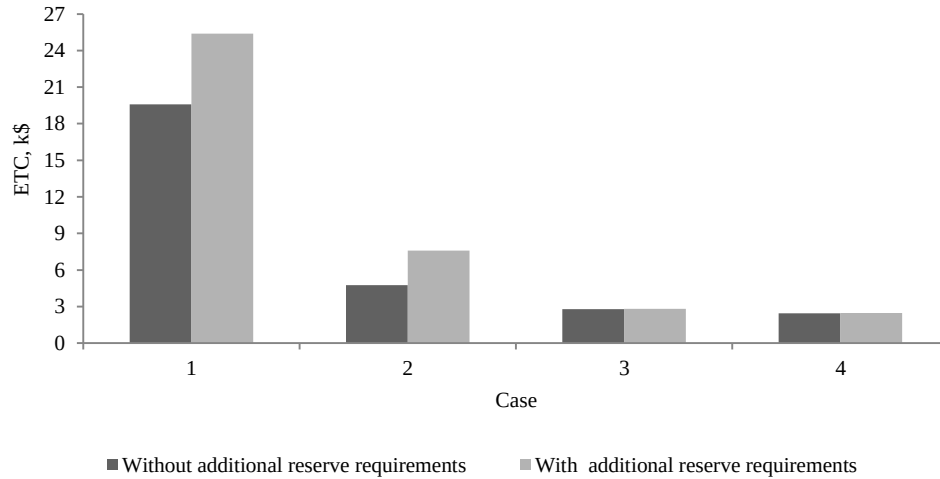


Figure 4-1 Comparison of *ETC* for isolated microgrid with and without reserve requirements

Table 4-3 shows the changes in UC decisions from Case-1 to Case-4, over a period of 24-hour. The grey cells are the ones that changed from ON-state to OFF-state when ESS and DR are considered (Case-4). It is noted that the controllable generators are de-committed during off-peak since ESS and DR with renewable generations take care of the system operating conditions. As a results, integrating DR and ESS in the microgrid help to reduce further the total daily microgrid emissions, as reported in Table 4-2.

Table 4-3 UC decisions for isolated microgrid

(Grey cells denote UC decisions when ESS and DR are introduced into the model)

Time Generator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
DG1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
DG2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
DG3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
DG4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0
DG5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
DG6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DG8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DG10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DG11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DG12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The 24-hour operations schedule for grid connected mode operation of the microgrid is determined using the proposed stochastic model without/with additional reserve requirements. The simulation results are presented in Table 4-4. It is observed that adding additional reserve requirements does not significantly affect the *ETC* of the grid connected microgrid for the considered cases, as shown in Figure 4-2. This is due to the fact that the main grid will provide a large portion of the reserve requirements, and therefore there is no need to commit more controllable units to do so. In Case-1, the *ETC* increases because of operating more controllable units to provide a portion of reserve requirements, and as a result exporting more power to the main grid, which enhances the *ETC* with respect to that without additional reserve requirements. In Case-4, the UC- schedule of controllable units and the *ETC* remain the same, indicating that ESS, DR, and the main grid provide the required flexibility in micorgrid operations, and therefore the operator's schedule is not affected by adding additional reserve requirements.

Table 4-4 Expected cost components and emissions for grid connected microgrids

Case	Expected operating cost (\$)	Expected revenue from exports (\$)	Expected import cost (\$)	Expected DR cost (\$)	<i>ETC</i> (\$)
1	2,493 (+41)	2,832 (+43)	767 (0)	0	428 (-2)
2	2,443 (+29)	2,855 (+14)	745 (-5)	44 (+10)	377 (+20)
3	2,452 (-37)	2,761 (-45)	705 (0)	0	396 (+8)
4	2,326 (0)	2,829 (0)	785 (0)	65 (0)	347 (0)

*Numbers in parenthesis indicate that the increased/decreased cost when additional reserve requirements are considered.

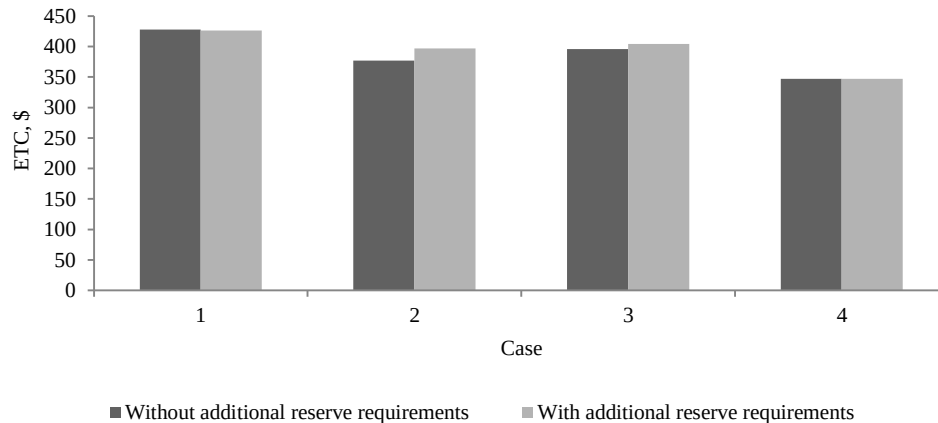


Figure 4-2 Comparison of the *ETC* for grid connected with and without reserve requirements

The changes in UC decisions for grid connected mode of the microgrid from Case-1 to Case-4, over a period of 24-hour are presented in Table 4-5. The grey cells indicate the ones that changed from ON-state to OFF-state when ESS and DR are introduced into the model. It is noted that some of the controllable generators are de-committed during off-peak load due to the fact that the main grid, ESS, and DR with renewable generations take care of the system operating conditions during these hours, as shown in Table 4-5.

Table 4-5 UC decisions for grid connected mode of the microgrid with and without ESS and DR
(Grey cells denote change in UC decisions when ESS and DR are introduced into the model)

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Generator																								
DG1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
DG2	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
DG3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0
DG4	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0
DG5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DG6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DG7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DG11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DG12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

4.5.2 Operation of a Remote Microgrid Considering High and Uncertainty levels of Renewable Generation

Reliably integrating high levels of RESs requires a high degree of flexibility in microgrid operations. The operation of ESS and DR can be coordinated into microgrids to increase their flexibility, allowing them to increase RE penetration to higher levels than currently possible. This subsection presents the impact of accommodating high levels of RE penetration on the operation of a remote microgrid. The stochastic optimization model and additional reserve requirements are combined to take into account uncertainties in load, wind and solar power forecasting errors.

Four cases with different levels of RE penetration are considered in this study. Case-1 ignores ESS and DR in order to focus on the impact of different levels of high RE integration. DR is included in Case-2 while Case-3 considers ESS, and finally a combination of both is presented as Case-4. To compare the cases, the *ETC* of the microgrid is determined for each case and different RE penetration levels, as depicted in Figure 4-3. The expected curtailed energy for each case with different renewable penetration levels is shown in Figure 4-4. It is noted that in Case-1 RE curtailment is required beyond an RE penetration level of 40%. In contrast, accommodation of DR (Case-2) and ESS (Case-3) into the microgrid and combining their operation (Case-4) can increase the level of RE penetration to 50%, without significantly increase the expected operation cost and/or wasting the renewable energy.

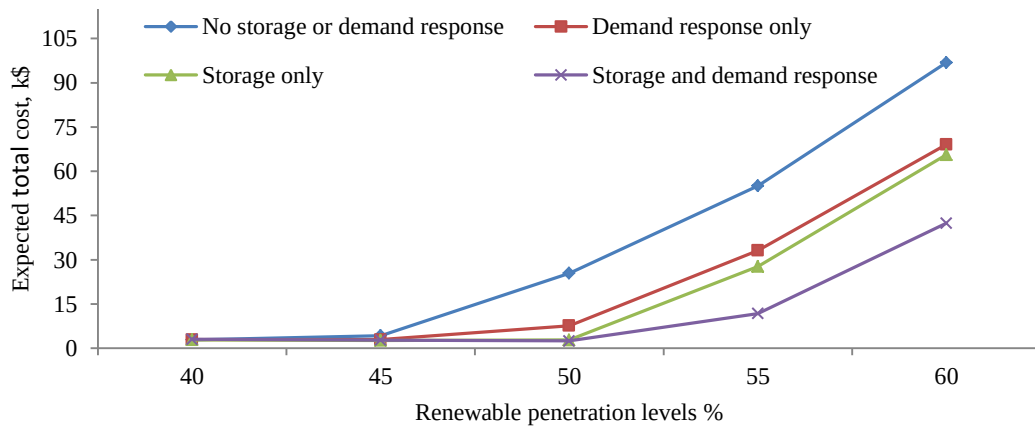


Figure 4-3 Comparison of total expected cost for different renewable penetration levels

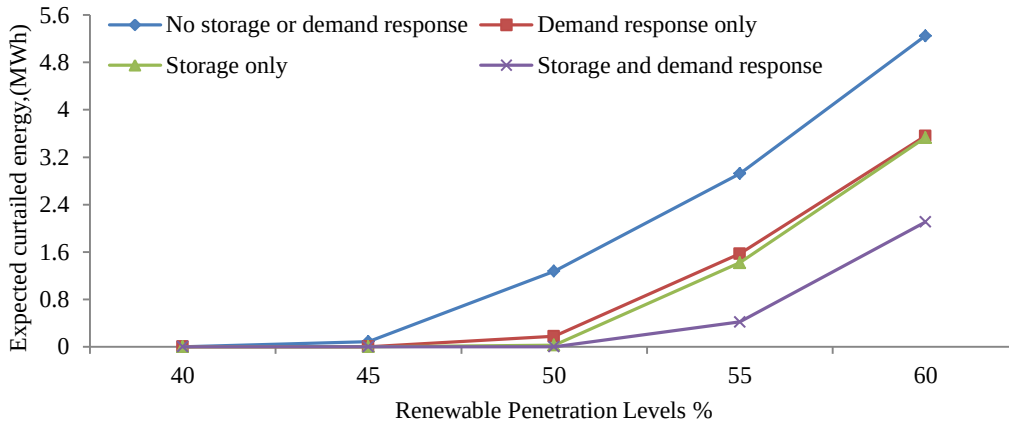


Figure 4-4 Comparison of curtailed energy for different renewable penetration levels

The expected cost of remote microgrid operation for the presented case studies, with 50% and 60% RE penetration levels, are given in Table 4-6 and Table 4-7, respectively. In Case-1, when the generation from renewables exceeds the microgrid load at a certain hour k , the excess renewable power is curtailed at that hour. Furthermore, in order to ensure that at least one controllable DG unit with enough capacity is dispatched to meet spinning reserve requirements, some further renewable power curtailment is made. DR is used in Case-2 to alter the microgrid load profile to be as close as possible to the renewable power curve, and hence maximizing the benefits of renewables, such as the *ETC* of the microgrid and RE curtailment levels are minimized. In Case-3, ESS is scheduled to store energy at periods of high renewable generation and release it during periods of low renewable generation, reducing the amount of curtailed energy or the RE wasted, while coordinating ESS and DR (Case-4) helps to reduce further the expected curtailed RE.

Table 4-6 Expected cost components and emissions in isolated microgrids with 50% renewables

Case	Expected operating Cost (\$)	Expected RE Curtailment Cost (\$)	Expected DR Cost (\$)	<i>ETC</i> (\$)	Expected Emissions (lb/kWh)
C1	2,454	22,944	0	25,398	2,468
C2	2,249	3,154	2,199	7,602	2,290
C3	2,285	515	0	2,800	2,304
C4	2,168	0	306	2,474	2,269

Table 4-7 Expected cost components and emissions in isolated microgrids with 60% renewables

Case	Expected operating Cost (\$)	Expected RE Curtailment Cost (\$)	Expected DR Cost (\$)	<i>ETC</i> (\$)	Expected Emissions (lb/kWh)
C1	2,359	94,506	0	96,865	2,397
C2	2,064	64,046	2,954	69,064	2,086
C3	2,044	63,554	0	65,598	2,079
C4	1,791	37,950	2,659	42,400	1,861

It is observed that the ETC of Case-1 is the highest because of the expected RE curtailment cost, indicating that it is not possible to accommodate high levels of RE penetration when ESS or DR are not present in remote or isolated microgrids. While DR or ESS helps, they may not be enough to accommodate high RE penetration and therefore a combination of both is essential in order to increase the flexibility of the microgrid, and thus increase RE penetration to a higher level but at which there would be no power curtailment. This combination also helps to reduce further the expected daily microgrid emissions, as reported in Table 4-6 and Table 4-7.

4.6 Summary

Short-term operations models of the microgrid systems for isolated and grid connected modes are developed; the models include unit commitment constraints, ESS, DR, and uncertainties of load, and renewable generation to examine the uncertainty effects on UC decision, dispatching of controllable DGs, and RE penetration levels. Uncertainties of load, wind, solar generation are handled in this chapter using a generated set of valid scenarios and reserve requirements, which can incorporate a wider spectrum of uncertainties in the presented problem, and as a result robust and reliable commitment schedules can be obtained.

The results of case studies in this chapter indicate that coordinated operation of ESS and DR is only beneficial if there is sufficiently excess renewable generation; otherwise, operating ESS or DR independently would be efficient enough. For instance, at an RE penetration level of 40%, when the generation is not sufficiently exceeding the demand, there are no benefits from the coordination of ESS and DR in terms of cost reductions. But on the other hand, at an RE penetration level of 50%, where there is sufficient excess generation, this combination achieves further benefits, for the micorgird operator, in terms of system flexibility and operation costs.

Chapter 5

Conclusions and Future Work

5.1 Summary

The significant increase in penetration of renewable generation is expected to affect the operational aspects of power systems and more specifically remote microgrids that rely on renewable sources. The intermittency of renewable sources needs to be therefore factored by microgrid operators in their operations scheduling models. In order to manage this increased intermittency, the microgrid operators need to have access to sufficient flexible resources, such as DR, and ESS, to mitigate the variability and intermittency associated with large-scale integration of renewable generation. This thesis addresses these operational challenges and introduces the coordination of ESS and DR as a preferable solution to mitigate the impacts of high penetration of renewable generation sources in a microgrid. In particular, the short-term operation planning problem with ESS and DR, in the presence of high renewable generation is addressed.

In Chapter 1, the motivations and objectives of the research presented in this thesis are discussed. Chapter 2 presents a literature review of the reported work on the related research topic. The UC problem and operational aspects of a microgrid are briefly reviewed. Then flexible resources such as ESS and DR, and the main approaches for managing uncertainties of load, wind, and power forecasting errors have been discussed.

In Chapter 3, short-term operations models are developed to examine the effects of the coordination of ESS and DR on microgrids with high renewable generation; one for grid connected and the other for isolated mode of operation. The devolved models are formulated as an MILP problem and solved using the CPLEX solver in GAMS environment. These models are used to investigate the impacts of renewable power variability, and penetration levels with and without ESS and DR.

In Chapter 4, a set of valid probabilistic scenarios and allocating reserve scenario requirements are considered for the uncertainties of load, and intermittency in wind and solar generation sources. Thereafter, a stochastic short-term operations scheduling model is developed to examine the advantages of coordinated operation of ESS and DR, vis-à-vis their independent operation in microgrids with high renewables generation. The potential for accommodating higher levels of renewable generation in remote microgrids, considering stochastic models and reserve requirements is also investigated.

5.2 Contributions of this Thesis

The main contributions of the research presented in this thesis can be summarized as follows:

- Comprehensive short-term operational planning models, for isolated and grid connected mode operation of microgrids, are developed in this thesis, which include unit commitment constraints, ESS, and DR.
- This thesis considers uncertainties of load, wind, and solar energy sources in the UC- problem with ESS and DR. A set of valid probabilistic scenarios and reserve requirements are incorporated into the models to handle uncertainties of load, and intermittency in wind and solar generation sources.
- The thesis examines the influence of coordinated operation of ESS and DR on microgrid operations with high renewables generation, vis-à-vis their independent presence in microgrid systems considering both deterministic and stochastic operational frameworks. The impact of coordinated operation of ESS and DR on the maximum possible level of penetration of renewable generation in remote microgrids is also examined and discussed.

5.3 Scope for Future Work

The possible extensions based on the research work reported in this thesis are as follows:

- The stochastic models can be improved by using alternative reliable methods for wind and solar power scenarios. For instance, using Monte-Carlo Simulations for generating wind power scenarios and Markov-chain models to improve the transitions for inter-hour wind speed correlations. Thereafter, these wind power generation scenarios can be reduced using reduction techniques.
- In the work presented in this thesis, only direct demand shifting is considered. In reality, only appliances, such as the washing machine, can be shifted in time. The problem formulations can be extended to include other DR applications such as price-responsive demand.
- The work can be extended to consider the investment costs of ESS and perform a cost /benefit analysis to determine the optimal sizing of ESS and its perspective parameters, with the consideration of DR, for isolated and grid connected modes, so as to minimize the planning and operating costs of microgrids.

- The developed short-term operational planning models can be improved by using a multi-stage stochastic programming model that includes all solar and wind power scenarios, which can be solved using the Bender Decomposition methods.

Publications from this Research

1. **W. Alharbi**, K. Bhattacharya, “Demand Response and Energy Storage in MV Islanded Microgrids for High Penetration of Renewables”, IEEE Canada 2013, Electrical Power and Energy Conference (EPEC) – Halifax, Nova Scotia, August 21-23.
2. **W. Alharbi**, K. Bhattacharya, “Coordination of Demand Response and Energy Storage in Microgrids for Optimal Utilization of Distributed Energy Resources”, 2013 CIGRÉ Canada Conference, Calgary, Alberta, September 9 -11.
3. **W. Alharbi**, K. Bhattacharya, “Accommodating High Levels of Renewable Generation in Remote Microgrids under Uncertainty”, IEEE PES General Meeting 2014– **In review**

Appendix A

Data of Environmental Emission Factors

Table A Pollution contaminants of different generators

Pollutant Gen.	Sox (lb/MWhr)	Nox (lb/MWhr)	CO2 (lb/MWhr)
DG1	0.2	0.5	160
DG2	0.2	0.5	160
DG3	0.019182	0.430435	210
DG4	0.019182	0.430435	210
DG5	0.2	0.5	160
DG6	0.2	0.5	160
DG7	0.019182	0.430435	210
DG8	0.019182	0.430435	210
DG9	0.016807	0.5	170
DG10	0.016807	0.5	170
DG11	0.016807	0.5	170
DG12	0.016807	0.5	170

Appendix B

Forecasting Errors Scenarios

Table B The generated 125 scenarios and their probabilities

S	Load (%)	Wind (%)	Solar (%)	λ_s
1	-2	-2.5	-2	0.00025
2	-2	-2.5	-1.5	0.00075
3	-2	-2.5	0	0.003
4	-2	-2.5	+1.5	0.00075
5	-2	-2.5	+2	0.00025
6	-2	-1	-2	0.000375
7	-2	-1	-1.5	0.001125
8	-2	-1	0	0.0045
9	-2	-1	+1.5	0.001125
10	-2	-1	+2	0.000375
11	-2	0	-2	0.00125
12	-2	0	-1.5	0.00375
13	-2	0	0	0.015
14	-2	0	+1.5	0.00375
15	-2	0	+2	0.00125
16	-2	+1	-2	0.000375
17	-2	+1	-1.5	0.001125
18	-2	+1	0	0.0045
19	-2	+1	+1.5	0.001125
20	-2	+1	+2	0.000375
21	-2	+2.5	-2	0.00025
22	-2	+2.5	-1.5	0.00075
23	-2	+2.5	0	0.003
24	-2	+2.5	+1.5	0.00075
25	-2	+2.5	+2	0.00025
26	-1.5	-2.5	-2	0.00075
27	-1.5	-2.5	-1.5	0.00225
28	-1.5	-2.5	0	0.009
29	-1.5	-2.5	+1.5	0.00225
30	-1.5	-2.5	+2	0.00075
31	-1.5	-1	-2	0.001125
32	-1.5	-1	-1.5	0.003375
33	-1.5	-1	0	0.0135

34	-1.5	-1	+1.5	0.003375
35	-1.5	-1	+2	0.001125
36	-1.5	0	-2	0.00375
37	-1.5	0	-1.5	0.01125
38	-1.5	0	0	0.045
39	-1.5	0	+1.5	0.01125
40	-1.5	0	+2	0.00375
41	-1.5	+1	-2	0.001125
42	-1.5	+1	-1.5	0.003375
43	-1.5	+1	0	0.0135
44	-1.5	+1	+1.5	0.003375
45	-1.5	+1	+2	0.001125
46	-1.5	+2.5	-2	0.00075
47	-1.5	+2.5	-1.5	0.00225
48	-1.5	+2.5	0	0.009
49	-1.5	+2.5	+1.5	0.00225
50	-1.5	+2.5	+2	0.00075
51	0	-2.5	-2	0.003
52	0	-2.5	-1.5	0.009
53	0	-2.5	0	0.036
54	0	-2.5	+1.5	0.009
55	0	-2.5	+2	0.003
56	0	-1	-2	0.0045
57	0	-1	-1.5	0.0135
58	0	-1	0	0.054
59	0	-1	+1.5	0.0135
60	0	-1	+2	0.0045
61	0	0	-2	0.015
62	0	0	-1.5	0.045
63	0	0	0	0.18
64	0	0	+1.5	0.045
65	0	0	+2	0.015
66	0	+1	-2	0.0045
67	0	+1	-1.5	0.0135
68	0	+1	0	0.054
69	0	+1	+1.5	0.0135
70	0	+1	+2	0.0045
71	0	+2.5	-2	0.003
72	0	+2.5	-1.5	0.009

73	0	+2.5	0	0.036
74	0	+2.5	+1.5	0.009
75	0	+2.5	+2	0.003
76	+2	-2.5	-2	0.00075
77	+2	-2.5	-1.5	0.00225
78	+2	-2.5	0	0.009
79	+2	-2.5	+1.5	0.00225
80	+2	-2.5	+2	0.00075
81	+2	-1	-2	0.001125
82	+2	-1	-1.5	0.003375
83	+2	-1	0	0.0135
84	+2	-1	+1.5	0.003375
85	+2	-1	+2	0.001125
86	+2	0	-2	0.00375
87	+2	0	-1.5	0.01125
88	+2	0	0	0.045
89	+2	0	+1.5	0.01125
90	+2	0	+2	0.00375
91	+2	+1	-2	0.001125
92	+2	+1	-1.5	0.003375
93	+2	+1	0	0.0135
94	+2	+1	+1.5	0.003375
95	+2	+1	+2	0.001125
96	+2	+2.5	-2	0.00075
97	+2	+2.5	-1.5	0.00225
98	+2	+2.5	0	0.009
99	+2	+2.5	+1.5	0.00225
100	+2	+2.5	+2	0.00075
101	+3	-2.5	-2	0.00025
102	+3	-2.5	-1.5	0.00075
103	+3	-2.5	0	0.003
104	+3	-2.5	+1.5	0.00075
105	+3	-2.5	+2	0.00025
106	+3	-1	-2	0.000375
107	+3	-1	-1.5	0.001125
108	+3	-1	0	0.0045
109	+3	-1	+1.5	0.001125
110	+3	-1	+2	0.000375
111	+3	0	-2	0.00125

112	+3	0	-1.5	0.00375
113	+3	0	0	0.015
114	+3	0	+1.5	0.00375
115	+3	0	+2	0.00125
116	+3	+1	-2	0.000375
117	+3	+1	-1.5	0.001125
118	+3	+1	0	0.0045
119	+3	+1	+1.5	0.001125
120	+3	+1	+2	0.000375
121	+3	+2.5	-2	0.00025
122	+3	+2.5	-1.5	0.00075
123	+3	+2.5	0	0.003
124	+3	+2.5	+1.5	0.00075
125	+3	+2.5	+2	0.00025

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