DISSERTATION

REDUCING CARBON DIOXIDE EMISSIONS IN THE ELECTRICITY SECTOR USING DEMAND SIDE MANAGEMENT

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Summer 2019

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ABSTRACT

REDUCING CARBON DIOXIDE EMISSIONS IN THE ELECTRICITY SECTOR USING DEMAND SIDE MANAGEMENT

Increasing demand for energy consumption leads to concerns of global Greenhouse Gas (GHG) emissions. Most of the supplied energy comes from dirty generating units. Since there are no regulations to limit emissions of CO_2 from electricity generation, power plants can emit unlimited amount of CO_2. This dissertation, first, aims to explain some government directed plans to reduce GHG emissions. It gives an overview about the Clean Power Plan (CPP) and its benefits and challenges. Further, it explains several options of CPP in reducing emissions and its repeal. Further, this dissertation, discusses the Climate Action Plan (CAP) corresponding to Fort Collins, Colorado, U.S. and its timeline targets.

Demand side management (DSM) is discussed as a solution from engineering practices to affect GHG. Several options from DSM are investigated to reduce emissions. In fact, reducing energy consumption through DSM leads to a reduction in harmful emissions to the environment. This dissertation aims to identify the best available DSM options that will make the biggest difference for GHG reductions.

A framework is created to examine several options of DSM in reducing carbon footprints. The framework states that affecting GHG in electric power system is the main goal. The goal can be achieved by implementing DSM technologies in distribution systems. The framework proposes criteria such as cost, power quality, reliability, environmental collateral, and socioeconomic equity to examine the effectiveness of several alternatives: energy management, communication and intelligence, electrification of heating and transportation, and distributed generation.

Multi-Criteria Decision Making (MCDM) algorithms have been proposed to prioritize alternatives and select the ones that achieve suitable emissions reduction. Analytic Hierarchy Process (AHP) is one of the most common tools to perform decision-making analysis. The findings from AHP show that the “communication and intelligence” option is the potential optimal alternative in achieving the goal. Analytic Network Process

(ANP) is another method for making decisions. It provides feedback and interdependence relationships between all nodes of the problem. It is more realistic and accurate than AHP. The results obtained from ANP suggest that "communication and intelligence" is the optimum technology to reach the target. By using ANP, the overall priority ranking has changed and the difference in priorities has reduced.

Institute of Electrical and Electronics Engineers (IEEE) 13-node test feeder is used, through Open Distribution System Simulator (OpenDSS), to perform power flow analysis on yearly load profile corresponding to Fort Collins, Colorado, U.S. The analysis includes simulation for several scenarios from the MCDM alternatives, either individual alternatives or mixed alternatives. The obtained results for the base case show the emissions decreased by 16.26% from 2005 level which comply with the results from emissions indicator released by the city. Integrating the MCDM alternatives indicates CO_2 emissions change as a result of variation in supply and demand curve. The findings for 2017 load profile demonstrated that "electric stationary storage" is the best option, environmentally, since it contributes in more than 18% emissions reduction from 2005 level. The second alternative is "energy conservation" by achieving a 20.39% reduction in emissions, merging both alternatives in one scenario could increase the emissions mitigation up to 22.17%. By simulation the residential sector, "communication and intelligence" shows about 14% reduction in emissions from 2005 level. A scenario that combines "electric stationary storage" with "communication and intelligence" diminishes the emissions by more than 15%. Indeed, combining "communication and intelligence" with "energy conservation" can decrease the environmental footprint by 18.04%. Last scenario examined combining all MCDM alternatives in one option. The result finds that this option can reach 19.72% emissions reduction.

Since the simulation part investigates the system from environmental perspective, this work deploys a Cost Benefit Analysis (CBA) to assess economic, technical, and environmental cost and benefits associated with each alternative. The economic evaluation shows that "electric stationary storage" is the potential best option. This is reasonable since ESS charges during lower electricity price and discharge during peaking demand. Thus, the customers can avoid the high electricity charges, and the utility is not required to run more generating units. "communication and intelligence" combined with "electric stationary storage" is the second option due to its flexibility in shifting the loads to off-peak periods is. The scenario that includes all MCDM options came in the third place since it provides almost 20% emissions reduction and its economic evaluation is beneficial. While "energy conservation" project and "electric stationary storage" with "energy conservation" project provide less economic impact than "communication and intelligence", those alternatives hold the fourth and fifth place, respectively, due to their environmental impact. The penultimate alternative is "communication and intelligence" because the Demand Response (DR) is designed to shift the peak load, and it has socioeconomic cost. Last alternative is combining "communication and intelligence" with "energy conservation". Although "energy conservation" performs environmentally better than "communication and intelligence", its socioeconomic cost plays a major role in selecting such alternative. However, the ranking might change according to the participants' choice. One can prefer environmental impact over economic output and vice versa. Therefore, this work presents a trade-off chart, so the decision maker can select the alternative based on their preference.

All analysis, simulation, and results in this work are particularly based on Fort Collins distribution system data and is not a general assessment. There are several factors might affect the result such as the location, the data, or the distribution system structure.

ACKNOWLEDGMENTS

I would like, first, to thank all people who helped me in accomplishing this work. I would like to thank my advisor, Prof. Siddharth Suryanarayanan, for his guidance, encouragement, and support in doing this work. My thanks go my committee members Prof. George J Collins, Prof. Daniel Zimmerle, Prof. Patricia Aloise-Young, and Peter O'Neill for their advice and support. Additionally, I would like to thank Peter O'Neill, for his work on the surveys related to prioritizing demand side management technologies.

I must extend my gratitude to my mother and all my family members for their encouragements and motivations. Special mention goes to my supportive wife, and my wonderful son, Azzam, for their help and patience during doing this work.

I hugely acknowledge the Saudi Arabian Cultural Mission and Qassim University, Qassim Province, Saudi Arabia for their financial support for pursuing a Ph.D. in Electrical and Computer Engineering at Colorado State University. My colleagues at Advanced Power Engineering Laboratory also deserve many thanks for their help and support.

TABLE OF CONTENTS

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

APPENDIX

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

AB32	California Assembly Bill
AEO	Annual Energy Outlook
AHP	Analytic hierarchy process
AMI	Advanced metering infrastructure
ANP	Analytic network process
BCR	Benefit to cost ratio
CAA	Clean Air Act
CAIDI	Customer Average Interruption Duration Index
CAP	Climate Action Plan
CI	Communication and intelligence
CBA	Cost benefit analysis
CO_2	Carbon dioxide
CPP	Clean Power Plan
DG	Distributed generation
DER	Distributed energy resources
DR	Demand response
DSM	Demand side management
EE	Energy efficiency
EC	Energy consumption
EGU	Electric utility generating unit
EHT	Electrification of heating and transportation
EPA	Environmental Protection Agency
ESS	Energy storage system
EV	Electric vehicles

GHG	Greenhouse gas
IEEE	Institute of Electrical and Electronics Engineers
IRR	Internal rate of return
IoT	Internet of things
MAIFI	Momentary Average Interruptions Frequency Index of durations under 5 minutes
MCDM	Multi Criteria Decision Making
NPV	Net present value
PRPA	Plate River Power Authority
RGGI	Regional Greenhouse Gas Initiative
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
TOU	Time-of-use
U.S.	United States

CHAPTER 1

INTRODUCTION AND OVERVIEW

1.1 Motivation

Growth in energy consumption leads to concerns of global GHG emissions. Most of the supplied energy is from carbon-emitting sources; the use of these sources increased by more than 25% in the last two decades. Further, an increase of 15% to 35% is expected by 2030. One third of the global energy consumption comes from the manufacturing sector [1]. In 2016, human-caused CO_2 emissions from the use of fossil fuels for energy usage was equivalent to 94% of the total of U.S. anthropogenic CO_2 emissions and 76% of U.S. GHG. The remaining 6% of CO_2 and 5% of total anthropogenic GHG come from other anthropogenic sources [2]. Further, coal is the dominant source of CO_2 emissions from electricity generation, as of 2017, in the U.S. as it accounts for 69% of total energy-related CO_2 emissions followed by natural gas, 29%, and petroleum 1% [3]. Therefore, regulating electricity generation for emissions and establishing climate action plans to mitigate CO_2 and GHG emissions can help achieve a meaningful impact. However, CPP repeal and the U.S. withdrawal from Paris Agreement diminish lowering GHG emissions. Further, DSM can directly and indirectly mitigate CO_2 emissions. Some options like DR and energy conservation can reduce peak loads and in turn reduce emissions from dirty generating units. Indeed, DSM provides ancillary services that can directly mitigate emissions. The growth penetration in Renewable Energy (RE) leads to indirect impact toward emissions reduction [4].

1.2 Objective

The objective of the work is to quantify the impact of climate action plans in reducing GHG emission from electric power systems. It also demonstrates that DSM can help in achieving a meaningful reduction in emissions. This dissertation aims to pare down the numerous options available for DSM to those that will make the biggest difference for GHG reductions. In that regard, this work demonstrates the choice of DSM options using AHP and ANP algorithms to study the impact of climate action plans on reducing CO_2 emissions, and in turn quantify the potential optimal alternatives that can achieve the goal. Another objective of this work is to incorporate the alternatives of ANP into a simulation to quantify GHG reduction. Further, this effort aims to evaluate the economics of the MCDM alternatives, along with the environmental analysis, find the optimal combination among DSM options.

1.3 Scope

The scope of the work is to discuss the impact of the CPP in reducing CO_2 emissions and to illustrate solutions from the engineering field to minimize carbon footprint. This dissertation proposes a framework using MCDM algorithms to find the potential best solutions to mitigate GHG using DSM taking into consideration several aspects such as cost, reliability, power quality, environmental collateral, and socio-economic equity.

AHP is one of the most common MCDM methods. AHP derives ratio scales from paired comparisons and uses it in making decisions that include ranking, organization, evaluation, and prediction. Hence, AHP is used to formulate the problem and demonstrate the final prioritization among the proposed options of DSM. ANP is another model of MCDM, and it is a generalization of AHP. Unlike AHP, ANP provides feedback and loops in addition to interdependency relationships. Therefore, ANP is used to help in making decisions with such complicated systems when hierarchal structures are not sufficient.

After obtaining the final ranking from MCDM, alternative solutions are simulated on the IEEE 13-node test system to investigate the optimal solution that can provide best option among DSM alternatives. Therefore, several scenarios will be implemented, and CBA will be employed to compare multiple scenarios and to select the alternative that reduces costs and maximizes benefits. Hence, this paper considers the Climate Action Plan (CAP) of Fort Collins, Colorado, US as a choice of study. We use this particular distribution system because of its proximity to the author's home institution and the associated access to expertise; further, the municipal entity that operates this system has a climate action plan; the plan's target is to make the city carbon neutral by 2050.

1.4 Literature survey

1.4.1 Climate change

Clean Power Plan (CPP) is a prime example because it was the most comprehensive and largest climate protection plan in the U.S. until its proposed repeal in 2017. The plan provides several approaches and options to meet the targeted reduction of emissions from Electric Generating Units (EGUs) or power plants. Several scenarios have been proposed to incorporate with the plan, which would lead to achieving the goal with less impact on electricity generation. Further, several successful state and international climate plans encourage governments, communities, individuals, and businesses to take additional actions to reduce GHG. AB32 is a plan launched in 2006 to reach an 80% emissions reduction below 1990 levels by 2050 [5]. Also, the RGGI is a cooperative program in the eastern U.S. to limit CO_2 from the power sector. Internationally, the province of Ontario in Canada launched a plan to mitigate CO_2 emissions from the electricity sector. The results show Ontario can achieve more than 50% emissions reduction by removing coal-fired power plants [6]. Additionally, China is considering plans to control and mitigate air pollution from electricity generation [7]. Since the CPP has been proposed for repeal, there is a dire need for identifying alternatives to regulations on EGUs that can mitigate CO_2 emissions from the electricity sector. In this regard, several options can be considered such as heat rate improvements, renewable energy installations, and electricity transmission and distribution improvements [8]. In fact, engineering solutions in the distribution system are one of the emerging strategies to reach CO_2 mitigation goals.

1.4.2 DSM

DSM is a planning, implementation, and monitoring of the electric utility activities to influence the end user's use of electricity to meet the customer's needs with the utility' goal [9-12]. One of the objectives of DSM is providing cost-effective energy in addition to incorporating modern technologies and innovation in the distribution system [11]. DSM options provide economic and reliability benefits such as deferring investment in the electric power system, minimizing emergency cases, and reducing power outages in the system. Also, it can play a major role in reducing electricity costs and emissions caused by energy consumption by displacing the onus of emissions production to the distribution entities [13-15]. In fact, there are some factors that can accelerate the implementation of DSM, such as the growth in installation of renewable energy resources, the development in information and communication technologies, and pending retirements of aging assets in the electric power system. However, there are several challenges associated with the implementation of DSM including some distribution systems lack an existing smart infrastructure, the complexity of operation of new technologies, and security issues [16].

1.4.3 AHP

AHP is one of the available approaches to solve MCDM problems that was originally developed by Prof. Thomas L. Saaty [17]. AHP uses a framework for problem solving that organizes judgments into a hierarchy of criteria that influence decisions. The decision maker uses AHP to estimate relative magnitudes through paired comparisons and use that information for making decisions [18, 19]. In fact, AHP has been used for more than 40 years including studying U.S. presidential elections in 1976 and 1980 [20, 21]. Another use of AHP is to examine the impact of global climate change. Further, AHP is applied in a wide range of electric power system to study scheduling local loads in energy smart buildings and decision-making analysis in electric microgrids [21]. Implementing AHP requires following several steps until obtaining final ranking. First, structuring the problem in a hierarchal structure. Second, the decision maker uses a ratio scale to compare pairwise preferences. Table 1-1 shows AHP scale based on Saaty scale, recreated from [22] .

The next step is to construct a judgment matrix for criteria. After that, we develop a judgment matrix for alternatives with respect to each criterion. Step four is to check for inconsistency that must be $\leq$10%. Then, overall ranking is used to select best choice [18, 19].

Table 1-1: The Fundamental Scale for Pairwise Comparison [22]

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favor very strong over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another it the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption

1.4.4 ANP

ANP is another tool to solve MCDM problems. It is a methodology that allows groups or individuals to deal with the interconnections between factors of complex problems in decision making processes. ANP allows to include relations of dependence and feedback among nodes of the system. The problem modeling is more complex, but it is more realistic [23]. ANP requires five major steps to obtain final prioritization. The first step is to construct the problem in a network model. Next is to perform a pairwise comparison for criteria and alternatives. The third step is to obtain a supermatrix that contains all nodes and then calculate a limit matrix. The last step is to select the optimal alternative based on final ranking [24].

Reference [25] demonstrates an example that explains the methodology of ANP and how it is different from AHP. The objective is to find the best solution in to manage a water reservoir. The decision is to choose one of the possible solutions of maintaining the water level in a dam at: low, medium, or high. The final decision depends on three-criteria, namely flood control, recreation, and the generation of hydroelectric power for the three options. The problem is constructed in a feedback system as shown in Figure 1.

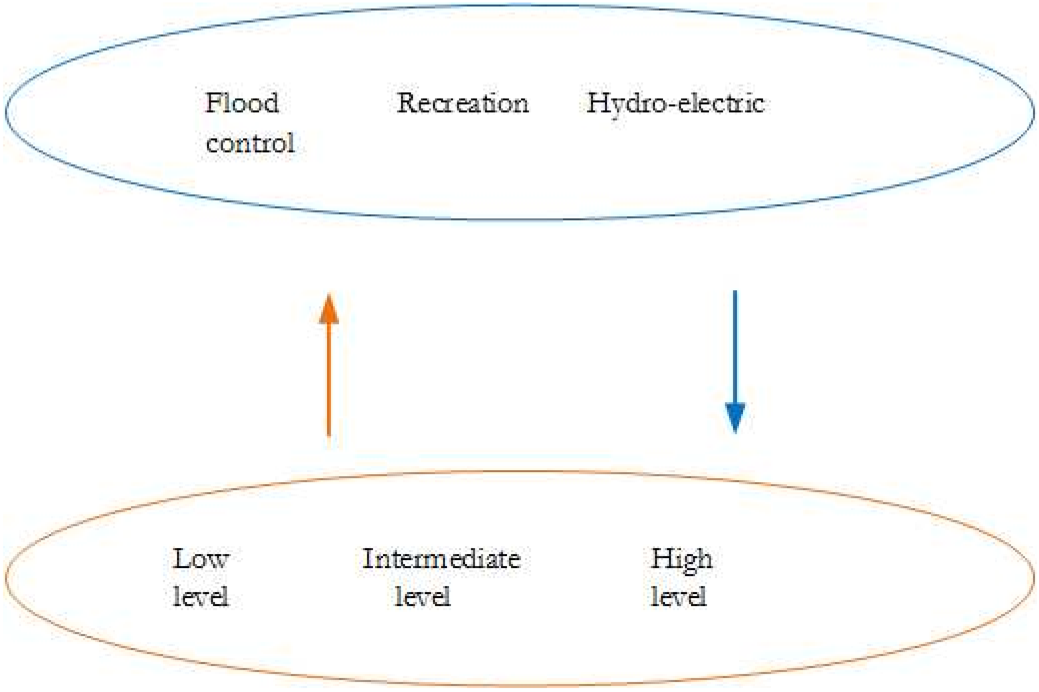

Figure 1-1: A Problem structure reproduced from [25]

Then, A pairwise comparison is conducted for each alternative with respect to each criterion. Tables 1-2 to 1-4 present judgment matrices for each alternative with respect to each criterion.

Table 1-2: Judgment Matrix for Alternatives with respect to Flood Control [25]

	Low	Medium	High	Priority
Low	1	5	7	0.722
Medium	1/5	1	4	0.205
High	1/7	1/4	1	0.073
			Inconsistency	10.7%

Table 1-3: Judgment Matrix for Alternatives with respect to Recreation [25]

	Low	Medium	High	Priority
Low	1	1/7	1/5	0.072
Medium	7	1	3	0.649
High	5	1/3	1	0.279
			Inconsistency	5.6%

Table 1-4: Judgment Matrix for Alternatives with respect to Hydroelectric Power [25]

	Low	Medium	High	Priority
Low	1	1/5	1/9	0.058
Medium	5	1	1/5	0.207
High	9	5	1	0.735
			Inconsistency	10.1%

Now, we examine the influence of each criterion on the alternatives. Tables 1-5 to 1-7 illustrate pairwise comparisons for each criterion with respect to each alternative.

Table 1-5: Judgment Matrix for Criteria with respect to Low Level [25]

	Low	Medium	High	Priority
Flood control	1	3	5	0.0637
Recreation	1/3	1	3	0.258
Hydroelectric power	1/5	1/3	1	0.105
			Inconsistency	3.3%

Table 1-6: Judgment Matrix for Criteria with respect to Medium Level [25]

	Low	Medium	High	Priority
Flood control	1	1/3	1	0.2
Recreation	3	1	3	0.6
Hydroelectric power	1	1/3	1	0.2
			Inconsistency	0%

Table 1-7: Judgment Matrix for Criteria with respect to High Level [25]

	Low	Medium	High	Priority
Flood control	1	1/5	1/9	0.060
Recreation	5	1	1/4	0.231
Hydroelectric power	9	4	1	0.709
			Inconsistency ratio	0.61%

After finishing all comparisons, the normalized supermatrix is obtained as shown in Table 1-8.

Table 1-8: Normalized Supermatrix [25]

	Flood control	Recreation	Hydroelectric power	Low	Medium	High
Flood control	0	0	0	0.637	0.2	0.060
Recreation	0	0	0	0.258	0.6	0.231
Hydroelectric power	0	0	0	0.105	0.2	0.709
Low	0.722	0.072	0.058	0	0	0
Medium	0.205	0.649	0.207	0	0	0
High	0.073	0.279	0.735	0	0	0

Then we obtain the final priorities for both, criteria and alternatives by raising the limiting power of the supermatrix where the matrix powers stabilize after 130 iterations as denoted in Table 1-9.

Table 1-9: Limit Matrix [25]

	Flood control	Recreation	Hydroelectric power	Low	Medium	High
Flood control	0	0	0	0.241	0.241	0.241
Recreation	0	0	0	0.374	0.374	0.374
Hydroelectric power	0	0	0	0.385	0.385	0.385
Low	0.223	0.223	0.223	0	0	0
Medium	0.372	0.372	0.372	0	0	0
High	0.405	0.405	0.405	0	0	0

The results show that a high dam has the highest preference with priority 0.405 for the criterion of hydroelectric power generation with priority 0.385. This indicates that ANP is able to solve any decision problem if interdependent relationships have significant impacts in the decision model. Table 1-10 shows the results of the same example solved by AHP.

Table 1-10: Final Prioritization Using AHP

	Flood control	Recreation	Hydroelectric power	Priority
Low	0.087	0.031	0.018	0.136
Medium	0.026	0.267	0.065	0.358
High	0.009	0.117	0.218	0.345

The findings show that the decision changes when the interdependent relationship is considered. Thus, interdependencies can affect final ranking.

1.4.5 IEEE 13-node test feeder

IEEE 13-node is a test feeder was developed to perform analysis in the distribution system [26]. The test feeder will be used to simulate and test the performance of ANP alternatives to achieve the goal. Several studies have been conducted using the IEEE 13-node system. One example is published in [27] to examine allocating DG units on the IEEE 13-node system. The results show a reduction in power losses, increasing reliability, and maintaining voltage levels between 0.95 to 1.05 p.u.

OpenDSS is an open-source environment to perform power flow studies in electric distribution systems developed by the Electric Power Research Institute (EPRI) [28]. It has several capabilities such as general distribution planning and analysis, integration of Distributed Energy Resources (DER), and load and storage simulators. IEEE 13-node test feeder is run on OpenDSS to calculate voltages, currents, and system losses. The summary of power flow solution is as follows:

```
Solution Mode = Snap
Number = 100
Load Mult = 1.000
Devices = 38
Buses = 16
Nodes = 41
Control Mode =STATIC
Total Iterations = 11
Control Iterations = 3
Max Sol Iter = 4

 - Circuit Summary -

Year = 0
Hour = 0
Max pu. voltage = 1.056
Min pu. voltage = 0.96083
Total Active Power:   3.56721 MW
Total Reactive Power: 1.73659 Mvar
Total Active Losses:   0.112409 MW, (3.151 %)
Total Reactive Losses: 0.327912 Mvar
Frequency = 60 Hz
Mode = Snap
Control Mode = STATIC
Load Model = PowerFlow
```

1.4.6 CBA

CBA is an economic framework to compare several options and select the one who provides maximum benefits. There are two major types of CBA; *ex ante* CBA where the analysis is constructed while the project is under consideration or before its implementation and *ex post* CBA that is conducted at the end of the project [29]. CBA is used to study the economic viability of several applications such as smart grid, DR, energy storage, and RES [30-35].

1.5 Software Tools

MATLAB® code was used for calculating local priorities and final priorities in chapters 4 and 5. Also, OpenDSS software was used to simulate IEEE 13 node test system and then complied to MATLAB®. All codes are presented in the appendix of this report.

1.6 Organization of the Dissertation

The remaining chapters of the report are organized as follows: a brief overview of the CPP and its approaches and scenarios and CAP of Fort Collins Colorado, U.S. are given in chapter 2. A background of DSM techniques and options is discussed in chapter 3 and chapter 4 explains the AHP, a MCDM methodology presents the problem framework and discusses the hierarchal structure through a case study on Fort Collins, Colorado, U.S. and its results. Chapter 5 explains the ANP, a MCDM methodology and presents the obtained results. Chapter 6 obtains modeling and simulation of the distribution system. Chapter 7 presents economic analysis using DSM alternatives. Chapter 8 concludes the work and presents the future path of the research. Part of chapter 1 and chapters 2-5 are verbatim reproduced from [36]. Also, part of chapter 1 and chapters 6-8 are verbatim reproduced from [37].

CHAPTER 2

GOVERNMENT DIRECTED PLANS TO REDUCE GHG EMISSIONS[1]

2.1 Introduction

This chapter discusses some climate action plans. It, first, gives an overview about the CPP and its benefits and challenges. Then, it explains several options of the CPP in reducing emissions and its repeal. Further, this chapter also discusses the CAP of Fort Collins and its timeline targets.

2.2 Clean Power Plan

Since there are no regulations to limit emissions of CO_2 from electricity generation, power plants can emit unlimited amount of CO_2. Consequently, about 40% of CO_2 emissions are emitted from conventional power plants [38]. Therefore, rules are needed to regulate electricity generation and reduce air pollution exposure that endangers health and welfare. Hence, the Clean Air Act. (CAA) is a federal law that protect human health and environment by regulating air emissions from stationary, modified and reconstructed sources. This law authorize Environmental Protection Agency (EPA) to establish standards to solve air pollution problems [39]. The CPP is an action that has been launched under the CAA to reduce emissions from the electricity sector by about 32% below 2005 levels by 2030 [40]. The goal of this legislation is to minimize air pollution and reduce the impact on climate change [41]. In the period between 1970 to 2015, total emissions of six common pollutants in the U.S., fell an average of 70% while gross domestic product grew 246%. [42, 43]. Figure 2-1 shows the U.S. electricity generation from coal in 2017 without CPP compared to the annual energy outlook 2016 reference case (AEO2016) [44]. The AEO2016 reference case assumes compliance with the CPP where all states and regions will implement the plan.

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[1] This chapter is verbatim reproduced from [36], and it is under review in the Utilities Policy Journal at the time of writing this dissertation

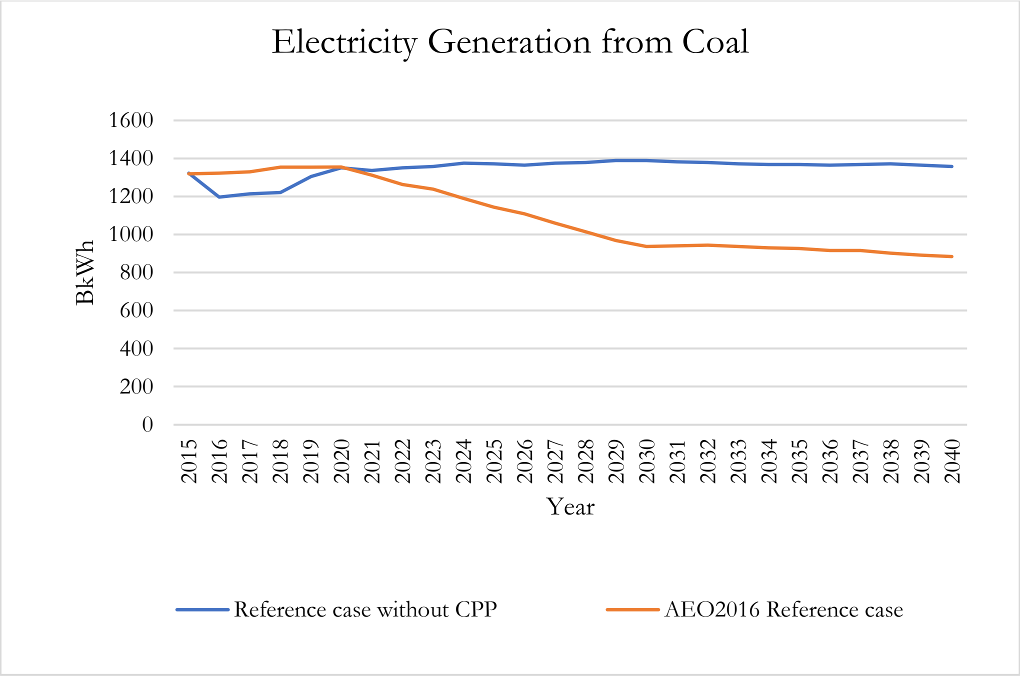

Figure 2-1: The U.S. Electricity Generation from Coal in 2017 [35]

In the CPP, section 111(b) directs EPA to develop a standard of performance for stationary sources of air pollution. Also, section 111(b) must establish an emission standard from modified and reconstructed sources where they must meet the standard. Section 111(d) mandates EPA to set emission standards for pollution emitted from existing sources. There is no specific form to perform section 111(b). Therefore, EPA requires states to design their standard of performance [45]. This might be identical to EPA's guideline or different but equivalent to EPA's guideline. The basic options include:

a. Performance standard that is limited or non-flexible
b. Flexible performance standard, with the option of banking, averaging, and trading, and
c. A state budget approach with banking and trading.

Reference [46] presents a study to examine the above options. The results show the first option is easy to administer, but it incorporates more cost per ton of CO_2 reduced. Moreover, the advantage of the second option is avoiding placing a specific limit on emissions. Hence, conventional generators could increase the electricity output and emissions, if they satisfy the standard of performance. The study concludes that second and third options can be considered in existing sources as they provide cost-effective compliance solutions and investment. Further, the emission standard, set by EPA, must meet the emissions mitigation that is achieved through application demonstrated by EPA of "best system of emission reduction". The emission standard should take into consideration some factors such as the emission cost reduction, non-air quality health and environmental effect in addition to energy requirements [47].

As the new generating sources can be built with compliance with the standard of performance, there are options to minimize CO_2 emissions from existing power generating units. It can be supply-side options to directly avoid CO_2 emissions from the power plant by increasing energy efficiency. Or, it can indirectly reduce CO_2 emissions from the power plant by increasing the penetration of less carbon-emitting sources and zero-carbon technologies such as renewable energy. Demand side can displace CO_2 emissions from the power plant by decreasing electricity demand. This could happen by reducing the overall amount of electricity generated at CO_2 emitting power plants or changing the dispatch of electric generators in response to lower electricity demand [41, 45, 48, 49]. Employing these options vary by state depending on the sources of electricity generation. Some factors that can play a role such are technologies, costs, and the emissions reduction. Therefore, states can combine several options to meet their goals.

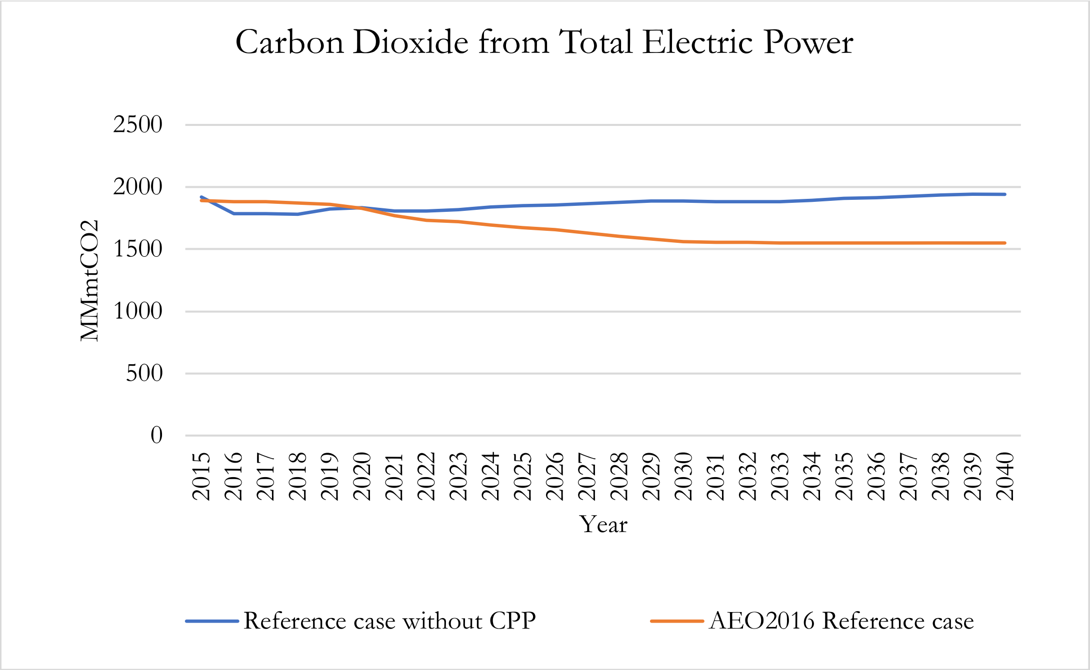

Figure 2-2: The U.S. Emission Reduction from Electric Sector in 2017 [41]

Also, states can join in multi-state or regional entities to find the best cost options for reducing their carbon emissions. Figure 2-2 illustrates the U.S. emission reduction from the electric sector in 2017 without CPP compared to the AEO2016 reference case [50]. According to [8], the CPP regulations allow states to choose one of two approaches to measure CO_2 emissions: mass-based or rate-based. A mass-based approach measures the annual limit of emissions the that can be produced from the affected power plants. A rate-based approach measures the annual emissions based on the emitted amount of CO_2 divided by generation from affected sources (lbs CO_2/MWh) which means capacity from non-emitting sources such as renewable energy resources is included. Reference [51] performed a study on implementing alternative cases of the CPP. The outcomes of the study should illustrate how the results can change with different implementation of the CPP. The alternative CPP cases are explained below:

A. *No CPP case:* Assumes that the CPP is repealed and there is no regulation to reduce the emissions from existing generating units, but other programs remain active such as RGGI and AB32.

B. *CPP case:* All regions can comply with the plan by meeting average rate-based targets in lbs CO_2/MWh.

C. *CPP interregional trading case:* Any region that performs below the standard level earns credit. Therefore, the case considers that all states can choose to meet their targets following the mass-based approach, and the regions can trade their carbon allowances.

D. *CPP extended case:* Aims to achieve a reduction in CO_2 beyond the target for 2030, 32% reduction below 2005. The goal is to reduce the emissions by about 45% below 2005 levels in 2040.

E. *CPP hybrid case:* Assumes regions with active plans can join with the CPP to meet the required reduction of CO_2 emissions.

F. *CPP allocation to generators case:* Considers that the allowances of emissions are allocated to electricity generating units rather than to load-serving entities.

The results show a 35% reduction below 2005 level in the reference case by 2030. Also, the same reduction can be achieved by implementing CPP rate case, but the mitigation reduces by 2% after 2030 due to the growth of generation. CPP extended case enforces more reduction as it continues the reduction to 45% by 2040. Figure 2-3 demonstrates the reduction of CO_2 emission in each case.

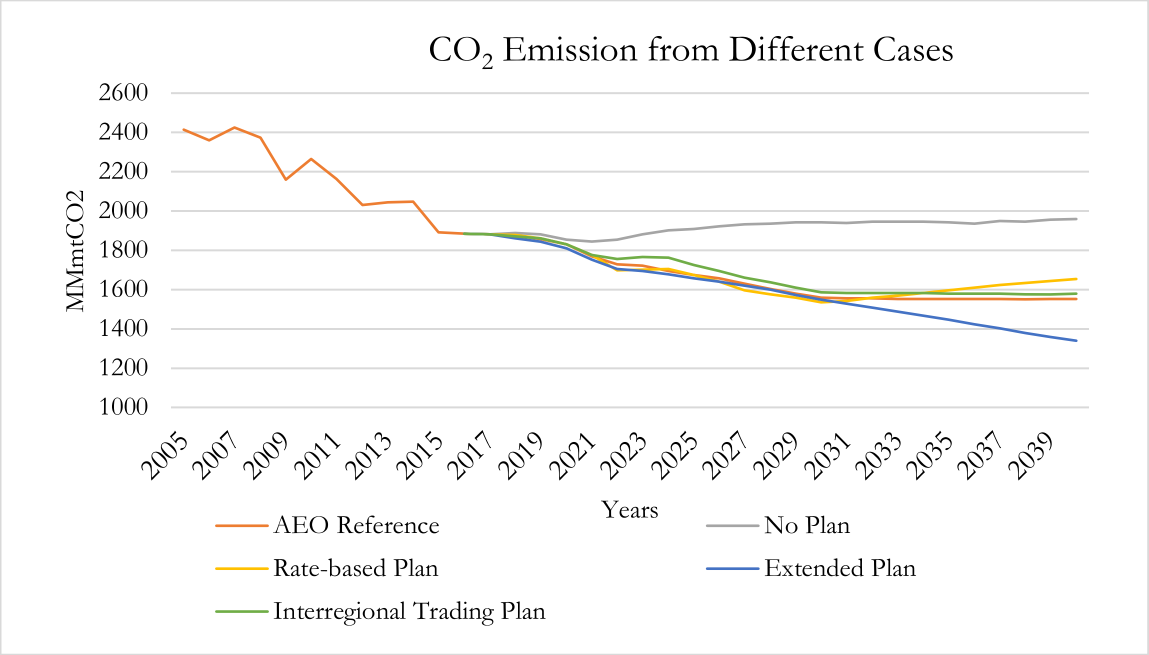

Figure 2-3: CO_2 Emissions from the Electric sector from the Alternative Cases [42]

The CPP could have a positive environmental impact as well as health benefits. **However, an executive order was signed on Tuesday October 10th, 2017 to repeal the CPP [52]**. This likely means emitting more emissions from electricity generation. Therefore, a comprehensive engineering plan must be conducted to find alternative solutions that can overcome the impending pollution. Several options can be considered such as high penetration of renewable energy, increasing energy efficiency and investing in nuclear power generation. Further, DSM is a good opportunity from engineering practices to reduce CO_2 emissions caused by electricity generation. DSM can also benefit the reliable and cost-effective operation of the distribution system.

2.3 Climate Action Plan

The CAP is chosen a case study to investigate DSM options in reducing emissions. This plan is considered because the CAP target is to make Collins carbon natural by 2050 and some DSM options are not yet implemented and are not yet prioritized. Total GHG emissions in Fort Collins, Colorado, U.S. is expected to increase, above 2005 levels, by 16% in 2030 and 39% in 2050 in the absence of actions to diminish the emissions. According to [53], about 95% of the emissions come from electricity generation, natural gas, and transportation activities. Indeed, 51% of the emissions inventory come from electricity generated by combusting fossil fuels. Electricity used in Fort Collins is generated by coal, natural gas, and renewable energy resources. Figure 2-4 shows the mix of electricity resources supplying Fort Collins's load.

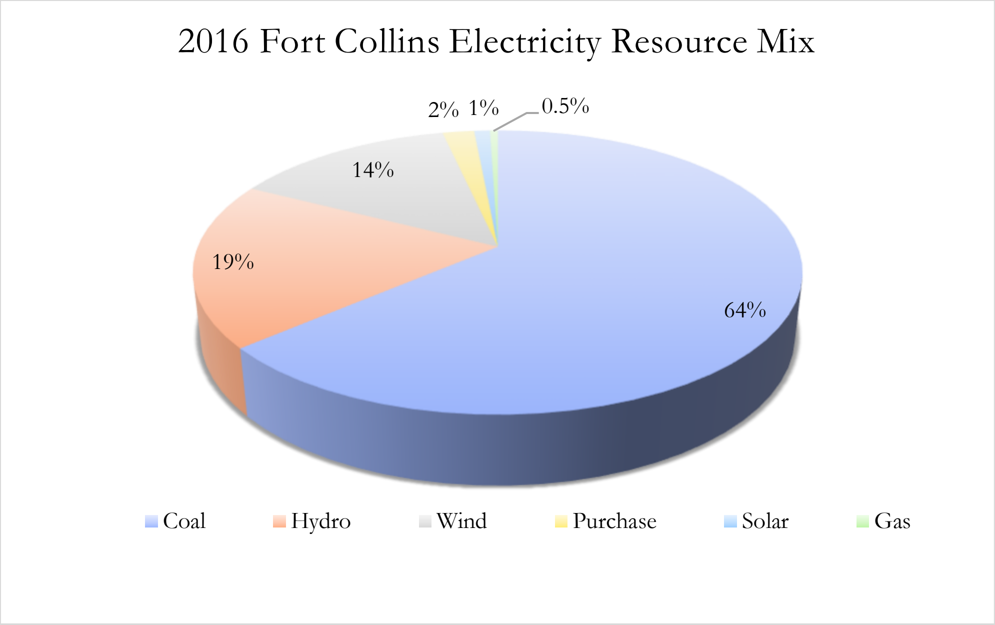

Figure 2-4: Fort Collins Generation Resources [44]

Fort Collins adopted a CAP to achieve GHG reduction goals. These goals are to reduce GHG 20% below 2005 levels by 2020, 80% by 2030 and 100% by 2050 [54]. While the population increased by 23% in 2016, compared to 2005, CO_2 emissions reduced by 12%. Indeed, as of 2017, Fort Collins' carbon emissions were 17% lower than 2005 levels. This is reasonable as 80% of the population in Fort Collins believes that climate change requires more actions and investments in programs to address and mitigate climate change impact [55]. As Fort Collins is among the top 10 environmentally friendly cities in the U.S., 1 in 3 businesses have engaged in EE programs while saving annual business energy costs of over $9.5 million [55].

Several renewable installations have led to this CO_2 reduction; a 30 MW utility-scale PV array increased clean energy installation by 2%, equivalent to the energy consumption of 3500 household, while two recent wind farms added another __% to renewable generation. Investments in EE in 2016 achieved a savings equivalent of reducing electricity consumption of 3750 homes, which lead to a reduction in CO_2 emissions [53]. However, though significant progress has been made through this combination of cleaner generation and DSM, we examined what could be done with only DSM given that Fort Collins municipal electric utility that own only distribution systems as associated assets. Thus, we investigate the optimal operation of DSM to achieve the city's goal. In that regard, we implement an AHP-based DSM model and ANP-based DSM model to examine the optimal options available from DSM.

This research is only dealing with the demand side, including DG on the distribution system, of the electric energy system. In doing so, not only must we consider electric demand reduction but also demand increases due to the electrification of other loads like transportation, heating for space, water, and processes.

CHAPTER 3

DEMAND SIDE MANAGEMENT[2]

3.1 Introduction

This chapter presents alternatives from literature for DSM implementation. Several options are discussed to explain the effect of these alternatives on minimizing carbon footprints. Moreover, this section demonstrates the impact of DSM options on the operation of power grid.

3.2 DSM

The essential impact of controlling the demand occurred in 1970s when there was a need to shape the load profile [56]. In recent years, DSM has been introduced as a solution to manage the load in the distribution system. DSM means modifying end-use electrical energy consumption by some measures and operations to change power consumption to a desired level [7]. In fact, applying DSM to the distribution system provides meaningful benefits in areas such as economy, reliability, and the environmental. Specifically, DSM leads to cost reduction by reducing energy prices. Also, DSM defers the investments in generation, transmission, and distribution systems. Further, DSM helps in minimizing the impact of emergency/contingency cases in the electric power system and in reducing the reach of blackouts, and in turn, increasing the reliability [57]. Moreover, reducing energy consumption through DSM leads to a reduction in harmful emissions to the environment. A survey shows that a reduction in global warming-related emissions of GHGs is one of the top four reasons for implementing DSM programs [58]. Via DSM programs, energy usage can be reduced or shifted to benefit the utility and consumer.

Some examples of popular DSM techniques include peak clipping, which reduces the system peak loads during specific periods of time and valley filling, which allocates loads during the off-peak period in addition to the load shifting technique [59]. Common DSM techniques are shown in Figure 3-1, recreated from [60].

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[2] This chapter is verbatim reproduced from [36], and it is under review in the Utilities Policy Journal at the time of writing this dissertation

Several examples of successful DSM programs illustrate significant improvements in electricity usage as well as economic and environmental impacts. In 2010, electric utility DSM programs in the U.S. reduced the peak load by 33.283 GW. This results in about 87,839 million kWh [61]. In 1999, about 459 utilities in the U.S. had implemented DSM programs. These programs saved about 50.6 billion kWh of energy generation. This represents 1.5% of the annual electricity sales of that year [62]. Globally, Vietnam has annual demand growth between 10% to 13%. Therefore, the country applied a DSM program to face the spiking increase in electricity demands. According to [7], the DSM program, in Vietnam, is expected to achieve a reduction in peak demand of 2,928 GWh, which is equivalent to saving roughly 724 million tons of oil or 3.5 million tons of carbon emissions. In this section, we investigate the most common DSM programs to cost-effectively decrease the negative environmental impact of emissions by conventional power plants.

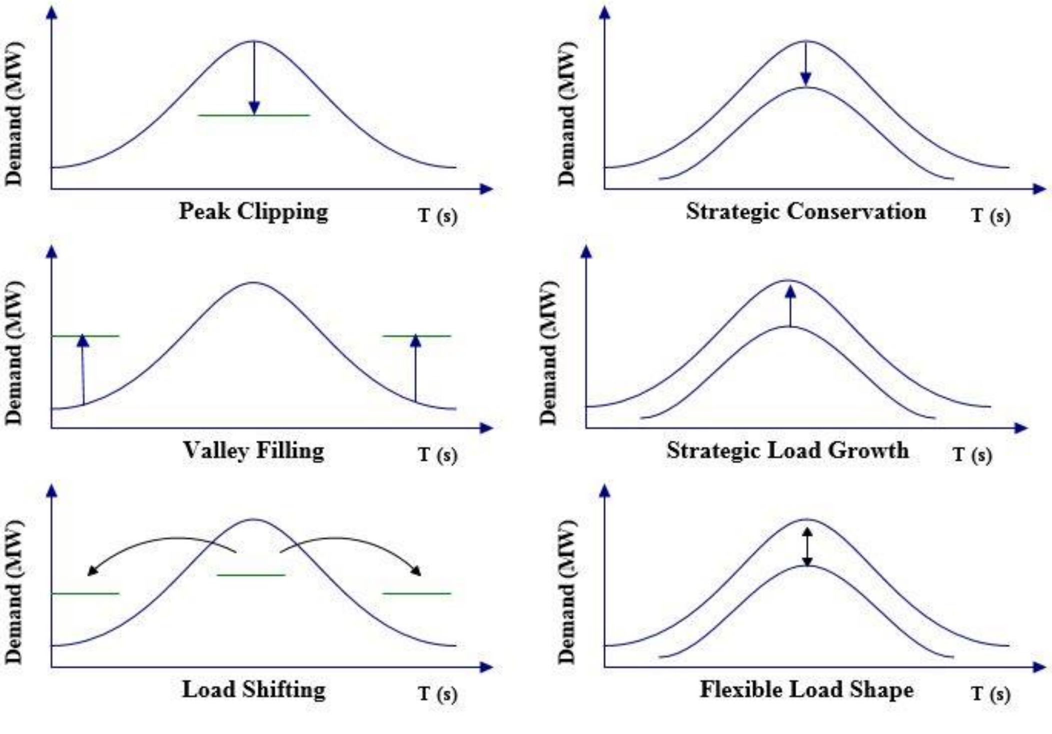

Figure 3-1: DSM Techniques[60]

3.2.1 Demand Response (DR)

DR refers to modifying the electricity usage by the end-user customers from their normal consumption patterns due to market price, system imbalance, or system stress. Specifically, DR programs are developed to increase electric system reliability by reducing peak hour loads [63]. DR can provide economic efficiency and environmental benefits. According to [64], DR can directly reduce CO_2 emissions between 1% to 2% in the U.S., where a 1% reduction is equivalent to removing 6 coal-fired power plants during peak loads. DR programs can be categorized as either time-based or incentive-based programs. Time-based programs use price signals to reduce energy demand. Alternatively, incentive-based programs provide direct load control to lower demand for a fixed or predetermined incentive [65]. Below is a detailed explanation of DR programs [57, 66]:

A. *Time-Based Rates DR*

- Time-of-use rates (TOU) where the utility offers consumers a schedule of electricity rate that vary with the time of day, day of the week, or even the season of the year, but that is not varying with the real-time operating conditions of the electric power delivery system.
- Critical peak pricing uses time-based pricing on a limited number of days per year when the total load in the grid is expected to be the highest.
- Real-time pricing works as TOU except the rates change is real time depending on the operating conditions of the electric power deliver system.

B. *Incentive-Based DR*

- Direct load control where the utility directly controls some loads.
- Interruptible rates where customers get a special contract to curtail part of their load.
- Emergency DR programs where consumers can volunteer to respond to emergency signals.
- Demand bidding programs where customers can bid to curtail their load at attractive prices.

DR can potentially affect the utilization and efficiency of the coal power plants. Reference [67] shows that the demand that occur 1% of time in many systems in the U.S. and Australia could cost about 10% of the total electricity costs. Moreover, customers in the PJM Interconnection saved about $1.2 billion from DR programs [68]. Beside its reliability and economic impacts, DR provides positive environment impacts. Reference [64] shows that reducing peak load and providing ancillary services can directly reduce CO_2 emissions by more than

1%. Further, EPRI found that DR programs that focus on reducing peak load can achieve energy savings and emissions reductions. EPRI estimates that these programs can save up to 4 billion kWh of energy in 2030, in turn mitigating CO_2 emissions by 2 million metric tons [69]. Aggregator-based DR can enhance economic and environmental sustainability. The results obtained from a proposed residential DR program show the demand is shifted from on-peak to off-peak periods and the total used energy before and after the DR program remains unchanged. This proposed strategy aims to increase capacity factor of peaking generators during off-peaking times. The study shows that although some generating units increased their CO_2 emissions the total emissions are reduced by 32.77 million metric tons due to the changes in capacity factors of peaking and off-peaking generating units [70].

3.2.2 Energy management

Energy response is one of the most successful techniques in DSM and it can be implemented through either targeted education or incentive programs. Energy Efficiency (EE) means change in technologies, operations, and behavior to reduce energy consumption. In comparison to new generating units, investing in EE is preferred because it is cheaper, cleaner, safer, faster, more reliable, and more secure [71]. EE has positive economic and environmental impacts. According to [72], EE standards can provide a reduction in peak demand by about 240 GW in 2035. Also, EE can cut CO_2 emissions by 470 million metric tons in 2035, which is equivalent to the emissions from 118 coal power plants. Also, behavioral EE programs provide a saving between 1.8 to 2.2 quadrillion BTUs per year, which amounts to 16% to 20% of the U.S. residential energy use [73]. Such actions can be achieved by increasing the setpoint of air cooling temperature, decreasing the heating temperature setpoint, reducing shower time, changing the settings of dishwashers and washing machines, and turning off unused lights and electronics [74]. Energy management programs can be implemented in different ways such as [7]:

A. Providing incentives to customers to change energy consumption or end-use equipment. As an example, switching to more efficient light bulbs or refrigerators.

B. Joining EE performance contracts and other third-party initiatives.

C. Educating customers on the available opportunities in efficiency programs.

D. Developing services in supply or end-use energy products.

Further, there are several tools to analyze the effect of EE. These tools are used to calculate energy usage by comparing peak load with baseline in addition to providing a weekly comparison of consumption time series. Also, these tools use benchmarks to compare performance to others and use process correlations of user settings with reference settings [11].

3.2.3 Energy Storage System (ESS)

Energy storage technologies, such as stationary batteries and electric vehicles, can play a major role in many aspects such as improving reliability, reducing energy cost, and minimizing CO_2 emissions. The energy stored in the ESS is used to meet the demand without burning fossil fuels to generate electricity from conventional generators. Further, ESS are used with DG to balance the production and enhance the benefits of DG to the end-user and to the electric system. Therefore, ESS allows the end-use customers to use the electricity generated by their DG at different times than when it is produced [71, 75] for valley-filling or load-shifting.

3.2.4 Distributed Generation (DG)

DG refers to generating facilities that are interconnected to a distribution system and located next to the load. The integration of DG technologies into electrical networks has become an interesting solution in recent years due to the value they provide to grids. DG units provide several benefits of reliability, environmental, and economics such as power loss reduction and reduction in emissions from the electric power sector. DG is classified as renewable and non-renewable sourced. The primary renewable distributed generation technology is solar photovoltaic panels. Far less available are small wind turbines, small water turbines, and geothermal systems due to their uncommon site requirements. Non-renewable DG technologies combust fuel locally so that their waste heat can be used for heating space and water, and providing process heat; such units are said to be in a combined heat and power (CHP) configuration. These include natural gas fueled reciprocating engines, microturbines, and fuel cells.

Recently, investment in DG has increased due to declining cost of components and technologies and the increased value to the electric system, costumers, and society. This decrease in cost is occurring at different rates for different technologies for different reasons [76, 77]. As an example, California has implemented policies for increasing DG and ESS in order to deploy 1.5 million zero-emission vehicles by 2025 [7].

CHAPTER 4

ANALYTIC HIERARCHY PROCESS ALGORITHM TO PRIORITIZE DEMAND SIDE MANAGEMENT ALTERNATIVES[3]

4.1 Introduction

This section describes one of the most common MCDM algorithms, AHP. First, it presents a brief overview about AHP. Section 4.2 also demonstrates several steps to calculate final ranking among alternatives. Further, a problem framework is created corresponding to the goal of the CAP of Fort Collins, Colorado, U.S. The results show the final prioritization of the potential optimum alternatives.

4.2 AHP

AHP is one of the well-known MCDM methods. AHP derives ratio scales from paired comparisons and uses to make decisions that include ranking, organization, and evaluation. Thus, the input can be derived from actual measurements or from subjective opinion. AHP can also evaluate the reliability of the judgment matrix by checking inconsistency ratio. AHP follows several steps to obtain final prioritization. The first step is to define the decision-making problem. After that, we build the problem as a hierarchy structure, as shown in Figure 4-1, that contains the objective, criteria, and alternatives.

The next step is to build a matrix for a pairwise comparison that contains priority among criteria and alternatives. Next, we derive judgments from the pairwise comparisons using a reciprocal matrix:

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & 1 & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \tag{1}$$

where, A is the judgment matrix, and a_{ij} is the element of row i column j of the matrix, and gives the comparison of Criterion or Alternative i compared to Criterion or Alternative j. Indices i, and j=1, 2…n, where, n is the number of elements and the lower triangular matrix is the reciprocal values of the

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[3] Part of this chapter is verbatim reproduced from [36], and it is under review in the Utilities Policy Journal at the time of writing this dissertation

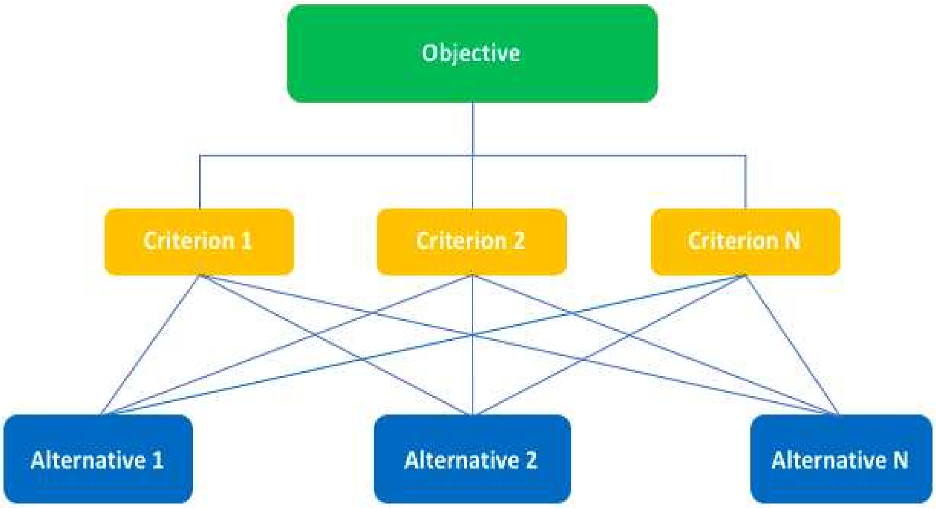

Figure 4-1: Hierarchical Structure of AHP [25]

upper diagonal. The next step is to calculate a weight vector, *x*, such that,

$$Ax = \lambda_{max} x \tag{2}$$

where, λ_{max} is the largest eigenvalue of *A*. The priority vector can be obtained by weighting the principal eigenvector of *A*. After that, it is important to check the consistency of the priorities. The degree of consistency can be obtained using the following formula:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

We use this index, *CI*, to compare it with the appropriate consistency index. The random consistency index is a fixed value of *RI* generated by [78]. Afterward, the consistency ratio is calculated to determined consistency ratio using equation 4. Generally, the matrix is considered consistent if the largest inconsistency is 10% or less [25, 78-80].

$$Consistency\ Ratio = \frac{CI}{RI} \tag{4}$$

After that, the previous steps are performed for all levels in the hierarchy. Then, we develop an overall priority ranking to select the best alternative.

4.3 Problem framework

AHP requires a carefully crafted hierarchy with the main goal, criteria, and alternatives. Therefore, an AHP survey requires clear objective and definitions of the criteria and identification of solution alternatives. First, we must state the goals of the CAP, which primarily are to reduce GHG emissions on a schedule. The CAP framework includes a varying set of secondary goals that include community health, new business opportunities, reduced economic outflow to purchase energy, and energy independence; but, GHG reduction is its major goal. Therefore, the objective focuses on reducing GHG emissions with an electric distribution system, its assets, and associated operations only. Figure 4-2 containing the objective, criteria, and alternatives used to evaluate the alternatives.

4.3.1 Criteria

The hierarchy problem includes criteria to study and evaluate each alternative. These constraints include:

- **CR1:** Cost includes the total direct cost to implement the alternative, i.e., fixed cost, operating and maintenance cost, and avoided cost. Also, cost excludes external costs, such as those associated with health effects.
- **CR2:** Reliability refers to the availability of power when the customer demands it. Reliability is quantified by popular indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Consumer Average Interruption Frequency Index (CAIFI), Consumer Average Interruption Duration Index (CAIDI), and Momentary Average Interruption Frequency Index (MAIFI) [81].
- **CR3:** Power quality delivered by the alternative. This criterion includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations.
- **CR4:** Environmental collateral is the damage caused by the alternative, e.g., toxic discharges and deforestation. Environmental collateral considers the footprint of the whole system, e.g., fuel extraction, in addition to fuel consumption

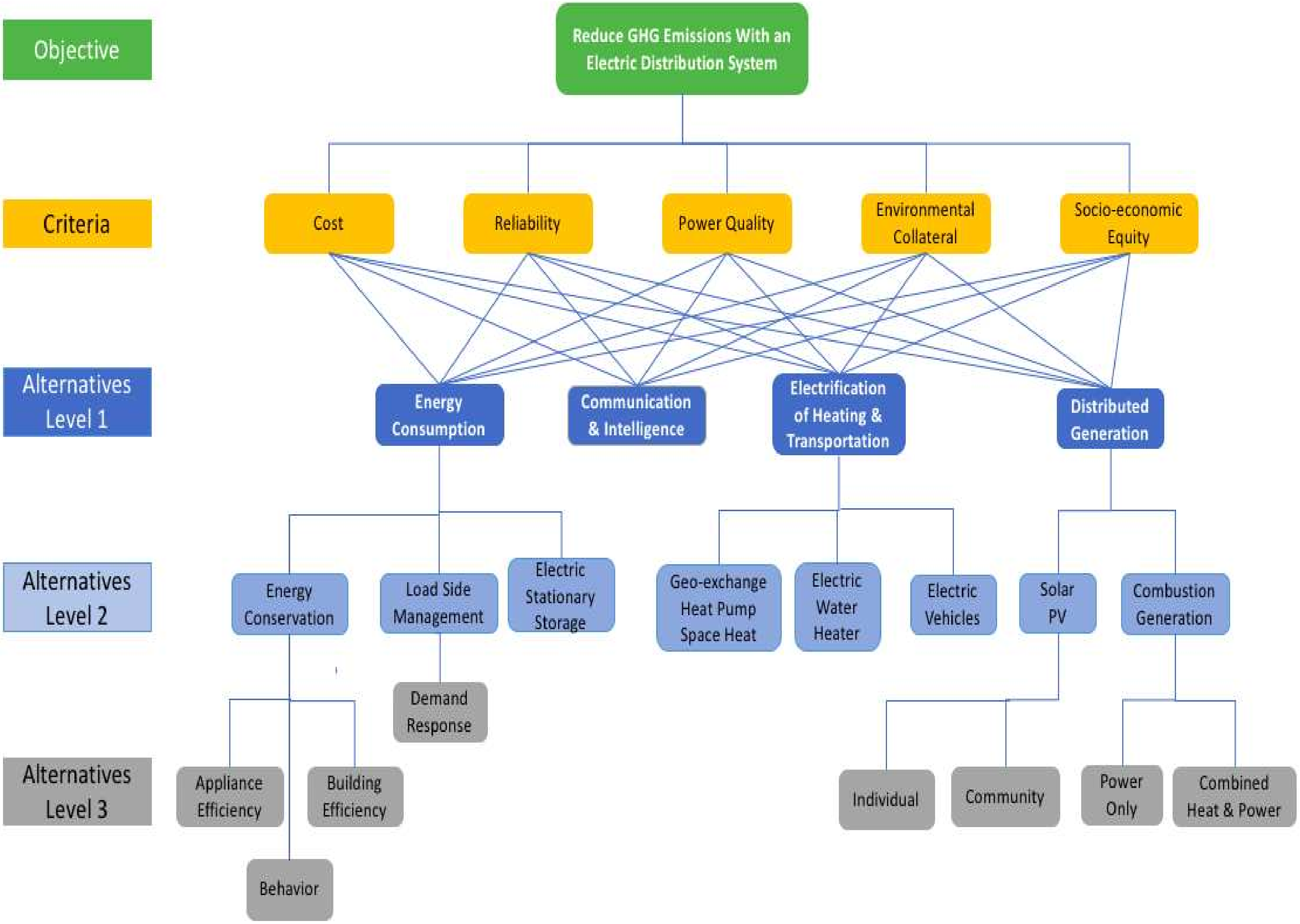

Figure 4-2: Hierarchy of Reducing GHG Emissions with an Electric Distribution System

- **CR5:** Socio-economic equity is the fairness in the access to and the benefit from the alternatives among social and economic groups.

4.3.2 Alternatives

The authors investigated options in the distribution system that can lead to achieving the goal. The options include a set of alternatives divided into three levels as shown in figure 7.

6.2.1 **EC:** energy consumption is the first alternative. It means reducing total amount of energy used by the community. This is a strategy alternative that encompasses energy conservation, load side management, and electric stationary storage. Energy conservation means reducing the useful work required. This can be implemented either by applying energy efficiency to reduce the energy input required to produce useful work or educational programs. Load side management is enabled to affect energy usage and in turn reduces GHG emission by generation's current GHG intensity. Electric stationary storage is an option to store and release electrical energy to balance load with the lowest GHG generation. Electric storage includes stationary battery that can be charged or discharged as needed to support grid operation.

6.2.2 **CI:** communication and intelligence is another option to achieve the goal. It is an automation to reduce energy or power and the time at which they are demanded. Communication and intelligence can include internet of things, smart meters and advanced metering infrastructure, real-time pricing, and smart appliance with controls automating energy conservation.

6.2.3 **EHT:** Electrification of heating and transportation is the third alternative. GHG can be reduced by transferring heating and transportation energy from combusting fossil fuels to renewable generation sources by electrification. This increase of the electric load on the distribution system must not be viewed as a failure of conservation but as a transfer from a dirty source a potentially cleaner source. A geo-exchange heat pump is the most efficient way to use electricity for space heating and cooling. It also is the most efficient way to use electricity to heat water for domestic use, not steam for industrial processes. Hot water can also be stored for up to a day, so a water heater, resistance or heat pump, is a very effective way to shift electric loads in time, which can be viewed as one-way electric storage. Charging electric vehicle can become an option which vehicle battery only whose charging can be scheduled to support grid operation.

6.2.4 **DG:** Distributed generation can be defined as decentralized generation on the electrical distribution system. It is a means to collect intrinsically distributed energy like sunshine and ground heat and to distribute low-grade heat. The most available distributed generation usually is solar PV, which can use sunlight to generate either electricity or heat. Distributed generation can also combust a fuel in a heat engine to generate electricity and using the waste heat for space, water, or process heat. Combustion generation can be used with any of the fuels to which it is being compared.

After building the hierarchy, we created a survey-like set of questions aimed at identifying the priority of the alternatives for achieving the abovementioned main goal. We used a slider scale to evaluate each criterion and each option. We used slider scale to evaluate each criterion and each option. The alternatives are subjected to each criterion based on the following:

- The closer to the option, the better in achieving the goal with lower cost
- The closer to the option, the better in achieving the goal with high reliability
- The closer to the option, the better in achieving the goal with acceptable levels of power quality
- The closer to the option, the better in achieving the goal with lower environmental impact
- The closer to the option, the better in achieving the goal with equal socio-economic status

The alternatives were evaluated on the criteria by the former chair of the city energy advisory board evaluated the alternatives on the criteria based on his knowledge on the municipal electric utility and citizen values, but not in any official capacity pertaining to that position.

4.4 Analysis and results

Since we identify the norms and the alternatives, the authors followed a pairwise comparison process to perform a judgment matrix for the criteria and alternatives. A normalized judgment matrix is obtained by dividing each value by the others.

4.4.1 Criteria

After normalizing the values, the results show the inconsistency ratio is 16.95%, which is above the 10% significance threshold mentioned in Section 4.2. Table 4-1 shows the normalized matrix and priority for the criteria.

Table 4-1: Judgment Matrix and Global Priority for Criteria (before fixing inconsistency ratio)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1	0.167	0.2	3	2	0.123
CR2	6	1	3	3	3	0.415
CR3	5	0.333	1	4	5	0.302
CR4	0.333	0.333	0.25	1	1	0.080
CR5	0.5	0.333	0.2	1	1	0.080
					Inconsistency	16.95%

Therefore, the authors fixed the inconsistency by modifying the eigenvector corresponding to λ_{max} [82]. As a result, the new consistency ratio is reduced to 2.94%, as shown in Table 4-2. Also, we observe that "reliability" has the highest priority among the criteria, followed by "power quality".

Table 4-2: Judgment Matrix and Global Priority for Criteria (after fixing inconsistency ratio)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1	0.167	0.2	3	2	0.123
CR2	**1.778**	1	3	3	3	0.415
CR3	5	0.333	1	4	5	0.302
CR4	0.333	0.333	0.25	1	1	0.080
CR5	0.5	0.333	0.2	1	1	0.080
					Inconsistency	2.94%

4.4.2 Alternatives

The next step is to compare all the alternatives with respect to each criterion. Table 4-3 shows a comparison between alternatives with respect to the CR1, "cost".

Table 4-3: Judgment Matrix for Alternatives with respect to CR1, i.e., Cost (before fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	8.000	9.000	9.000	0.676
CI	0.125	1.000	5.000	4.000	0.190
EHT	0.111	0.200	1.000	3.000	0.086
DG	0.111	0.250	0.333	1.000	0.047
				Inconsistency	28.14%

Table 4-4: Judgment Matrix for Alternatives with respect to CR1, i.e., Cost (after fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	8.000	**1.149**	9.000	0.676
CI	0.125	1.000	5.000	4.000	0.190
EHT	0.111	0.200	1.000	3.000	0.086
DG	0.111	0.250	0.333	1.000	0.047
				Inconsistency	5.08%

Table 4-4 illustrates that the inconsistency ratio is reduced from 28.14% to 5.08%. "Energy consumption" has the highest priority among the alternatives with respect to cost. The result is not surprising since energy consumption requires operating cost.

Table 4-5: Judgment Matrix for Alternatives with respect to CR2, i.e., Reliability (before fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	6.000	8.000	9.000	0.639
CI	0.167	1.000	8.000	4.000	0.233
EHT	0.125	0.125	1.000	0.333	0.045
DG	0.111	0.250	3.000	1.000	0.083
				Inconsistency	23.78%

When the alternatives are examined against reliability, "energy consumption" has the highest followed by "communication and intelligence" as presented in Table 4-6. The inconsistency ratio is also reduced using the technique described in [82] from 23.78%, as illustrated in Table 4-5, to 1.12%.

Table 4-6: Judgment Matrix for Alternatives with respect to CR2, i.e., Reliability (after fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	6.000	8.000	**1.171**	0.638
CI	0.167	1.000	8.000	4.000	0.233
EHT	0.125	0.125	1.000	0.333	0.044
DG	0.111	0.250	3.000	1.000	0.083
				Inconsistency	1.12%

Table 4-7: Judgment Matrix for Alternatives with respect to CR3, i.e., Power Quality (before fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	0.167	2.000	5.000	0.192
CI	6.000	1.000	6.000	6.000	0.617
EHT	0.500	0.167	1.000	4.000	0.134
DG	0.200	0.167	0.250	1.000	0.057
				Inconsistency	18.50%

Table 4-7 illustrates the normalized weight for each alternative with respect to "power quality". From Table 4-8, with respect to "power quality", "communication and intelligence" has the highest priority (0.617) followed by "energy consumption" and "electrification of heating and transportation", respectively. This is reasonable since "communication and intelligence" includes smart appliances and advanced metering infrastructure. The inconsistency in this judgment matrix is corrected to 8.25% from 18.50%.

Table 4-8: Judgment Matrix for Alternatives with respect to CR3, i.e., Power Quality (after fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	0.167	2.000	5.000	0.192
CI	6.000	1.000	6.000	**0.554**	0.617
EHT	0.500	0.167	1.000	4.000	0.134
DG	0.200	0.167	0.250	1.000	0.057

Inconsistency 8.25%

Table 4-9: Judgment Matrix for Alternatives with respect to CR4, i.e., Environmental Collateral (before fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	2.000	2.000	5.000	0.389
CI	0.500	1.000	0.167	4.000	0.152
EHT	0.500	6.000	1.000	8.000	0.406
DG	0.200	0.250	0.125	1.000	0.053

Inconsistency 18.54%

Table 4-10 shows reducing the inconsistency ratio from 18.54%, from Table 4-9, to 6.18%. Almost 80% of the importance for reducing "environmental collateral" is attributed to "electrification of heating and transportation" and to "energy consumption". Electrification of heating and transportation potentially replaces the use of fossil fuels in heating or transportation; the reduction in energy consumption reduces GHG emissions, if this electricity is generated by low carbon sources.

Table 4-10: Judgment Matrix for Alternatives with respect to CR4, i.e., Environmental Collateral (after fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	2.000	2.000	5.000	0.389
CI	0.500	1.000	0.167	4.000	0.152
EHT	0.500	6.000	1.000	**1.044**	0.406
DG	0.200	0.250	0.125	1.000	0.053

Inconsistency 6.18%

Table 4-11: Judgment Matrix for Alternatives with respect to CR5, i.e., Socio-economic Equity (before fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	5.000	8.000	6.000	0.576
CI	0.200	1.000	6.000	8.000	0.277
EHT	0.125	0.167	1.000	4.000	0.097
DG	0.167	0.125	0.250	1.000	0.050

Inconsistency 34.61%

Socio-economic equity is difficult to quantify; therefore, it is hard to make a precise judgment. Hence, the inconsistency ratio for the alternatives with respect to socio-economic equity, from Table 4-11, was 34.61%. The author successfully reduced the inconsistency ratio to 1.75%. Table 4-12 shows the “energy consumption” alternative as the most effective with respect to socio-economic equity.

Table 4-12: Judgment Matrix for Alternatives with respect to CR5, i.e., Socio-economic Equity (after fixing inconsistency ratio)

	EC	CI	EHT	DG	Priority
EC	1.000	5.000	**1.347**	6.000	0.576
CI	0.200	1.000	6.000	**1.449**	0.276
EHT	0.125	0.167	1.000	4.000	0.097
DG	0.167	0.125	0.250	1.000	0.050

Inconsistency 1.75%

4.4.3 Sub-alternatives

As explained earlier, the alternatives of the problem include sub-alternatives that propose solutions toward achieving the goal.

A. Energy consumption

As mentioned in Section 4.3, "energy consumption" contains three options: energy conservation, load side management, and electric stationary storage. Each sub-alternative is compared to each criterion to calculated local priority. Table 4-13 shows that the inconsistency ratio is 26.39%, above the acceptable limit.

Table 4-13: Judgment Matrix for Sub-alternatives with respect to CR1, i.e., Cost (before fixing inconsistency ratio)

	Energy conservation	Load side management	Stationary storage	Priority
Energy conservation	1.000	6.000	9.000	0.717
Load side management	0.167	1.000	7.000	0.227
Stationary storage	0.111	0.143	1.000	0.055

Inconsistency 36.39%

We successfully reduced the inconsistency ratio to 1.18% by fixing the comparison between "energy conservation" and "stationary storage". Table 4-14 presents the judgment matrix after obtaining the new inconsistency ratio.

Table 4-14: Judgment Matrix for Sub-alternatives with respect to CR1, i.e., Cost (after fixing inconsistency ratio)

	Energy conservation	Load side management	Stationary storage	Priority
Energy conservation	1.000	6.000	**0.690**	0.717
Load side management	0.167	1.000	7.000	0.227
Stationary storage	0.111	0.143	1.000	0.055

Inconsistency 36.39%

Table 4-15 and Table 4-16 demonstrate that the inconsistency related to "energy consumption" is below the acceptable limit 10%. It is 4.03% with respect to reliability and 3.84% when compared to power quality.

Table 4-15: Judgment Matrix for Sub-alternatives with respect to CR2, i.e., Reliability

	Energy conservation	Load side management	Stationary storage	Priority
Energy conservation	1.000	0.250	0.143	0.080
Load side management	4.000	1.000	0.333	0.265
Stationary storage	7.000	3.000	1.000	0.656

Inconsistency 4.03%

Table 4-16: Judgment Matrix for Sub-alternatives with respect to CR3, i.e., Power Quality

	Energy conservation	Load side management	Stationary storage	Priority
Energy conservation	1.000	0.111	0.200	0.070
Load side management	9.000	1.000	1.000	0.510
Stationary storage	5.000	1.000	1.000	0.420

Inconsistency 3.84%

As environmental collateral is an important factor to minimize GHG emissions, the comparison overestimates "energy conservation" and "load side management" against "stationary storage". The results are inconsistent by about 60.26% in that judgment as shown in Table 4-17.

Table 4-17: Judgment Matrix for Sub-alternatives with respect to CR4, i.e., Environmental Collateral (before fixing inconsistency ratio)

	Energy conservation	Load side management	Stationary storage	Priority
Energy conservation	1.000	7.000	9.000	0.711
Load side management	0.143	1.000	9.000	0.237
Stationary storage	0.111	0.111	1.000	0.052

Inconsistency 60.26%

However, the inconsistency ratio successfully reduced to 0% by modifying the eigenvector corresponding to λ_{max} of "stationary storage". Table 4-18 illustrates judgment matrix after the new inconsistency.

Table 4-18: Judgment Matrix for Sub-alternatives with respect to CR4, i.e., Environmental Collateral (after fixing inconsistency ratio)

	Energy conservation	Load side management	Stationary storage	Priority
Energy conservation	1.000	7.000	**0.646**	0.711
Load side management	0.143	1.000	**1.937**	0.237
Stationary storage	0.111	0.111	1.000	0.051

Inconsistency 0%

Socio-economic equity is a difficult factor that measures the effectiveness of "energy consumption" in reducing GHG emissions. The results obtained in Table 4-19 show the we are 5.87% above the limit.

Table 4-19: Judgment Matrix for Sub-alternatives with respect to CR5, i.e., Socioeconomic Equity (before fixing inconsistency ratio)

	Energy conservation	Load side management	Stationary storage	Priority
Energy conservation	1.000	5.000	7.000	0.709
Load side management	0.200	1.000	4.000	0.214
Stationary storage	0.143	0.250	1.000	0.077

Inconsistency	15.87%

The inconsistency ratio is reduced to 0.42% by affecting the judgment between "load side management" and stationary storage". Table 4-20 explains the change in the judgment matrix that results a reduction in the inconsistency.

Table 4-20: Judgment Matrix for Sub-alternatives with respect to CR5, i.e., Socioeconomic Equity (after fixing inconsistency ratio)

	Energy conservation	Load side management	Stationary storage	Priority
Energy conservation	1.000	5.000	7.000	0.709
Load side management	0.200	1.000	**1.421**	0.214
Stationary storage	0.143	0.250	1.000	0.076

Inconsistency	0.42%

The global priority of a sub-alternative is calculated by multiplying its local priority by the respective alternative. Table 4-21 demonstrates that "energy conservation" is the highest preferred option with respect to cost. Also, load side management is the suitable option for both reliability and power quality. For environmental collateral and socio-economic equity, we observe that energy conservation is the highest-ranked sub-alternative.

Table 4-21: Local Priority and Global Priority for Energy Consumption with respect to Each Criterion

Criterion		Local priority	Global priority
CR1	Energy conservation	0.717	0.060
	Load side management	0.227	0.019
	Stationary storage	0.055	0.005
CR2	Energy conservation	0.080	0.021
	Load side management	0.265	0.070
	Stationary storage	0.655	0.173
CR3	Energy conservation	0.070	0.004
	Load side management	0.510	0.030
	Stationary storage	0.420	0.024
CR4	Energy conservation	0.711	0.022
	Load side management	0.237	0.007
	Stationary storage	0.051	0.002
CR5	Energy conservation	0.709	0.033
	Load side management	0.214	0.010
	Stationary storage	0.076	0.004

Further, “energy conservation” is the first most important option toward achieving the goal. It consists of three options; efficient appliances, efficient buildings, and behavior. Therefore, we constructed a pairwise comparison between the considered solutions under “energy conservation”. Table 4-22 shows that the inconsistency ratio for those options violates the 10% limit.

Table 4-22: Judgment Matrix for Alternatives under Energy Conservation with respect to CR1, i.e., Cost (before fixing inconsistency ratio)

	Efficient appliances	Efficient buildings	Behavior	Priority
Efficient appliances	1.000	4.000	0.167	0.191
Efficient buildings	0.250	1.000	0.125	0.069
Behavior	6.000	8.000	1.000	0.739

Inconsistency 17.90%

The inconsistency is successfully reduced to 4.55% as shown in Table 4-23.

Table 4-23: Judgment Matrix for Alternatives under Energy Conservation with respect to CR1, i.e., Cost (after fixing inconsistency ratio)

	Efficient appliances	Efficient buildings	Behavior	Priority
Efficient appliances	1.000	**1.445**	0.167	0.191
Efficient buildings	0.250	1.000	0.125	0.069
Behavior	6.000	8.000	1.000	0.739

Inconsistency 4.55%

The weighted matrix for the previously mentioned options is constructed and illustrated in Table 4-24.

Table 4-24: Judgment Matrix for Alternatives under Energy Conservation with respect to CR2, i.e., Reliability

	Efficient appliances	Efficient buildings	Behavior	Priority
Efficient appliances	1.000	1.000	0.200	0.131
Efficient buildings	1.000	1.000	0.125	0.112
Behavior	5.000	8.000	1.000	0.756

Inconsistency 2.93%

Table 4-25 presents that the judgment matrix for power quality contains inconsistence comparison as the inconsistency was 17.98%.

Table 4-25: Judgment Matrix for Alternatives under Energy Conservation with respect to CR3, i.e., Power Quality (before fixing inconsistency ratio)

	Efficient appliances	Efficient buildings	Behavior	Priority
Efficient appliances	1.000	6.000	4.000	0.658
Efficient buildings	0.167	1.000	0.200	0.079
Behavior	0.250	5.000	1.000	0.261

Inconsistency 17.98%

The inconsistency ratio is corrected after modifying eigenvector corresponding to "behavior" against "efficient appliances" as demonstrated in Table 4-26.

Table 4-26: Judgment Matrix for Alternatives under Energy Conservation with respect to CR3, i.e., Power Quality (after fixing inconsistency ratio)

	Efficient appliances	Efficient buildings	Behavior	Priority
Efficient appliances	1.000	6.000	4.000	0.658
Efficient buildings	0.167	1.000	0.200	0.079
Behavior	0.250	**1.513**	1.000	0.261

Inconsistency 2.88%

The normalized comparison with respect to environmental collateral in Table 4-27 shows an increase by about 10% above the permissible limit for inconsistency. Therefore, Table 4-28 explains that the best reduction in the inconsistency was 10%.

Table 4-27: Judgment Matrix for Alternatives under Energy Conservation with respect to CR4, i.e., Environmental Collateral (before fixing inconsistency ratio)

	Efficient appliances	Efficient buildings	Behavior	Priority
Efficient appliances	1.000	0.333	0.125	0.073
Efficient buildings	3.000	1.000	0.125	0.152
Behavior	8.000	8.000	1.000	0.774
			Inconsistency	20%

Table 4-28: Judgment Matrix for Alternatives under Energy Conservation with respect to CR4, i.e., Environmental Collateral (after fixing inconsistency ratio)

	Efficient appliances	Efficient buildings	Behavior	Priority
Efficient appliances	1.000	0.333	0.125	0.073
Efficient buildings	3.000	1.000	**0.637**	0.152
Behavior	**0.755**	8.000	1.000	0.774
			Inconsistency	10%

The last matrix has been generated to compare the three-option of "energy conservation" with respect to CR5. i.e, Socio-economic equity. Table 4-29 shows the weighted matrix for this comparison.

Table 4-29: Judgment Matrix for Alternatives under Energy Conservation with respect to CR5, i.e., Socio-economic Equity

	Efficient appliances	Efficient buildings	Behavior	Priority
Efficient appliances	1.000	1.544	0.250	0.267
Efficient buildings	0.167	1.000	0.143	0.069
Behavior	4.000	7.000	1.000	0.664
			Inconsistency	3.03%

Table 4-30 demonstrates the weight for each alternative under "energy conservation". The result shows that educational programs are the best way to reduce energy use followed by efficient appliances and efficient buildings.

Table 4-30: Energy Conservation Final Prioritization

	Priority	Ranking
Behavior	0.100	1
Efficient appliances	0.027	2
Efficient buildings	0.012	3

B. Communication and intelligence

The judgment matrix is constructed for the communication and intelligence alternative. As mentioned in Section 4.3, this alternative includes Internet of Things (Iot), smart meters and Advanced Metering Infrastructure (AMI), real-time pricing, and smart appliances. The framework compares all sub-alternatives to evaluate the best option under "communication and intelligence". Table 4-31 illustrates the first comparison under "communication and intelligence" with a 21.85% inconsistency.

Table 4-31: Judgment Matrix for Sub-alternatives with respect to CR1, i.e., Cost (before fixing inconsistency ratio)

	Iot	Smart meters & AMI	Real-time pricing	Smart appliances	Priority
Iot	1.000	0.200	1.000	0.333	0.118
Smart meters & AMI	5.000	1.000	1.000	0.200	0.228
Real-time pricing	1.000	1.000	1.000	0.333	0.146
Smart appliances	3.000	5.000	3.000	1.000	0.508
				Inconsistency	21.85%

This violation has been solved after fixing cost estimation between smart appliances and smart meters and AMI as shown in Table 4-32.

Table 4-32: Judgment Matrix for Sub-alternatives with respect to CR1, i.e., Cost (after fixing inconsistency ratio)

	Iot	Smart meters & AMI	Real-time pricing	Smart appliances	Priority
Iot	1.000	0.200	1.000	0.333	0.118
Smart meters & AMI	5.000	1.000	1.000	0.200	0.228
Real-time pricing	1.000	1.000	1.000	0.333	0.146
Smart appliances	3.000	2.249	3.000	1.000	0.508
				Inconsistency	0.54%

With respect to CR2, Reliability, the decision maker was consistence during the pairwise comparison process as illustrated in Table 4-33.

Table 4-33: Judgment Matrix for Sub-alternatives with respect to CR1, i.e., Reliability

	Iot	Smart meters & AMI	Real-time pricing	Smart appliances	Priority
Iot	1.000	0.500	0.250	2.000	0.147
Smart meters & AMI	2.000	1.000	2.000	5.000	0.421
Real-time pricing	4.000	0.500	1.000	5.000	0.359
Smart appliances	0.500	0.200	0.200	1.000	0.073
				Inconsistency	7.27%

A 22.52% increase in the inconsistency limit was observed when the potions under "communication and intelligence" were compared with respect to CR3, Power quality. Table 4-34 denotes to the inconsistency.

Table 4-34: Judgment Matrix for Sub-alternatives with respect to CR3, i.e., Power Quality (before fixing inconsistency ratio)

	Iot	Smart meters & AMI	Real-time pricing	Smart appliances	Priority
Iot	1.000	0.167	0.200	3.000	0.099
Smart meters & AMI	6.000	1.000	6.000	6.000	0.581
Real-time pricing	5.000	0.167	1.000	7.000	0.266
Smart appliances	0.333	0.167	0.143	1.000	0.054
				Inconsistency	32.52%

The inconsistency was solved by fixing the comparison between smart meters and AMI and real-time pricing. The new inconsistency was reduced by 29.21% as shown in Table 4-35.

Table 4-35: Judgment Matrix for Sub-alternatives with respect to CR3, i.e., Power Quality (after fixing inconsistency ratio)

	Iot	Smart meters & AMI	Real-time pricing	Smart appliances	Priority
Iot	1.000	0.167	0.200	3.000	0.099
Smart meters & AMI	6.000	1.000	**2.747**	6.000	0.581
Real-time pricing	5.000	0.167	1.000	7.000	0.266
Smart appliances	0.333	0.167	0.143	1.000	0.054
				Inconsistency	3.31%

The decision maker was consistent when those local alternatives are compared. Table 4-36 tells that the inconsistency was 2.99% below the maximum limit.

Table 4-36: Judgment Matrix for Sub-alternatives with respect to CR4, i.e., Environmental Collateral

	Iot	Smart meters & AMI	Real-time pricing	Smart appliances	Priority
Iot	1.000	2.000	0.333	0.500	0.150
Smart meters & AMI	0.500	1.000	0.250	0.200	0.083
Real-time pricing	3.000	4.000	1.000	3.000	0.488
Smart appliances	2.000	5.000	0.333	1.000	0.277
				Inconsistency	7.01%

CR5, Socio-economic equity, leads the decision maker to be inconsistence by more than 25%. The relationship between smart meters and AMI and real-time pricing caused this violation in the inconsistency as explained in Table 4-37.

Table 4-37: Judgment Matrix for Sub-alternatives with respect to CR5, i.e., Socio-economic Equity (before fixing inconsistency ratio)

	Iot	Smart meters & AMI	Real-time pricing	Smart appliances	Priority
Iot	1.000	0.167	0.200	1.000	0.096
Smart meters & AMI	6.000	1.000	4.000	3.000	0.501
Real-time pricing	5.000	0.250	1.000	0.200	0.166
Smart appliances	1.000	0.333	5.000	1.000	0.237
				Inconsistency	35.43%

Therefore, the inconsistency ratio was reduced to 7.35% by modifying the largest eigenvector, in Table 4-38.

Table 4-38: Judgment Matrix for Sub-alternatives with respect to CR5, i.e., Socio-economic Equity (after fixing inconsistency ratio)

	Iot	Smart meters & AMI	Real-time pricing	Smart appliances	Priority
Iot	1.000	0.167	0.200	1.000	0.096
Smart meters & AMI	6.000	1.000	**1.325**	3.000	0.501
Real-time pricing	5.000	0.250	1.000	0.200	0.166
Smart appliances	1.000	0.333	5.000	1.000	0.237
				Inconsistency	7.35%

Final prioritization for a sub-alternative is calculated by multiplying its local priority by the respective alternative. Table 4-39 demonstrates that "smart appliances" is the highest preferred option with respect to cost. Also, smart meters & AMI is the suitable option for both reliability, power quality, and socio-economic equity. For environmental collateral, we observe that real-time pricing is the highest-ranked sub-alternative.

Table 4-39: Local Priority and Global Priority for Communication and Intelligence with respect to Each Criterion

Criterion		Local priority	Global priority
CR1	Iot	0.118	0.003
	Smart meters & AMI	0.228	0.005
	Real-time pricing	0.146	0.003
	Smart appliances	0.507	0.012
CR2	Iot	0.146	0.014
	Smart meters & AMI	0.421	0.041
	Real-time pricing	0.359	0.035
	Smart appliances	0.073	0.007
CR3	Iot	0.099	0.018
	Smart meters & AMI	0.581	0.108
	Real-time pricing	0.266	0.050
	Smart appliances	0.054	0.010
CR4	Iot	0.150	0.002
	Smart meters & AMI	0.083	0.001
	Real-time pricing	0.488	0.006
	Smart appliances	0.277	0.003
CR5	Iot	0.096	0.002
	Smart meters & AMI	0.501	0.011
	Real-time pricing	0.166	0.004
	Smart appliances	0.237	0.005

C. Electrification of heating and transportation

The judgment matrix is constructed for the electrification of heating and transportation alternative. This alternative contains three alternatives: geo-exchange heat pump, electric water heater, and electric vehicles as grid to vehicle capability. Each sub-alternative is compared to each criterion in order to determine local priority. When we constructed a judgment matrix for the options under "electrification of heating and transportation" against "cost", the inconsistency ratio was 123.17%. Table 4-40 illustrates the judgment matrix before fixing the inconsistency ratio.

Table 4-40: Judgment Matrix for Sub-alternatives with respect to CR1, i.e., Cost (before fixing inconsistency ratio)

	Geo-exchange heat pump	Electric water heater	Electric vehicles	Priority
Geo-exchange heat pump	1.000	1.000	0.111	0.182
Electric water heater	1.000	1.000	3.000	0.416
Electric vehicles	9.000	0.333	1.000	0.401

Inconsistency 123.17%

We tried to reduce the inconsistency, but the best potential minimization for the inconsistency was 13.59%, as demonstrated in Table 4-41, which is higher than 10%.

Table 4-41: Judgment Matrix for Sub-alternatives with respect to CR1, i.e., Cost (after fixing inconsistency ratio)

	Geo-exchange heat pump	Electric water heater	Electric vehicles	Priority
Geo-exchange heat pump	1.000	0.143	0.333	0.082
Electric water heater	7.000	1.000	6.000	0.739
Electric vehicles	3.000	0.167	1.000	0.179

Inconsistency 13.59%

The judgment matrix in Table 4-42 shows the decision maker were not precisely comparing the three-option of "electrification of heating and transportation". However, the inconsistency was reduced after revisiting the compared objects as demonstrated in Table 4-43.

Table 4-42: Judgment Matrix for Sub-alternatives with respect to CR2, i.e., Reliability (before fixing inconsistency ratio)

	Geo-exchange heat pump	Electric water heater	Electric vehicles	Priority
Geo-exchange heat pump	1.000	0.167	0.500	0.098
Electric water heater	6.000	1.000	8.000	0.761
Electric vehicles	2.000	0.125	1.000	0.141

Inconsistency 15.51%

Table 4-43: Judgment Matrix for Sub-alternatives with respect to CR2, i.e., Reliability (after fixing inconsistency ratio)

	Geo-exchange heat pump	Electric water heater	Electric vehicles	Priority
Geo-exchange heat pump	1.000	0.167	0.500	0.098
Electric water heater	6.000	1.000	8.000	0.761
Electric vehicles	**1.390**	0.125	1.000	0.141

Inconsistency 10.96%

Power quality is an important criterion when we construct a pairwise comparison for the electrification of heating and transportation alternative. In Table 4-44, inconsistency is below 10%.

Table 4-44: Judgment Matrix for Sub-alternatives with respect to CR3, i.e., Power Quality

	Geo-exchange heat pump	Electric water heater	Electric vehicles	Priority
Geo-exchange heat pump	1.000	0.333	2.000	0.252
Electric water heater	3.000	1.000	3.000	0.589
Electric vehicles	0.500	0.333	1.000	0.159

Inconsistency 5.33%

As "environmental collateral" is an essential factor to quantify GHG reduction. Therefore, a 11.76% inconsistency ratio, in Table 4-45, was not acceptable during comparing the options of "electrification of heating and transportation.

Table 4-45: Judgment Matrix for Sub-alternatives with respect to CR4, i.e., Environmental Collateral (before fixing inconsistency ratio)

	Geo-exchange heat pump	Electric water heater	Electric vehicles	Priority
Geo-exchange heat pump	1.000	0.143	3.000	0.155
Electric water heater	7.000	1.000	9.000	0.777
Electric vehicles	0.333	0.111	1.000	0.069

Inconsistency 11.76%

Hence, we fixed the relationship between geo-exchange heat pump and electric vehicles to reduce the inconsistency to 2.69% as illustrated in Table 4-46.

Table 4-46: Judgment Matrix for Sub-alternatives with respect to CR4, i.e., Environmental Collateral (after fixing inconsistency ratio)

	Geo-exchange heat pump	Electric water heater	Electric vehicles	Priority
Geo-exchange heat pump	1.000	0.143	**1.316**	0.155
Electric water heater	7.000	1.000	9.000	0.777
Electric vehicles	0.333	0.111	1.000	0.069

Inconsistency 2.69%

Moreover, the pairwise comparison in Table 4-47 shows a spike increase in the inconsistency ratio with reference to "socio-economic equity". However, a reduction by more than 30% was successfully achieved as demonstrated in Table 4-48.

Table 4-47: Judgment Matrix for Sub-alternatives with respect to CR5, i.e., Socio-economic Equity (before fixing inconsistency ratio)

	Geo-exchange heat pump	Electric water heater	Electric vehicles	Priority
Geo-exchange heat pump	1.000	0.200	0.250	0.094
Electric water heater	5.000	1.000	6.000	0.686
Electric vehicles	4.000	0.167	1.000	0.220

Inconsistency 35.52%

Table 4-48: Judgment Matrix for Sub-alternatives with respect to CR5, i.e., Socio-economic Equity (after fixing inconsistency ratio)

	Geo-exchange heat pump	Electric water heater	Electric vehicles	Priority
Geo-exchange heat pump	1.000	0.200	0.250	0.094
Electric water heater	**0.685**	1.000	6.000	0.686
Electric vehicles	4.000	0.167	1.000	0.220

Inconsistency 5.07%

The results obtained in Table 4-49 show that electric water heater is superior to the other sub-alternatives. The electric vehicles option is the second-ranked solution with respect to the criteria, except for power quality.

Table 4-49: Local Priority and Global Priority for Electrification of Heating and Transportation with respect to Each Criterion

		Local priority	Global priority
CR1	Geo-exchange heat pump	0.082	0.001
	Electric water heater	0.739	0.008
	Electric vehicles	0.179	0.002
CR2	Geo-exchange heat pump	0.098	0.002
	Electric water heater	0.761	0.014
	Electric vehicles	0.141	0.003
CR3	Geo-exchange heat pump	0.252	0.010
	Electric water heater	0.589	0.024
	Electric vehicles	0.159	0.006
CR4	Geo-exchange heat pump	0.155	0.005
	Electric water heater	0.777	0.025
	Electric vehicles	0.068	0.002
CR5	Geo-exchange heat pump	0.094	0.001
	Electric water heater	0.686	0.005
	Electric vehicles	0.220	0.002

D. DG

The last alternative is “DG”. This alternative consists of two solutions apropos distribution systems, i.e., solar PV and combustion generation. Solar PV can be either individual installations at an end user or an aggregated installation such as a community share facility. The authors consider combustion generation as two categories only: power and CHP installations. As mentioned in Section 4.2, inconsistency ratio is applied when is are more than two alternatives. Thus, the inconsistency ratio is not calculated for the options of “DG”. The results in Tables from 4-50 to 4-54 show the judgment matrixes for the DG alternatives with respect to each criterion.

Table 4-50: Judgment Matrix for Sub-alternatives with respect to CR1, i.e., Cost

	Solar PV	Combustion generation	Priority
Solar PV	1	6.00	0.857
Combustion generation	0.167	1	0.143

Table 4-51: Judgment Matrix for Sub-alternatives with respect to CR2, i.e., Reliability

	Solar PV	Combustion generation	Priority
Solar PV	1	0.14	0.125
Combustion generation	7	1	0.875

Table 4-52: Judgment Matrix for Sub-alternatives with respect to CR3, i.e., Power Quality

	Solar PV	Combustion generation	Priority
Solar PV	1.000	3.000	0.750
Combustion generation	0.333	1.000	0.250

Table 4-53: Judgment Matrix for Sub-alternatives with respect to CR4, i.e. Environmental Collateral

	Solar PV	Combustion generation	Priority
Solar PV	1.000	9.000	0.900
Combustion generation	0.111	1.000	0.100

Table 4-54: Judgment Matrix for Sub-alternatives with respect to CR5, i.e., Socio-economic Equity

	Solar PV	Combustion generation	Priority
Solar PV	1.000	5.000	0.833
Combustion generation	0.200	1.000	0.167

The results are not surprising since solar PV is more important in terms of cost while combustion generation is preferable when it comes to reliability. Table 4-55 presents the local priorities and global priorities for the previous mentioned options with respect to each criterion.

Table 4-55: Local Priority and Global Priority for DG with respect to Each Criterion

Criterion		Local priority	Global priority
CR1	Solar PV	0.857	0.005
	Combustion generation	0.143	0.001
CR2	Solar PV	0.125	0.004
	Combustion generation	0.875	0.030
CR3	Solar PV	0.750	0.013
	Combustion generation	0.250	0.004
CR4	Solar PV	0.900	0.004
	Combustion generation	0.100	0.000
CR5	Solar PV	0.833	0.003
	Combustion generation	0.167	0.001

4.4.4 Final prioritization

As mentioned in section 4.2, the last step in AHP is to calculate the overall rank of the alternatives to arrive at the final prioritization. Global priorities are calculated for each alternative and each sub-alternative to obtain the total weight of the respective solution. The option with the highest priority is the most optimal alternative for achieving the goal. Table 4-56 shows final prioritization for each alternative and the overall ranking, and the difference between the options. The reason for calculating the differences between the alternatives is to trim down the options for further evaluation.

From Table 4-56, “communication and intelligence” is the most important alternative in reducing GHG in the distribution system. The second alternative is “electric stationary storage” followed by “energy conservation", and "load side management". Electric stationary storage has the second highest importance because it enables greater utilization of variable renewable generating sources, both those on the distribution system and those from the bulk generation provider, and for its contribution to reliability.

Table 4-56: Final Prioritization Using AHP

	Global priority	Overall ranking	Difference
Communication and intelligence	0.341	1	0.133
Electric stationary storage	0.207	2	0.068
Energy conservation	0.140	3	0.004
Load side management	0.136	4	0.060
Electric water heater	0.076	5	0.040
Combustion generation	0.036	6	0.007
Solar PV	0.029	7	0.011
Geo-exchange heat pump	0.019	8	0.004
Electric vehicles	0.015	9	

4.5 Conclusion

The paper presents a framework of AHP to analyze and investigate the potential DSM solution to reduce GHG emissions from an electric distribution system. The results suggest that "communication and intelligence" technologies are the most important to achieve the goal. As mentioned in Chapter 1, AHP aims to find the most important alternative in achieving the goal. AHP evaluates the decision elements in a hierarchical way with ignoring the impact of alternatives on the weight of criteria. Therefore, final ranking might be affected, overestimating or underestimating criteria or alternatives, with such a complex problem. In that regard, ANP in another model in MCDM that allows interdependencies, outerdependencies and feedbacks connections among decision elements in the network structure to effectively rank alternatives.

CHAPTER 5

ANALYTIC NETWORK PROCESS ALGORITHM TO PRIORITIZE DEMAND SIDE MANAGEMENT ALTERNATIVES[4]

5.1 Introduction

This chapter presents a general overview regarding ANP. It defines ANP and describes general steps to calculate final prioritization by means of ANP. After that, ANP DSM-based problem is constructed to obtain important available option in reducing carbon footprint. Analysis and observations are discussed at the end of this chapter.

5.2 ANP

ANP is an MCDM method that is a generalization of the AHP. In detail, ANP is used to help make decisions in complex problems where a hierarchical model is not sufficient for prioritizing the alternative [24]. Key features of ANP are feedback connections and loops and providing interdependence relationships. The ANP structure is organized as nodes in a network, where the nodes might be criteria, sub-criteria, alternatives, or sub-alternatives. Hence, the ranking of alternatives might not depend on the weight of the criteria, but the alternatives can influence final prioritization [83, 84].

Solving a problem based on ANP requires a network modularization of the problem and weighting of the elements. Modeling any ANP problem as a network starts by identifying the elements of the network, criteria, and alternatives. Next step is to group the elements into clusters and analyzing the specific influence within the network. After that, ANP can obtain final ranking by the following six steps [83-85];

A. Calculating the priorities among criteria and alternatives
B. Calculating the priorities among the nodes
C. Building the original supermatrix that includes all nodes, criteria, sub-criteria, alternatives, or sub-alternatives

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[4] Part of this chapter is verbatim reproduced from [36], and it is under review in the Utilities Policy Journal at the time of writing this dissertation

D. Normalizing the unweighted supermatrix after finalizing all comparisons

E. Calculating the limit supermatrix by raising the normalized supermatrix to powers until it converges

F. Obtaining final prioritization of the alternatives

Table 5-1: Original Supermatrix [73]

		Criteria			Alternatives		
	Goal	CR1	CR2	CR3	Alternative 1	Alternative 2	Alternative 3
Goal							
CR1					🟧	🟧	🟧
CR2					🟧	🟧	🟧
CR3					🟧	🟧	🟧
Alternative 1		🟩	🟩	🟩			
Alternative 2		🟩	🟩	🟩			
Alternative 3		🟩	🟩	🟩			

ANP is more flexible than AHP, making the model closer to reality and promising more precise results. However, ANP requires more calculations and time due to its complexity [24, 86].

5.3 Problem framework

As mentioned in the previous section, ANP provides feedback and interdependence relationships. Network connection helps in prioritizing criteria with considering alternatives. This means a judgment matrix is constructed for criteria with respect to each alternative. Final ranking of criteria could be changed by asking how important they are if the alternatives being considered, the decision maker learn from feedback. Figure 5-1 illustrates network structure for our example where interdependence relationship is considered. In this figure, “energy conservation”, “load side management”, and “electric stationary storage” are options under “energy consumption”. Further, “geo-exchange heat pump”, “electric water heater”, and “electric vehicles” are under “electrification of heating and transportation” while “DG” contains “PVs” and “combustion generation”.

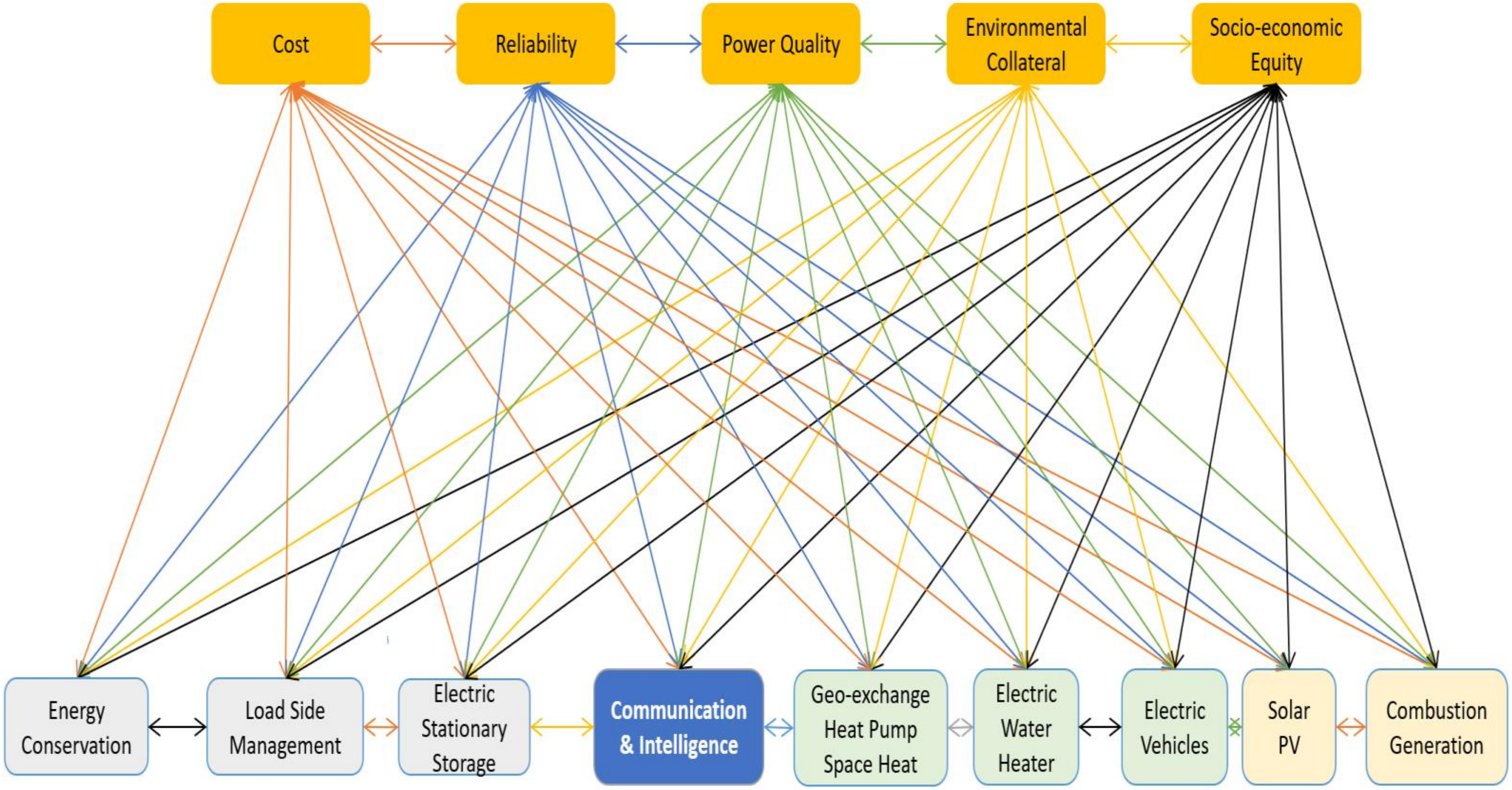

Figure 5-1: Network Structure for ANP Problem

5.4 Analysis and results

As has been done in the previous chapter, all alternatives are compared with respect to each criterion. However, ANP aims to study the importance of each criterion with respect to each alternative. This could strengthen or weaknesses the importance of that criterion based on its relationship with that alternative. In that regard, pairwise comparisons are conducted for criteria with reference to each alternative. The impact of alternatives on criteria is evaluated by the same expert who completed the AHP survey. Table 5-2 shows a judgment matrix for criteria with respect to "energy conservation" before fixing the inconsistency.

Table 5-2: Judgment Matrix for Criteria with respect to Energy Conservation (before fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	0.250	0.500	3.000	6.000	0.178
CR2	4.000	1.000	3.000	7.000	3.000	0.430
CR3	2.000	0.333	1.000	6.000	5.000	0.247
CR4	0.333	0.143	0.167	1.000	0.200	0.041
CR5	0.167	0.333	0.200	5.000	1.000	0.104

Inconsistency 19.05%

Therefore, we follow the same steps to fix the inconsistency as shown in Table 5-3. We observe that CR2, reliability, is the most suitable criterion in present of "energy conservation".

Table 5-3: Judgment Matrix for Criteria with respect to Energy Conservation (after fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	0.250	0.500	3.000	**3.506**	0.178
CR2	4.000	1.000	3.000	7.000	3.000	0.430
CR3	2.000	0.333	1.000	6.000	**2.105**	0.247
CR4	0.333	0.143	0.167	1.000	0.200	0.041
CR5	0.167	0.333	0.200	5.000	1.000	0.104

Inconsistency 7.26%

Inconsistent comparisons caused about 10% violation when criteria compared to “load side management” as illustrated in Table 5-4.

Table 5-4: Judgment Matrix for Criteria with respect to Load Side Management (before fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	0.250	0.250	5.000	5.000	0.169
CR2	4.000	1.000	4.000	7.000	6.000	0.476
CR3	4.000	0.250	1.000	5.000	3.000	0.232
CR4	0.200	0.143	0.200	1.000	0.250	0.039
CR5	0.200	0.167	0.333	4.000	1.000	0.084

Inconsistency 19.58%

However, more than a 15% reduction were successfully achieved by modifying maximum eigenvector vectors. The findings show that priority of reliability will increase by considering “load side management” as explained in Table 5-5.

Table 5-5: Judgment Matrix for Criteria with respect to Load Side Management (before fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	0.250	0.250	5.000	**2.485**	0.169
CR2	4.000	1.000	**1.950**	7.000	6.000	0.476
CR3	4.000	0.250	1.000	5.000	3.000	0.232
CR4	0.200	0.143	0.200	1.000	0.250	0.039
CR5	0.200	0.167	0.333	4.000	1.000	0.084

Inconsistency 5.13%

Further, the decision maker was not accurate in comparing CR1, Cost, against CR5, Socio-economic equity, with respect to “electric stationary storage”. This results a higher limit in the inconsistency ratio by more than 5% as denoted in Table 5-6. Thus, the inconsistency was reduced from 15.52% to 8.43% and CR1, Cost, is superior among other criteria.

Table 5-6: Judgment Matrix for Criteria with respect to Electric Stationary Storage (before fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	6.000	6.000	5.000	3.000	0.471
CR2	0.167	1.000	1.000	0.333	0.250	0.061
CR3	0.167	1.000	1.000	3.000	0.167	0.094
CR4	0.200	3.000	0.333	1.000	0.200	0.089
CR5	0.333	4.000	6.000	5.000	1.000	0.286
					Inconsistency	15.52%

Table 5-7: Judgment Matrix for Criteria with respect to Electric Stationary Storage (after fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	6.000	6.000	5.000	**1.822**	0.471
CR2	0.167	1.000	1.000	0.333	0.250	0.061
CR3	0.167	1.000	1.000	3.000	0.167	0.094
CR4	0.200	3.000	0.333	1.000	0.200	0.089
CR5	0.333	4.000	6.000	5.000	1.000	0.286
					Inconsistency	8.43%

“communication and intelligence” option contains four options as mentioned in section 4.3. One of the most challenges is how to quantify those options in reducing GHG. Hence, this leads to inaccurate estimation for criteria with respect to that alternative and in turn cause a spike increase in the inconsistency as shown in Table 5-8. Therefore, four comparisons are fixed in order to maintain the inconsistency below 10%.

Table 5-8: Judgment Matrix for Criteria with respect to Communication and Intelligence (before fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	7.000	4.000	9.000	0.333	0.334
CR2	0.143	1.000	3.000	9.000	1.000	0.203
CR3	0.250	0.333	1.000	8.000	0.200	0.098
CR4	0.111	0.111	0.125	1.000	0.200	0.030
CR5	3.000	1.000	5.000	5.000	1.000	0.335

Inconsistency 33.32%

Table 5-9: Judgment Matrix for Criteria with respect to Communication and Intelligence (after fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	**4.254**	4.000	9.000	0.333	0.334
CR2	0.143	1.000	3.000	**1.330**	1.000	0.203
CR3	0.250	0.333	1.000	**2.449**	0.200	0.098
CR4	0.111	0.111	0.125	1.000	0.200	0.030
CR5	3.000	1.000	**1.463**	5.000	1.000	0.335

Inconsistency 5.95%

A consistent judgment matrix occurred when the criteria is compared to "geo-exchange heat pump". Table 5-10 illustrates the judgment matrix. A 0.24% increase in the inconsistency is acceptable since it has no effect on the inconsistency ratio. Moreover, "electric water heater" shows a surprise increase the inconsistency. The decision maker overestimated CR1, Cost, and CR3, Power quality against CR2, Reliability and CR4, Environmental collateral, respectively. However, the inconsistency ratio was effectively reduced to 10.21 as explained in Table 5-12.

Table 5-10: Judgment Matrix for Criteria with respect to Geo-exchange Heat Pump

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	3.000	9.000	8.000	3.000	0.484
CR2	0.333	1.000	1.000	6.000	0.250	0.135
CR3	0.111	1.000	1.000	1.000	0.250	0.066
CR4	0.125	0.167	1.000	1.000	0.167	0.046
CR5	0.333	4.000	4.000	6.000	1.000	0.270

Inconsistency 10.24%

Table 5-11: Judgment Matrix for Criteria with respect to Electric Water Heater (before fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	9.000	4.000	6.000	0.333	0.342
CR2	0.111	1.000	1.000	5.000	0.333	0.115
CR3	0.250	1.000	1.000	7.000	0.333	0.139
CR4	0.167	0.200	0.143	1.000	0.333	0.051
CR5	3.000	3.000	3.000	3.000	1.000	0.353

Inconsistency 29.42%

Unlike "electric water heater", a judgment matrix for "electric vehicles" shows a consistent ratio as Table 5-13 illustrates. CR5, Socio-economic equity is the optimal criterion followed by CR1, Cost with a higher margin.

Table 5-12: Judgment Matrix for Criteria with respect to Electric Water Heater (after fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	**3.026**	4.000	6.000	0.333	0.342
CR2	0.111	1.000	1.000	5.000	0.333	0.115
CR3	0.250	1.000	1.000	**2.568**	0.333	0.139
CR4	0.167	0.200	0.143	1.000	0.333	0.051
CR5	3.000	3.000	3.000	3.000	1.000	0.353
					Inconsistency	10.21%

Table 5-13: Judgment Matrix for Criteria with respect to Electric Vehicles

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	4.000	9.000	7.000	2.000	0.487
CR2	0.250	1.000	1.000	2.000	0.333	0.104
CR3	0.111	1.000	1.000	0.250	0.250	0.059
CR4	0.143	0.500	4.000	1.000	0.333	0.099
CR5	0.500	3.000	4.000	3.000	1.000	0.252
					Inconsistency	8.07%

When the criteria are compared with respect to “solar PV”, the inconsistency increased to 42.60%. This requires following steps to minimize this violation or revisiting some comparisons to reduce the inconsistency. So, Table 5-15 demonstrates that the inconsistency ratio was reduced to % after modifying the largest eigenvectors.

Table 5-14: Judgment Matrix for Criteria with respect to Solar PV (before fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	6.000	9.000	0.250	4.000	0.332
CR2	0.167	1.000	0.333	0.250	0.200	0.035
CR3	0.111	3.000	1.000	0.200	0.143	0.057
CR4	4.000	4.000	5.000	1.000	0.250	0.276
CR5	0.250	5.000	7.000	4.000	1.000	0.300
					Inconsistency	42.60%

Table 5-15: Judgment Matrix for Criteria with respect to Solar PV (after fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	**0.633**	**1.545**	0.250	**3.614**	0.332
CR2	0.167	1.000	0.333	0.250	0.200	0.035
CR3	0.111	3.000	1.000	0.200	0.143	0.057
CR4	4.000	**0.507**	**1.033**	1.000	0.250	0.276
CR5	0.250	**0.583**	**1.330**	**3.680**	1.000	0.300
					Inconsistency	8.03%

Table 5-16: Judgment Matrix for Criteria with respect to Combustion Generation (before fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	0.333	3.000	0.143	2.000	0.118
CR2	3.000	1.000	6.000	0.200	4.000	0.255
CR3	0.333	0.167	1.000	0.167	0.333	0.042
CR4	7.000	5.000	6.000	1.000	1.000	0.433
CR5	0.500	0.250	3.000	1.000	1.000	0.151
					Inconsistency	26.53%

Last comparison is to compare the criteria with respect to "combustion generation". Final ranking shows CR4, Environmental collateral is the most important criterion as denoted in Table 5-17.

Table 5-17: Judgment Matrix for Criteria with respect to Combustion Generation (after fixing inconsistency)

	CR1	CR2	CR3	CR4	CR5	Priority
CR1	1.000	0.333	3.000	0.143	2.000	0.118
CR2	3.000	1.000	6.000	0.200	**2.369**	0.255
CR3	0.333	0.167	1.000	0.167	0.333	0.042
CR4	**1.908**	5.000	6.000	1.000	1.000	0.433
CR5	0.500	0.250	3.000	1.000	1.000	0.151

Inconsistency 8.70%

As discussed in section 5.2, we build the original supermatrix after completing all comparisons. Table 5-18 shows a supermatrix that contains all nodes. After that, the weighted supermatrix is calculated after normalizing the matrix in Table 5-18 as demonstrated in Table 5-19. The next step is to calculate the limit matrix. The limit matrix is obtained by raising the weighted super matrix to powers until it converges. Table 5-20 and Table 5-21 show the limit matrix and the normalized matrix, respectively.

Table 5-18: Original Supermatrix for All Nodes

	CR1	CR2	CR3	CR4	CR5	Energy conservation	Load side management	Stationary storage	Communication & intelligence	Geo-exchange heat pump	Electric water heater	Electric vehicles	Solar PV	Combustion generation
CR1	1	0	0	0	0	0.178	0.169	0.471	0.334	0.484	0.342	0.487	0.332	0.118
CR2	0	1	0	0	0	0.430	0.476	0.061	0.203	0.135	0.115	0.104	0.035	0.255
CR3	0	0	1	0	0	0.247	0.232	0.094	0.098	0.066	0.139	0.059	0.057	0.042
CR4	0	0	0	1	0	0.041	0.039	0.089	0.030	0.046	0.051	0.099	0.276	0.433
CR5	0	0	0	0	1	0.104	0.084	0.286	0.335	0.270	0.353	0.252	0.300	0.151
Energy conservation	0.060	0.021	0.004	0.022	0.033	1	0	0	0	0	0	0	0	0
Load side management	0.019	0.070	0.030	0.007	0.010	0	1	0	0	0	0	0	0	0
Stationary storage	0.005	0.173	0.024	0.002	0.004	0	0	1	0	0	0	0	0	0
Communication & intelligence	0.023	0.097	0.186	0.012	0.022	0	0	0	1	0	0	0	0	0
Geo-exchange heat pump	0.002	0.002	0.010	0.005	0.001	0	0	0	0	1	0	0	0	0
Electric water heater	0.004	0.014	0.024	0.025	0.005	0	0	0	0	0	1	0	0	0
Electric vehicles	0.004	0.003	0.006	0.002	0.002	0	0	0	0	0	0	1	0	0
Solar PV	0.005	0.004	0.013	0.004	0.003	0	0	0	0	0	0	0	1	0
Combustion generation	0.001	0.030	0.004	0.000	0.001	0	0	0	0	0	0	0	0	1

Table 5-19: Normalized Supermatrix for All Nodes

	CR1	CR2	CR3	CR4	CR5	Energy conservation	Load side management	Stationary storage	Communication & intelligence	Geo-exchange heat pump	Electric water heater	Electric vehicles	Solar PV	Combustion generation
CR1	0.891	0	0	0	0	0.089	0.085	0.235	0.167	0.242	0.171	0.243	0.166	0.059
CR2	0	0.707	0	0	0	0.215	0.238	0.030	0.102	0.067	0.058	0.052	0.018	0.128
CR3	0	0	0.768	0	0	0.124	0.116	0.047	0.049	0.033	0.070	0.029	0.029	0.021
CR4	0	0	0	0.926	0	0.021	0.020	0.044	0.015	0.023	0.026	0.049	0.138	0.217
CR5	0	0	0	0	0.926	0.052	0.042	0.143	0.168	0.135	0.177	0.126	0.150	0.076
Energy conservation	0.053	0.015	0.003	0.020	0.030	0.5	0	0	0	0	0	0	0	0
Load side management	0.017	0.050	0.023	0.007	0.009	0	0.5	0	0	0	0	0	0	0
Stationary storage	0.004	0.123	0.019	0.001	0.003	0	0	0.5	0	0	0	0	0	0
Communication & intelligence	0.021	0.068	0.143	0.011	0.020	0	0	0	0.5	0	0	0	0	0
Geo-exchange heat pump	0.002	0.001	0.008	0.005	0.001	0	0	0	0	0.5	0	0	0	0
Electric water heater	0.004	0.010	0.018	0.023	0.005	0	0	0	0	0	0.5	0	0	0
Electric vehicles	0.004	0.002	0.005	0.002	0.002	0	0	0	0	0	0	0.5	0	0
Solar PV	0.004	0.003	0.010	0.004	0.003	0	0	0	0	0	0	0	0.5	0.0
Combustion generation	0.001	0.021	0.003	0.000	0.001	0	0	0	0	0	0	0	0	0.5

Table 5-20: Limit Matrix for All Clusters

	CR1	CR2	CR3	CR4	CR5	Energy conservation	Load side management	Stationary storage	Communication & intelligence	Geo-exchange heat pump	Electric water heater	Electric vehicles	Solar PV	Combustion generation
CR1	0.26	0.26	0.26	0.26	0.26	0.262	0.262	0.262	0.262	0.262	0.262	0.262	0.262	0.262
CR2	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.0899	0.0899
CR3	0.07	0.07	0.07	0.07	0.07	0.0656	0.0656	0.0656	0.0656	0.0656	0.0656	0.0656	0.0656	0.0656
CR4	0.09	0.09	0.09	0.09	0.09	0.0861	0.0861	0.0861	0.0861	0.0861	0.0861	0.0861	0.0861	0.0861
CR5	0.30	0.30	0.30	0.30	0.30	0.2989	0.2989	0.2989	0.2989	0.2989	0.2989	0.2989	0.2989	0.2989
Energy conservation	0.0525	0.0525	0.0525	0.0525	0.0525	0.0525	0.0525	0.0525	0.0525	0.0525	0.0525	0.0525	0.0525	0.0525
Load side management	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274	0.0274
Stationary storage	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288
Communication & intelligence	0.0562	0.0562	0.0562	0.0562	0.0562	0.0562	0.0562	0.0562	0.0562	0.0562	0.0562	0.0562	0.0562	0.0562
Geo-exchange heat pump	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034
Electric water heater	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132	0.0132
Electric vehicles	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043
Solar PV	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066
Combustion generation	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051	0.0051

Table 5-21: Normalized Limit Matrix for All Clusters

	CR1	CR2	CR3	CR4	CR5	Energy conservation	Load side management	Stationary storage	Communication & intelligence	Geo-exchange heat pump	Electric water heater	Electric vehicles	Solar PV	Combustion generation
CR1	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326	0.326
CR2	0.112	0.112	0.112	0.112	0.112	0.112	0.112	0.112	0.112	0.112	0.112	0.112	0.112	0.112
CR3	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082
CR4	0.107	0.107	0.107	0.107	0.107	0.107	0.107	0.107	0.107	0.107	0.107	0.107	0.107	0.107
CR5	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372	0.372
Energy conservation	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266	0.266
Load side management	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139
Stationary storage	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146
Communication & intelligence	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285
Geo-exchange heat pump	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
Electric water heater	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
Electric vehicles	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
Solar PV	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
Combustion generation	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026

The last step is to prioritize alternatives. The findings show the final ranking changes when interdependent relationships are considered. Table 5-22 shows the final ranking after implementing ANP on the problem. The results show “communication and intelligence” is the most preferred alternative followed by “energy conservation”. We observe from Tables 5-22 and 5-23 that “electric stationary storage” is the third suitable option while it was the second alternative in AHP. Also, “solar PV” and “combustion generation” are flipped while “load side management” and “electric water heater” maintain the same rank.

Table 5-22: Final Ranking for Alternatives Using ANP

	Priority	Ranking
Communication & intelligence	0.284	1
Energy conservation	0.266	2
Electric stationary storage	0.146	3
Load side management	0.139	4
Electric water heater	0.067	5
Solar PV	0.033	6
Combustion generation	0.026	7
Electric vehicles	0.022	8
Geo-exchange heat pump	0.017	9

Table 5-23: Final Ranking for Alternatives Using AHP

	Priority	Ranking
Communication & intelligence	0.341	1
Stationary storage	0.207	2
Energy conservation	0.140	3
Load side management	0.136	4
Electric water heater	0.076	5
Combustion generation	0.036	6
Solar PV	0.029	7
Geo-exchange heat pump	0.019	8
Electric vehicles	0.015	9

From the previous tables, we realize the final ranking of priorities has changed when alternatives linked to criteria. In AHP, the decision maker traverses the problem top-down by making comparisons, without considering the impact of the actual alternatives. This over-estimates the importance of reliability and power quality. The following table illustrates final ranking for criteria using AHP. Table 5-24 illustrates final prioritization using AHP.

Table 5-24: Final Ranking for Criteria Using AHP

	Priority
CR1	0.123
CR2	0.415
CR3	0.302
CR4	0.080
CR5	0.080

In our case study, the expert learned through feedback comparisons in ANP that the originally assigned priority for reliability and power quality are not as high as expected, when the question was phrased abstractly. Table 5-25 illustrates final ranking for criteria using ANP

Table 5-25: Final Ranking for Criteria Using ANP

	Priority
CR1	0.327
CR2	0.112
CR3	0.082
CR4	0.108
CR5	0.372

5.5 Conclusion and discussion

This chapter descripted the methodology of ANP and its steps. It illustrated some differences between ANP and AHP. ANP can provide measures that are more accurate since it contains interdependence relationships. The results show "communication and intelligence" is the most suitable alternative to reduce GHG emissions followed by "energy conservation" and "stationary storage", respectively. However, implementing DSM in the electrical system requires incorporating new innovations and technologies. It requires telecommunication, automation, and network control. Therefore, there are several challenges facing the implementation of DSM. One of the challenges is that DSM increases the complexity in operation compared to the traditional electric system. However, providing flexibility in DSM plays an important role in dealing with complexity and uncertainty in the system. Further, cyber security is one of the issues in such a smart distribution system. Changing price signal will change load scheduling in the distribution system. Also, incorporating smart technologies makes the system vulnerable to injecting misinformation into the system and in turn changing the load decision or the generation capacity. Therefore, security is a big challenge in a networked DSM system [15, 87].

According to [15], although DSM provides efficient use of generation capacity, it might present more complexity to the market structure. In some electric systems, implementing DSM is a challenge because of the lack of information and communication technologies infrastructure. Enhancement of DSM needs deployment of sensors, advanced measurement, control technologies, communication systems and intelligence equipment. In recent years, new technologies, initiatives, and changing consumer behavior have shown a significant reduction in energy consumption. Further, load forecasting and smart management of electric vehicle charging will increase the utilization factor of loads. In addition, improving energy storage capabilities can play a major role in an efficient operation of DSM. However, more research is needed to examine, incorporate and understand new technologies and future implementation of DSM [16]. In that regard, environmental modeling of Fort Collins distribution system using IEEE 13-node test system will be implemented to quantify the effectiveness of the potential alternatives in reducing carbon footprint.

CHAPTER 6

MODELING AND SIMULATION OF THE DISTRIBUTION SYSTEM[5]

6.1 Introduction

This chapter presents methods from literature for calculating GHG emissions from a distribution system using the IEEE 13-node test feeder. It explains basic characteristics of the IEEE 13-node system and original power flow results. This chapter also analyzes 2017 hourly load data, from [88], corresponding to Fort Collins, Colorado area. The analysis includes simulating the base case load profile and then considering the MCDM options as a solution for emissions reduction. Such analysis includes performing radial power flow studies on the IEEE 13-node test feeder in normal steady-state operation. Power flow analysis focuses on various aspects such as active power, reactive power, and distribution system losses for each hour. Then, the obtained results are converted into environmental metrics to calculate GHG contribution from such particular load [89].

6.2 IEEE 13-node test feeder

According to [26], IEEE 13-node system is a small circuit model that was designed to test some features in the distribution system and benchmark algorithms in solving unbalanced three phase radial systems. This distribution system is supplied at one end as illustrated in Figure 6-1 [90]. The system is characterized by being short and highly loaded and interconnected with:

- 10 overhead and underground lines
- one generation unit
- one voltage regulator unit
- one ΔY 115/4.16 kV transformer
- one YY 4.16/0.480 kV (in-line transformer)
- two shunt capacitor banks, and

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[5] Part of this chapter is verbatim reproduced from [37], and it is submitted to the Journal of Energy Transitions at the time of writing this dissertation

- unbalanced spot and distributed loads

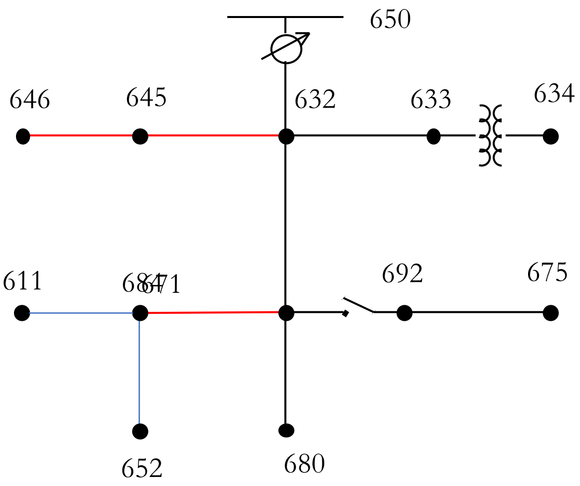

Figure 6-1: IEEE 13-node Test Feeder, recreated from [90]

This test feeder includes data for lines, transformers, capacitors, spot loads, and distributed loads, included in Appendix. Next section explains the findings after simulating the base case on the Fort Collins, C. distribution system as well as some strategies to test the ability of the MCDM solutions in achieving the goal.

6.3 Simulation analysis

As known, load profiles change per daily, seasonally, and annually. Therefore, this simulation considers the yearly load profile from which we can obtain the output of the generators to meet the demand and in turn get an estimated amount of GHG emissions.

To determine the environmental impact, the load profile corresponding to Fort Collins is translated and mapped on the IEEE 13-node system through OpenDSS simulation tool. The IEEE 13 node test feeder is designed to evaluate and benchmark algorithms, and this test system provides simple ways to make modifications on the test feeders to include DERs. Thus, it is used to adapt the load of Fort Collins distribution grid on the small circuit test system. The load curve in 2017 has a peak of 660 MW. This demand curve is scaled down to match the peak of the test system, 3.577 MW. To establish a strategy for GHG reduction, this section simulates the load profile and generation mix for the base case. After that, the analysis considers different scenarios from the MCDM options to reduce the GHG emissions compared to the base case. The analysis also combines several scenarios from MCDM alternatives to examine the expected impact in reducing the emissions and investigate the effectiveness of each alternative in achieving the goal. In that regard, the work studies the most preferred alternatives from the MCDM ranking list, communication and intelligence, stationary storage, and energy conservation.

6.3.1 Base case

In order to obtain the load profile and generation mix for the year of 2017, using OpenDSS with the COM interface, the actual load curve in mapped on the test system. A meter was embedded at bus 650 (main bus) to obtain hourly power flow data of the system for the entire year. Figure 6-2 illustrates demand curve and generation mix for the base case on the IEEE 13-node test feeder using Fort Collins load data. This figure indicates that the peak demand occurs on July 19th at 3 pm. After performing analysis on the supply and demand curves, environmental assessment calculates the emissions generated from conventional generating units for meeting the demand. In fact, there are four dirty generating units in the system. Each unit has its associated emissions as follow:

- Rawhide coal: ≈ 0.929 Kg/kWh
- Craig coal (unit 1): ≈ 1.02 Kg/kWh
- Craig coal (unit 2): ≈ 1.02 Kg/kWh
- Rawhide CTs: ≈ 0.635 Kg/kWh

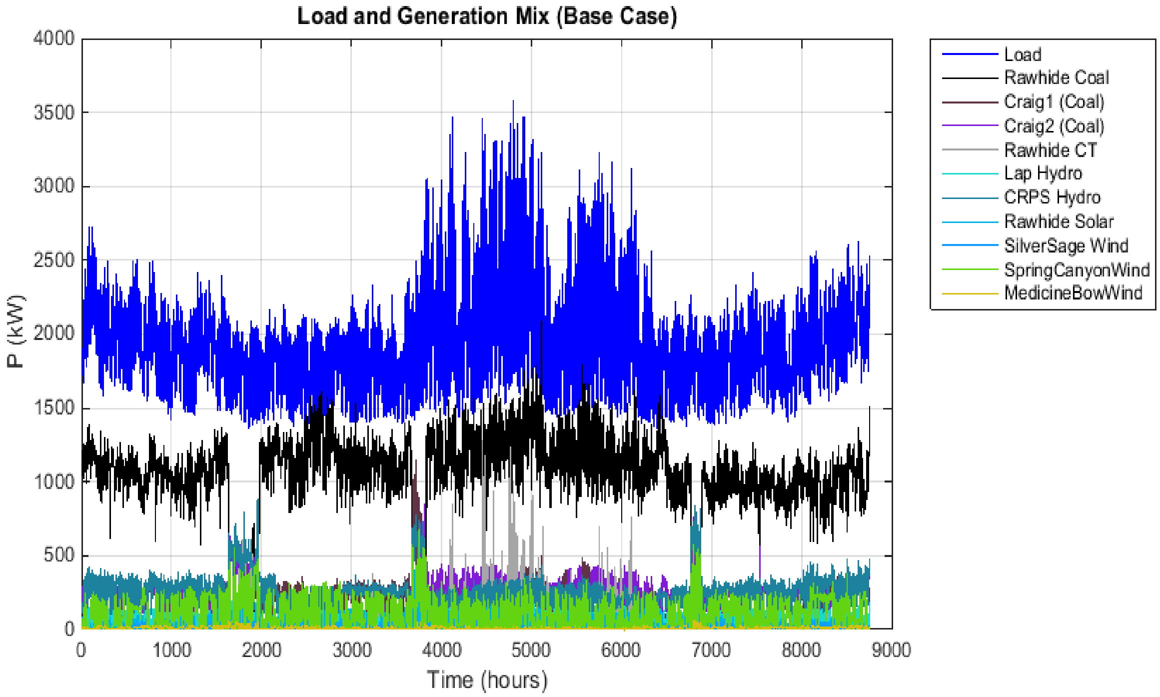

Figure 6-2: Load profile and generation mix, from the IEEE test system, for 2017 (base case)

The results pertaining to the base case show that the amount of emissions from the electricity sector is equivalent to 13,692 tons of CO_2 per year, as shown in Figure 6-3. Table 6-1 illustrates the generated emissions per source. A GHG equivalence calculator demonstrates that this amount of emissions equals the emissions produced by burning more than 7,484 tons of coal per year and the captured emissions from about 16,115 acres of the U.S. forests in one year [91]. As the city's energy environmental indicator shows a 16% emissions reduction in 2017 from 2005 level, the simulation illustrates that the reduction in emissions from 2005 level is 16.26% for the same year [92].

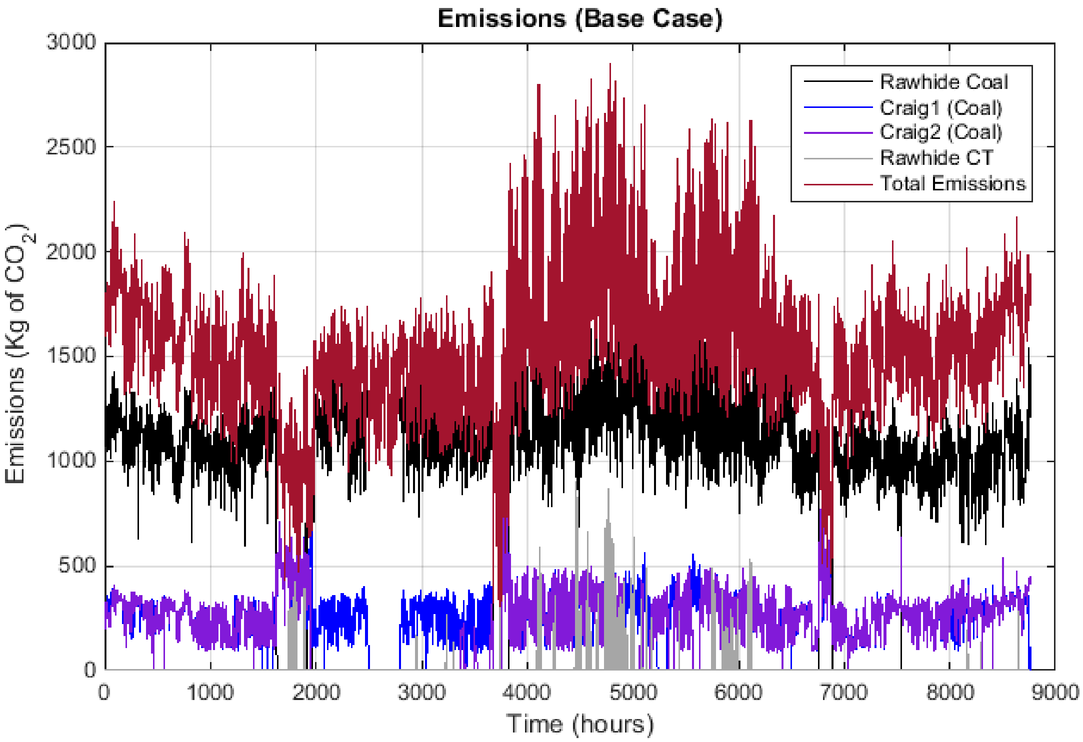

Figure 6-3: Emissions from the electricity sector, from the IEEE test system, for 2017 (base case)

6.3.2 Stationary storage

Storage is one of the top-prioritized MCDM technologies. According to [93], ESS can be used during peak hours to shave the load using the energy stored in ESS during off-peak periods and in turn minimize the need for high emission generators during the high demand times. Platte River Power Authority (PRPA) proposes using a Lithium-ion battery since it is the second most used technology (after lead acid) in the stationary storage market. PRPA wants to use Lithium-ion battery because it can operate over more and deeper cycles than a lead acid battery, resulting in a lower cost per cycle. PRPA proposes batteries for a capacity of 50 MW for four-peak load hours, 200 MWh. This simulation scales down the storage parameters to fit the test system. Therefore, the ESS provides about 271 kW for the duration of four hours (1084 kWh) to shave the peak load. Looking at the 2017 load curve, , it is noteworthy that the peak hourly load usually exceeds the average load by 20%. Thus, the simulation is designed to enable ESS to shave 10% of the peak load when the load at the specified hour exceeds the average load by 20%. A storage system can provide aggressive reduction in peaking load, up to 15%, during the coincident peak, the highest user demand that occurs one hour a month when the system demand is at its highest [94]. The storage system remains inactive when the load is lower than 120% of the average load. The system charges the deployed energy during off-peak hours when the load is at its lowest.

$$if \left[\begin{array}{c} L(t) > avg.\ load * 1.2\ then\ L(t)_{New} = L(t) * 0.9 \\ L(t) > avg.\ load * 1.2\ at\ coincident\ peak\ then\ L(t)_{New} = L(t) * 0.85 \\ L(t) \le avg.\ load * 1.2\ then\ L(t)_{New} = L(t) \end{array} \right.$$

Figure 6-4 shows the load and generation mix, from the test system, for 2017. To explain the previous figure in more detail, Figure 6-5 represents a simulation pertaining to the load profile on September 5th, 2019. The results show that the storage system is enabled for two hours to shave the peak demand. The amount of energy provided by storage system displaced the demand from Rawhide coal power plant. As scheduled, the batteries start charging when the demand at its lowest. More than 50% of storage charging come from hydro power plants.

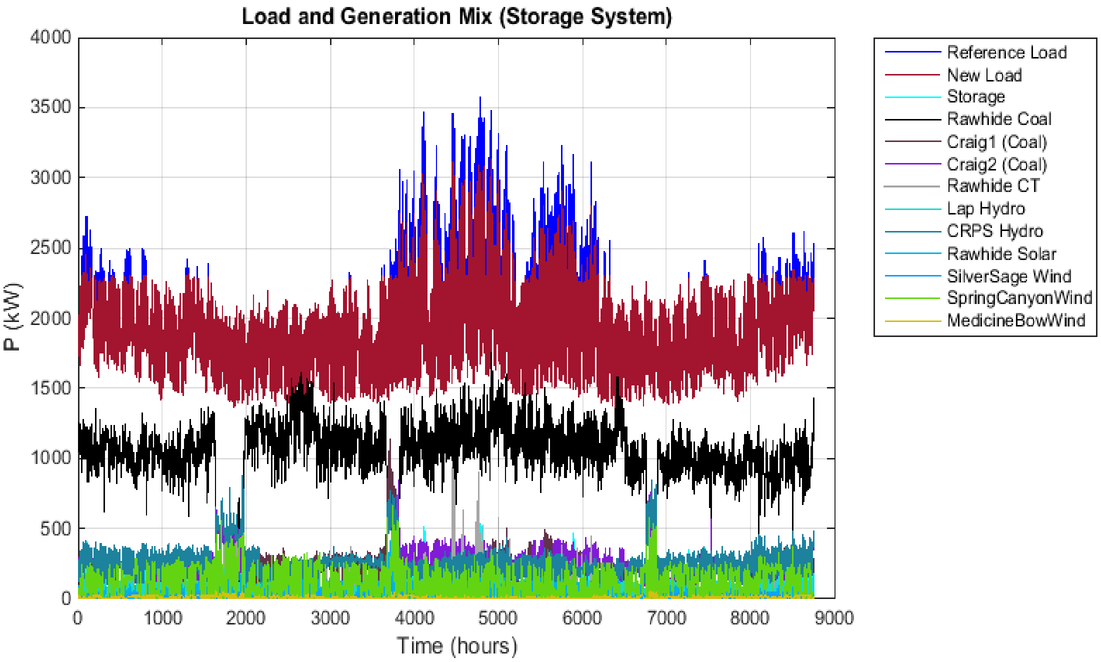

Figure 6-4: Load profile and generation mix, from the IEEE test system, for 2017 after applying ESS

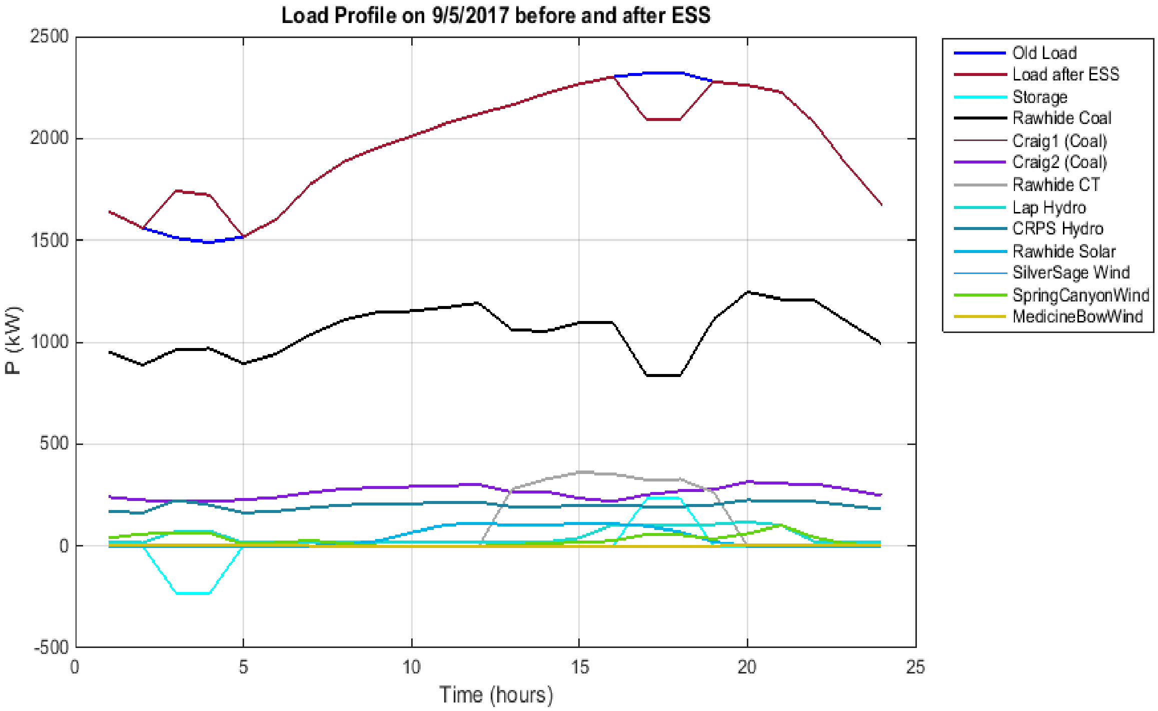

Figure 6-5: Load profile and generation mix, from the IEEE test system, on 9/5/2019 after applying ESS

The results show ESS with this technique mitigates the total emissions from 2005 level by 18.13%, equivalent to 13,385 tons of CO_2 per year. Figure 6-6 explains the emissions reduction per source after integrating ESS. This mitigation comes from diminishing the emissions from Rawhide coal power plant. Table 6-1 indicates the emissions reduction per source after ESS.

Table 6-1: Emissions, from the IEEE Test System, after ESS

	Base Case (tons of CO_2)	After ESS (tons of CO_2)	Emissions Reduction (%)
Rawhide coal	9,284	9,046	2.57
Craig coal (unit 1)	2,361	2,361	0
Craig coal (unit 2)	1,916	1,916	0
Rawhide CTs	130	130	0

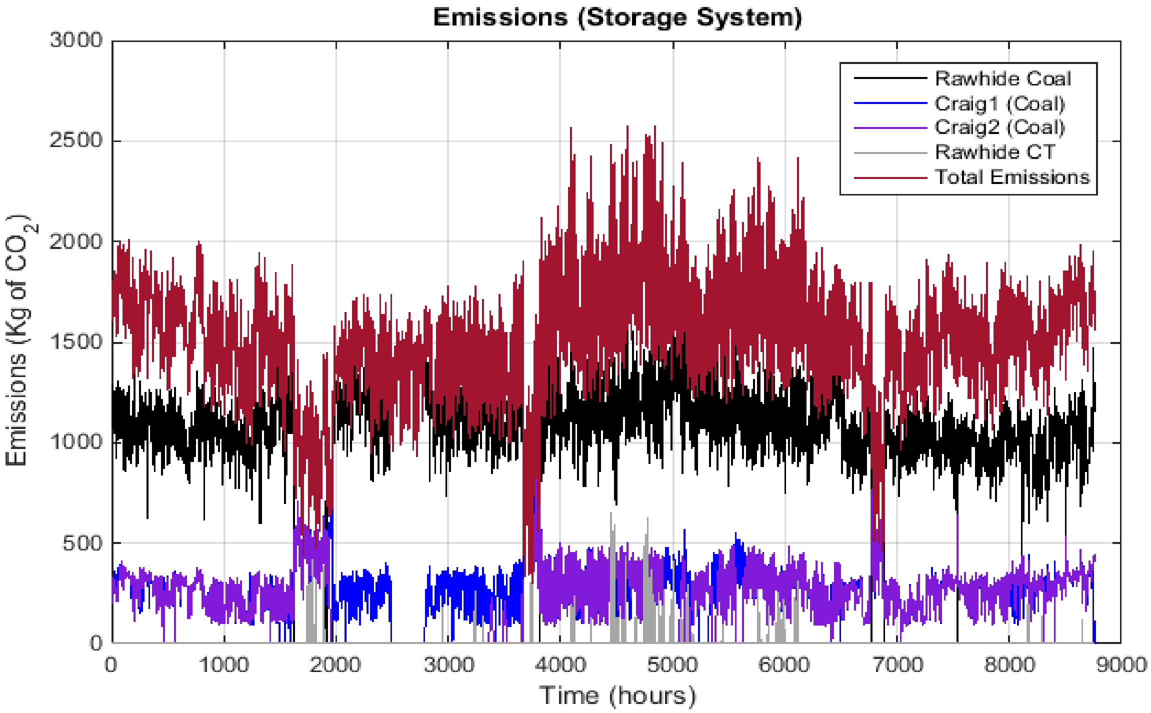

Figure 6-6: Emissions from the electricity sector, from the IEEE test system, for 2017 after applying ESS

6.3.3 Energy conservation

This alternative means reducing the energy input to meet the demand. As mentioned in section 4.3.1, energy conservation can be implemented either by applying energy efficiency to reduce the energy input required to produce useful work or educational programs to reduce the work requested of the system. In that regard, this scenario uses the ideal case for the simulation analyses based on a 5% curtailment in the entire load. Therefore, a one-year simulation is implemented after reducing the demand by 5%. The red curve in Figure 6-7 points out such a reduction in the total demand curve for 2017.

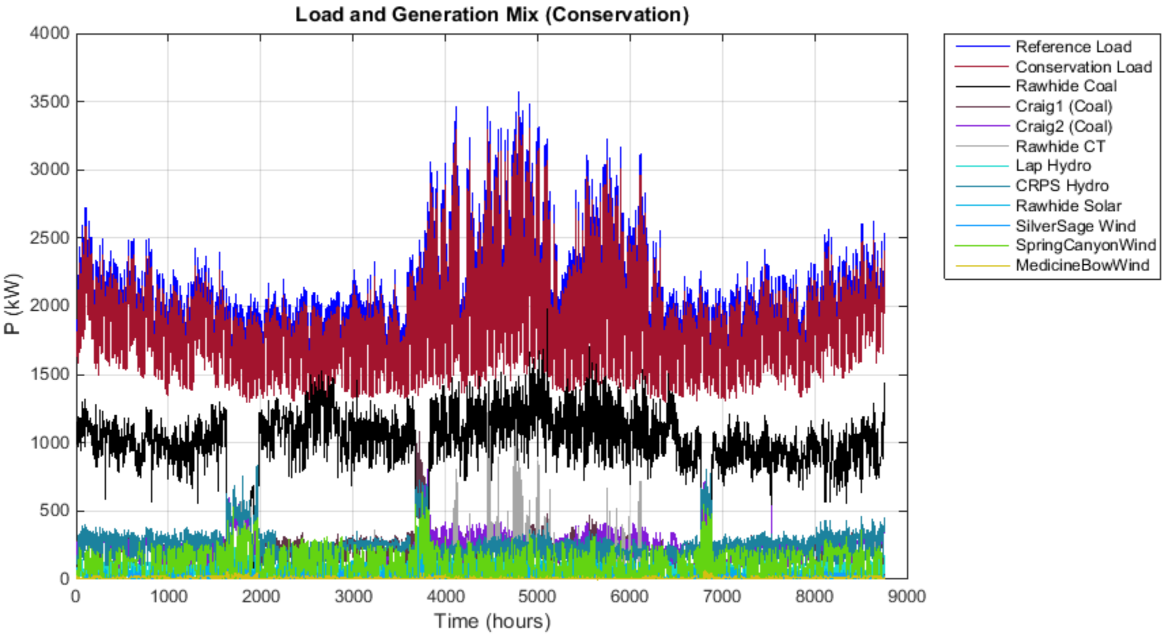

Figure 6-7: Load profile and generation mix, from the IEEE test system, for 2017 after applying energy conservation

This energy saving successfully minimized the total emissions by more than 20%, compared to the 2005 level. The emissions generated from the test system after curtailing the energy demand is equal to 13,016 tons of CO_2 per year, compared to 16,350 tons of CO_2 in 2005. Figure 6-8 demonstrates this notable mitigation in emissions. The major reduction comes from Rawhide coal power plant where the emissions from this unit is reduced by about 458 CO_2 tons as shown in Table 6-2:

Table 6-2: Emissions, from the IEEE Test System after Energy Conservation

	Base Case (tons of CO_2)	After Energy Conservation (tons of CO_2)	Emissions Reduction (%)
Rawhide coal	9,284	8,826	4.93
Craig coal (unit 1)	2,361	2,244	4.93
Craig coal (unit 2)	1916	1,821	4.93
Rawhide CTs	130	123	4.95

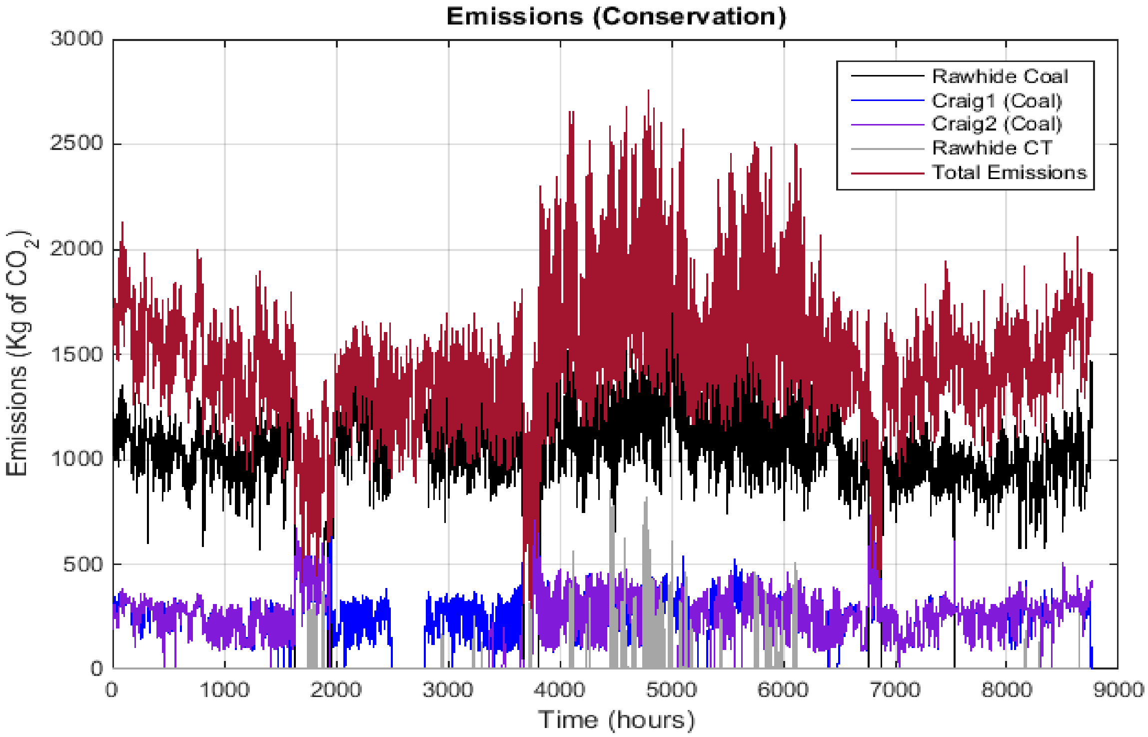

Figure 6-8: Emissions from the electricity sector, from the IEEE test system, for 2017 after applying energy conservation

6.3.4 Stationary storage with energy conservation

This scenario studies the load behavior and emissions amount after combining two options: ESS and energy conservation. The aim of considering such scenario is to investigate the availability of achieving more emissions reduction. This scenario follows the same simulation strategies for ESS and conservation programs that are explained in subsections 6.3.2 and 6.3.3. Figure 6-9 illustrates that such a combination affected the total energy demand.

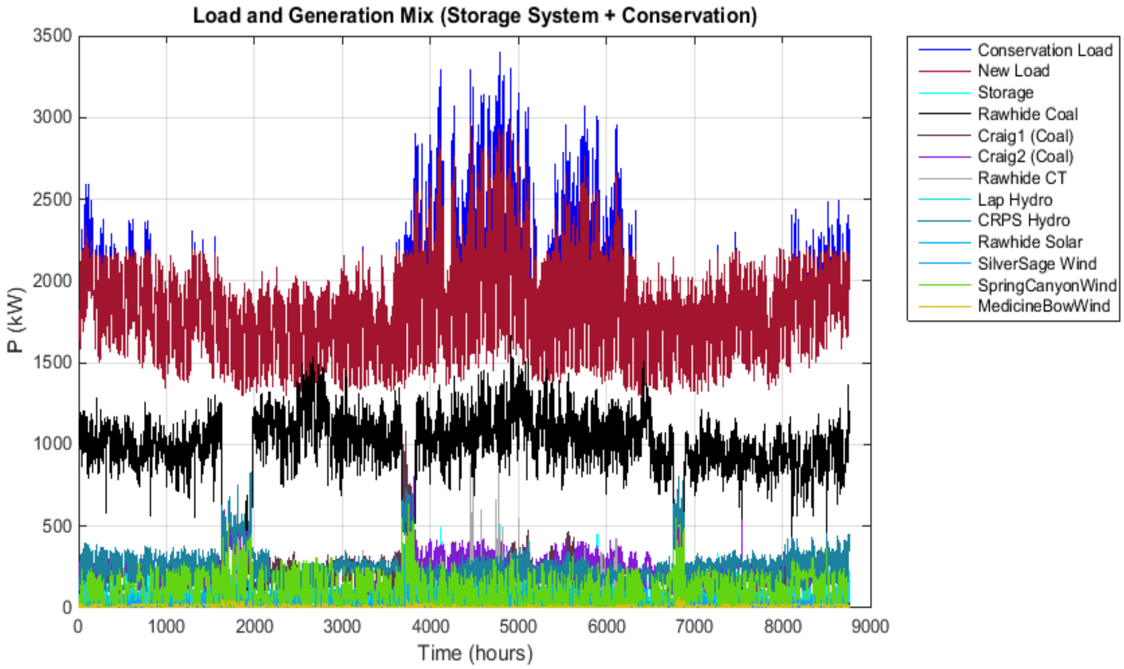

Figure 6-9: Load profile and generation mix, from the test system, for 2017 after combining ESS and energy conservation

This scenario can achieve reduction in emissions more than the city's goal. While the city has a goal of reaching a 20% emissions reduction by 2020, this scenario is able to reduce the carbon footprints by about 22%. As stated, the base case generates 16,350 ton of emissions while this option can minimize it to 12,725 CO_2 ton. Figure 6-10 presents the generated emissions from each emitting source, and Table 6-3 represents the values of emissions. From this table, we observe that ESS displaced energy needed from Rawhide coal.

Table 6-3: Emissions, from the IEEE Test System, after using ESS with Energy Conservation

	Base Case (tons of CO_2)	After ESS with Energy Conservation (tons of CO_2)	Emissions Reduction (%)
Rawhide coal	9,284	8,600	7.37
Craig coal (unit 1)	2,361	2,244	4.93
Craig coal (unit 2)	1916	1,821	4.94
Rawhide CTs	130	123	4.95

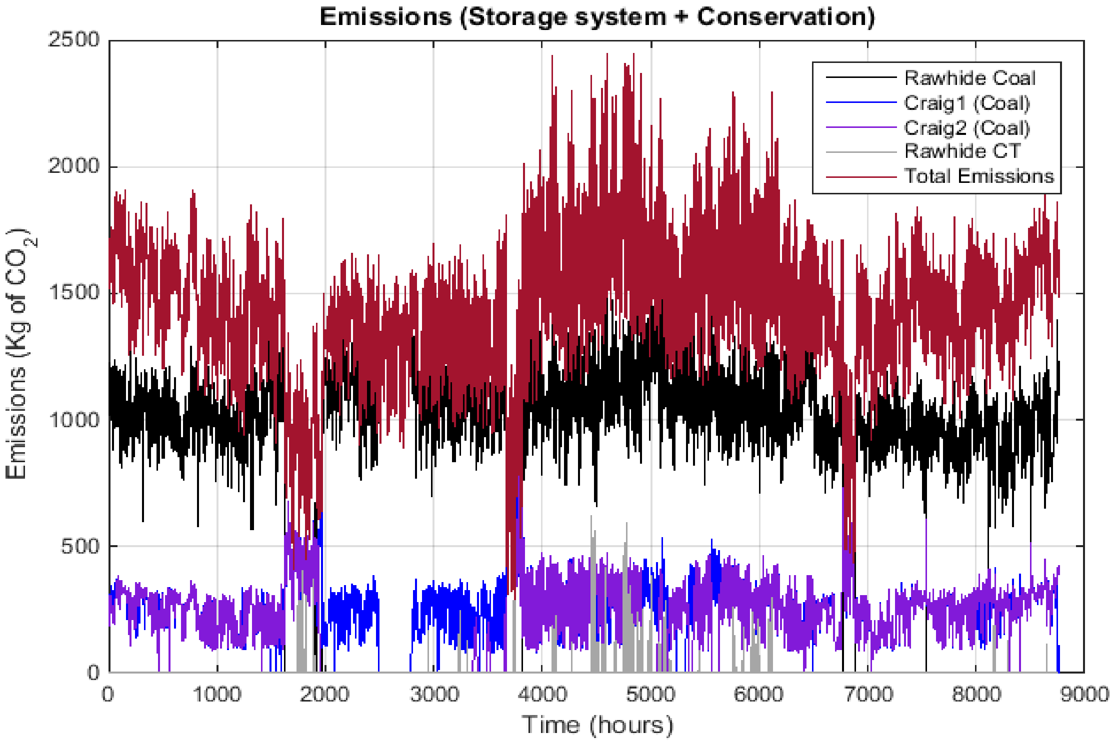

Figure 6-10: Emissions from the electricity sector, from the IEEE test system, for 2017 after combining ESS and energy conservation

6.3.5 Communication and intelligence

The aim of using communication and intelligence is to improve the matching of load to the availability of variable clean generating sources and to reduce peak demand. We treat this option as a residential DR since this option includes internet of things, smart meters and advanced metering infrastructure, real-time pricing, and smart appliance with controls automating energy conservation. Therefore, the simulation uses only the residential load curve to apply the DR program. According to [95], Fort Collins utility has a new Time-of-Day pricing mechanism for summer and non-summer seasons. Figure 6-11 and Figure 6-12 show electricity daily prices, regenerated from [96]. In DR, the demand changes as the prices change. The formula for price elasticity of demand is:

$$\varepsilon = \frac{\%\Delta Q_D}{\%\Delta P} \tag{5}$$

where ΔQ_D is the change is demand and ΔP is the change is prices [97]. In [98], there are two values for price elasticity of demand; long-term and short-term. Since this work conducts a one-year simulation, we consider the price elasticity for the short-term demand, -0.02.

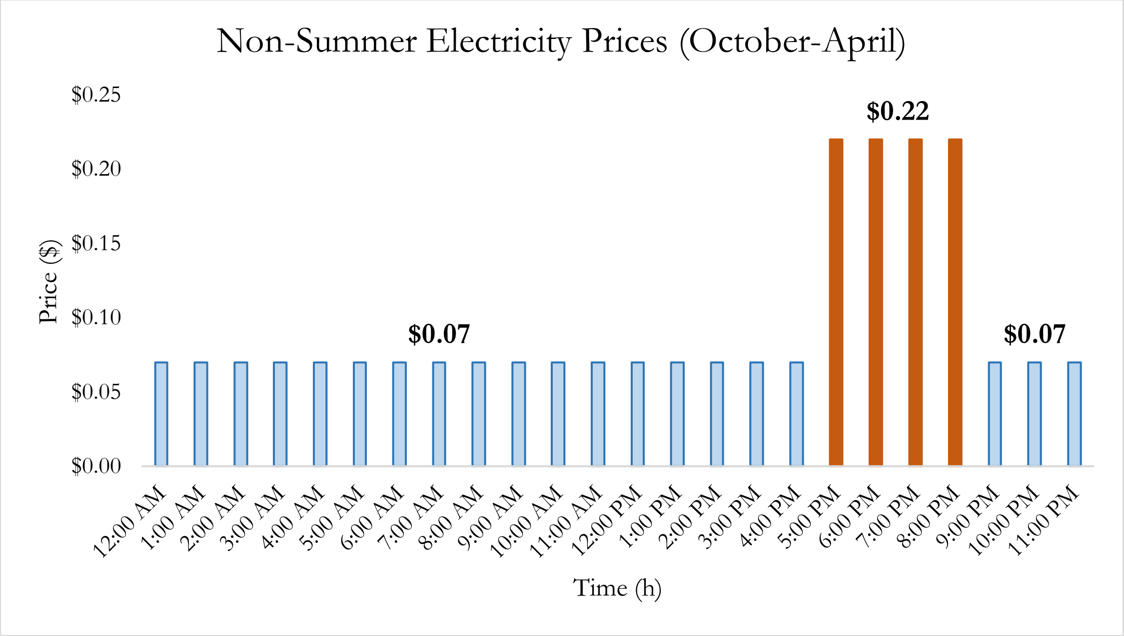

Figure 6-11: Non-Summer electricity prices corresponding to Fort Collins

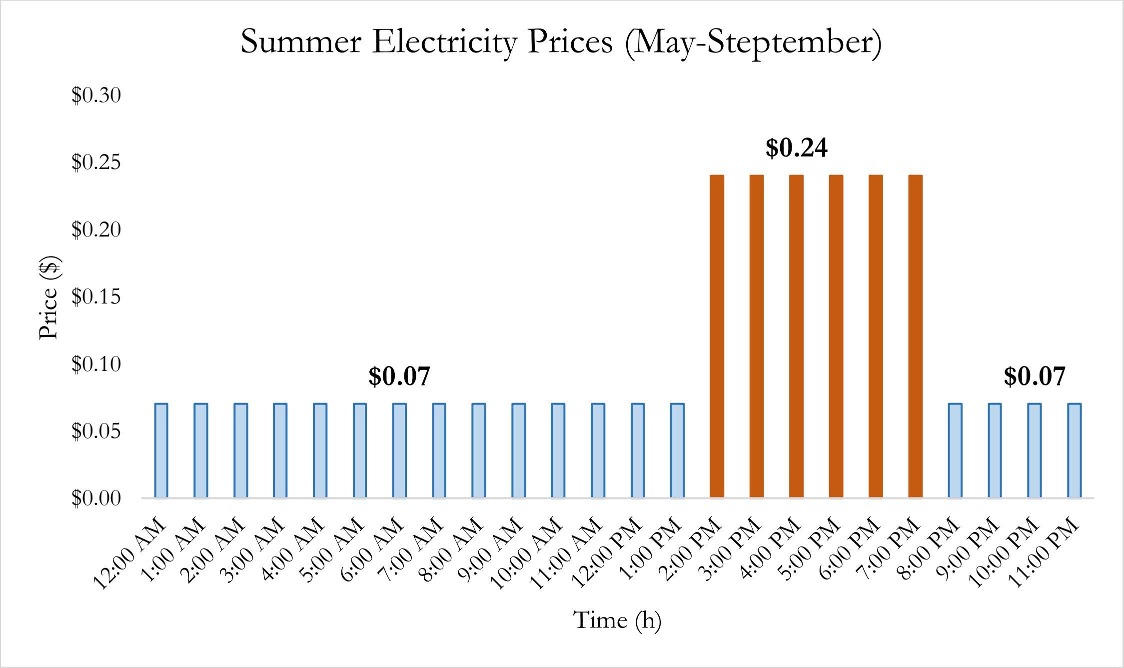

Figure 6-12: Summer electricity prices corresponding to Fort Collins

After performing the analysis, the Time-of-Day rates helped in reducing the load during peak hours. Figure 6-13 illustrates the residential load profile after applying DR in the residential sector. To explain the change in the demand during the summer season and the non-summer season, Figure 6-14 and Figure 6-15 demonstrates the load behavior with DR, respectively.

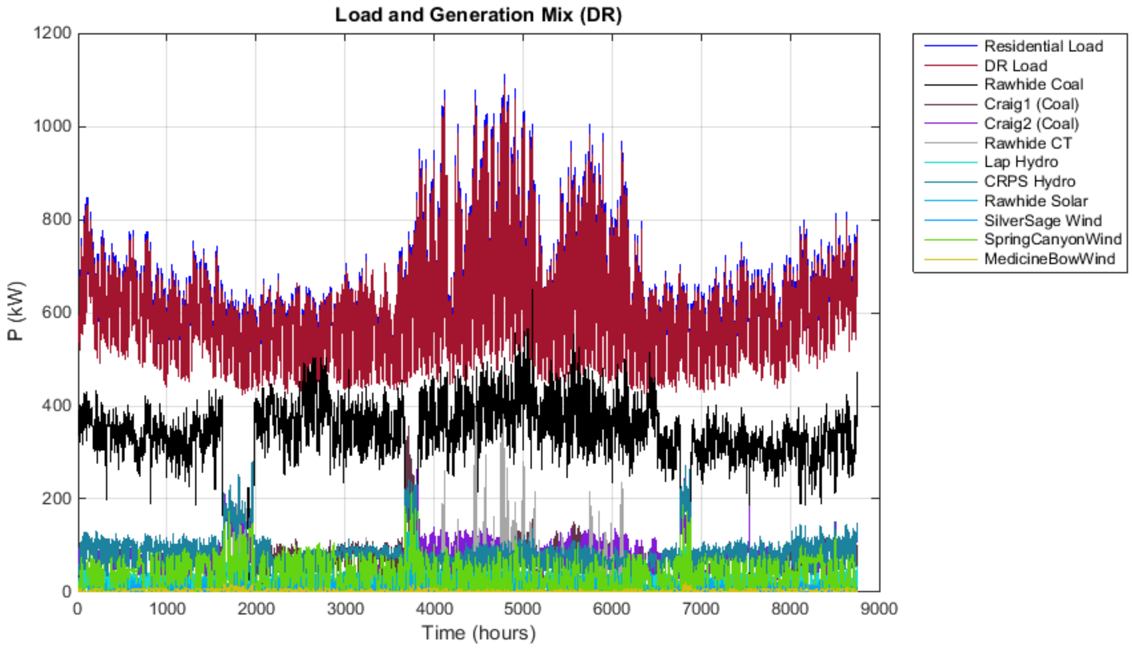

Figure 6-13: Residential load profile and generation mix, from the IEEE test system, for 2017 after using residential DR

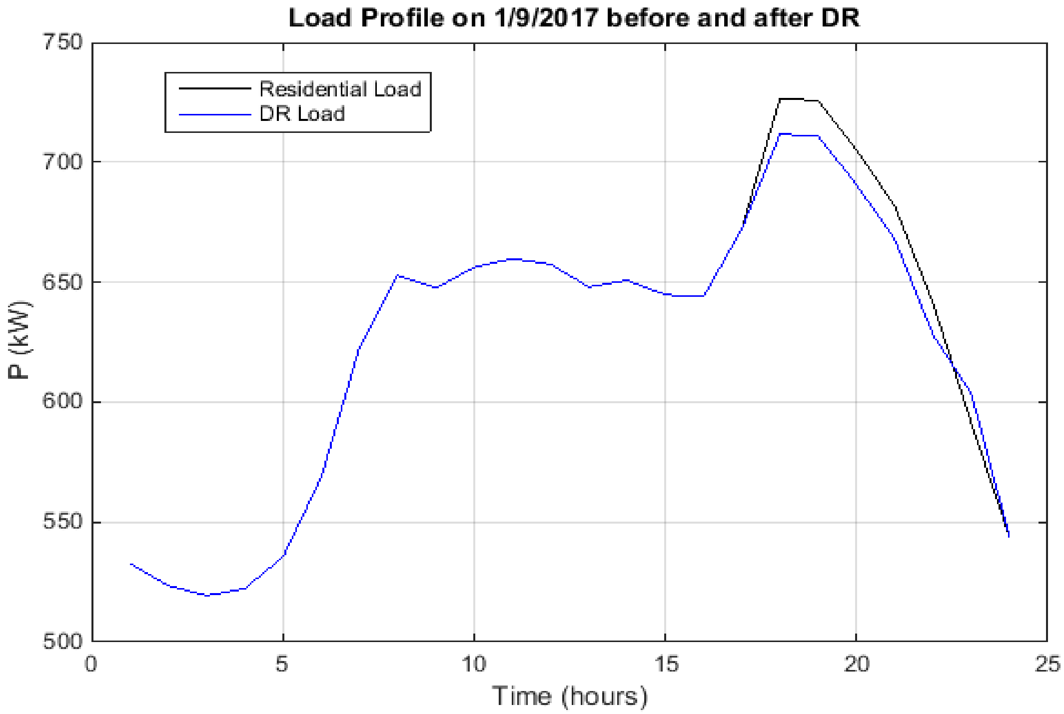

Figure 6-14: Residential load profile and generation mix, from the IEEE test system, on 1/9/2017

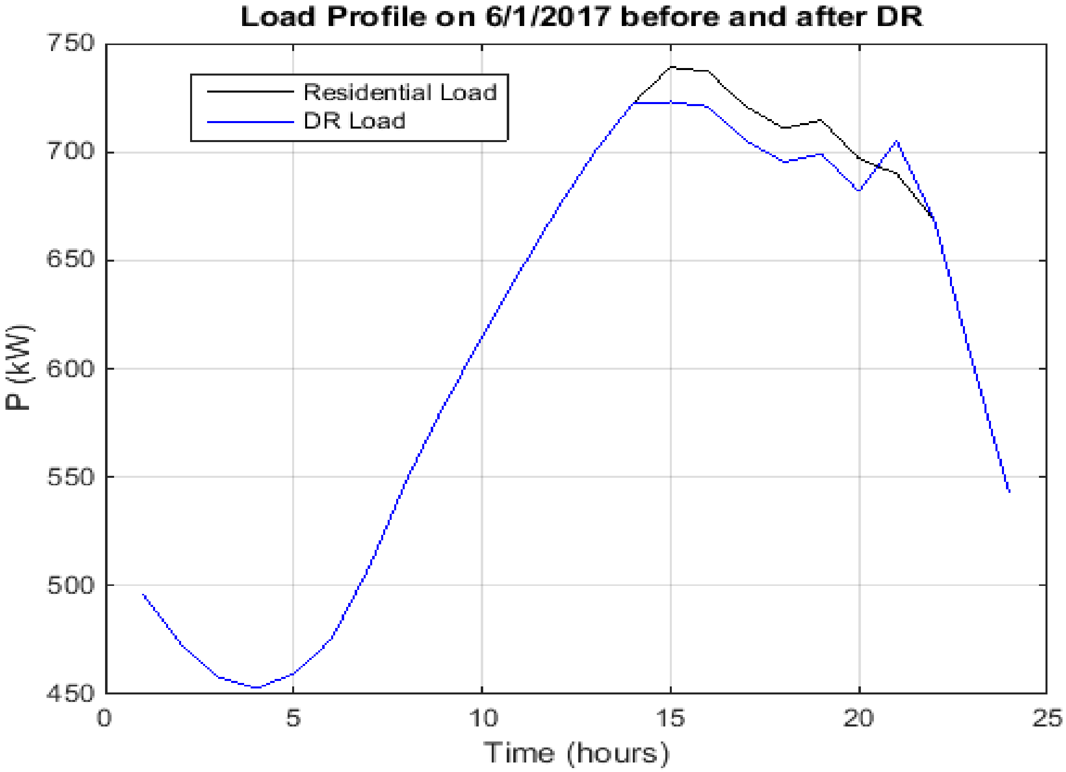

Figure 6-15: Residential load profile and generation mix, from the IEEE test system, on 6/1/2017

While the goal of deploying DR is shaving the peak load, the total emissions from the residential sector is reduced by about 14% from residential emissions in 2005 level. The pollution for residential sector was 5,068 CO_2 tons in 2005 and then DR dropped the emissions to 4,363 CO_2 tons. Table 6-4 shows the reduction in emissions, from the base case, after DR, and Figure 6-16 explains the emissions curve for each source.

Table 6-4: Emissions, from the IEEE Test System, after using Residential DR

	Residential Base Case (tons of CO_2)	After Residential DR (tons of CO_2)	Emissions Reduction (%)
Rawhide coal	2,972	2,960	0.41
Craig coal (unit 1)	755	750	0.71
Craig coal (unit 2)	613	610	0.45
Rawhide CTs	41	40	1.28

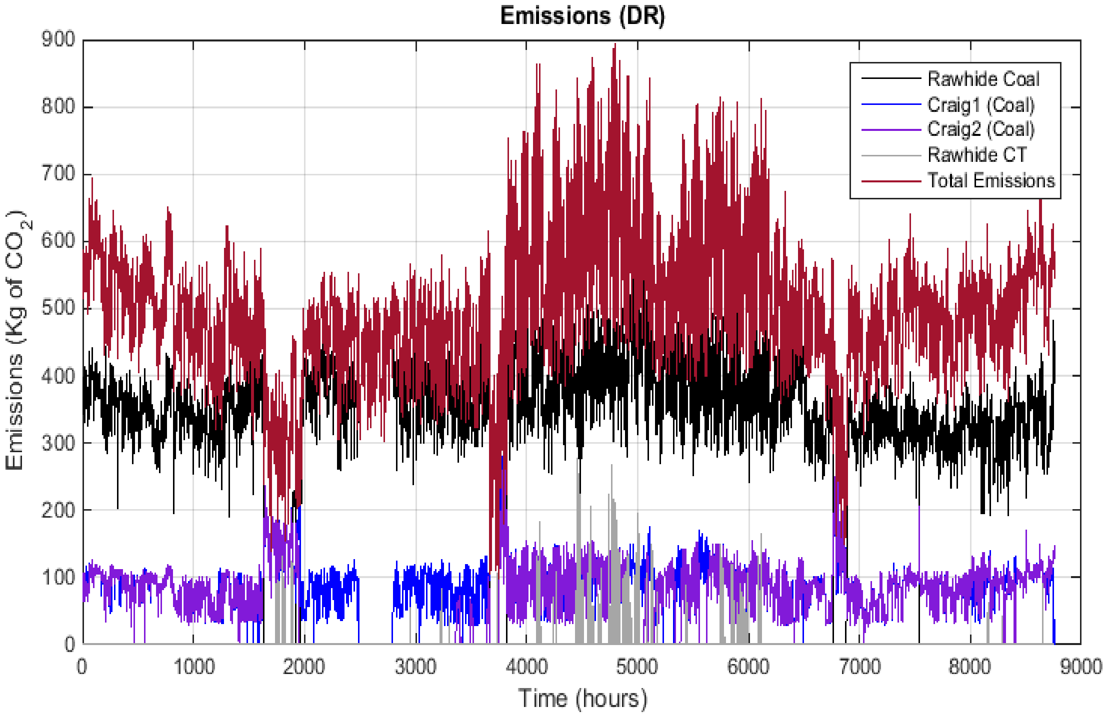

Figure 6-16: Emissions from the electricity residential sector, from the IEEE test system, for 2017 after using residential DR

6.3.6 Communication and intelligence with ESS

This subsection investigates the combination between residential DR and ESS in diminishing the pollution from the residential electric sector. In such simulation, we apply the same above-described approaches for residential DR and ESS. Since both these options aim to shave the peaking load, Figure 6-17 demonstrates the reduction in the peak load. Integrating ESS helped in saving emissions from the residential sector by about 2.48%. As a result, this scenario helped in minimizing the total emissions to almost 15.68% compared to 2005 level. The total emissions obtained from the IEEE 13-node system dropped to 4,2734 CO_2 tons for this scenario. Table 6-5 explains the associated emissions reduction per source while Figure 6-18 illustrates the generated emissions after applying this scenario.

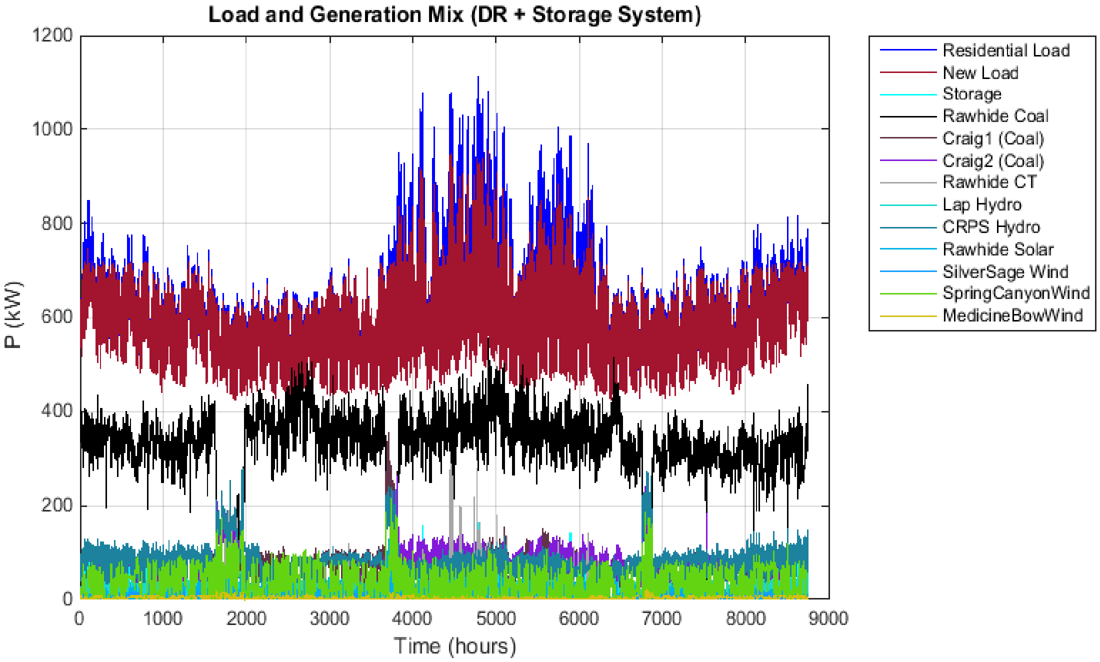

Figure 6-17: Residential load profile and generation mix, from the IEEE test system, for 2017 after using residential DR with ESS

Table 6-5: Emissions, from the IEEE Test System, after using Residential DR with ESS

	Residential Base Case (tons of CO_2)	After Residential DR with ESS (tons of CO_2)	Emissions Reduction (%)
Rawhide coal	2,972	2,891	2.72
Craig coal (unit 1)	755	752	0.46
Craig coal (unit 2)	613	610	0.45
Rawhide CTs	41	20	51.62

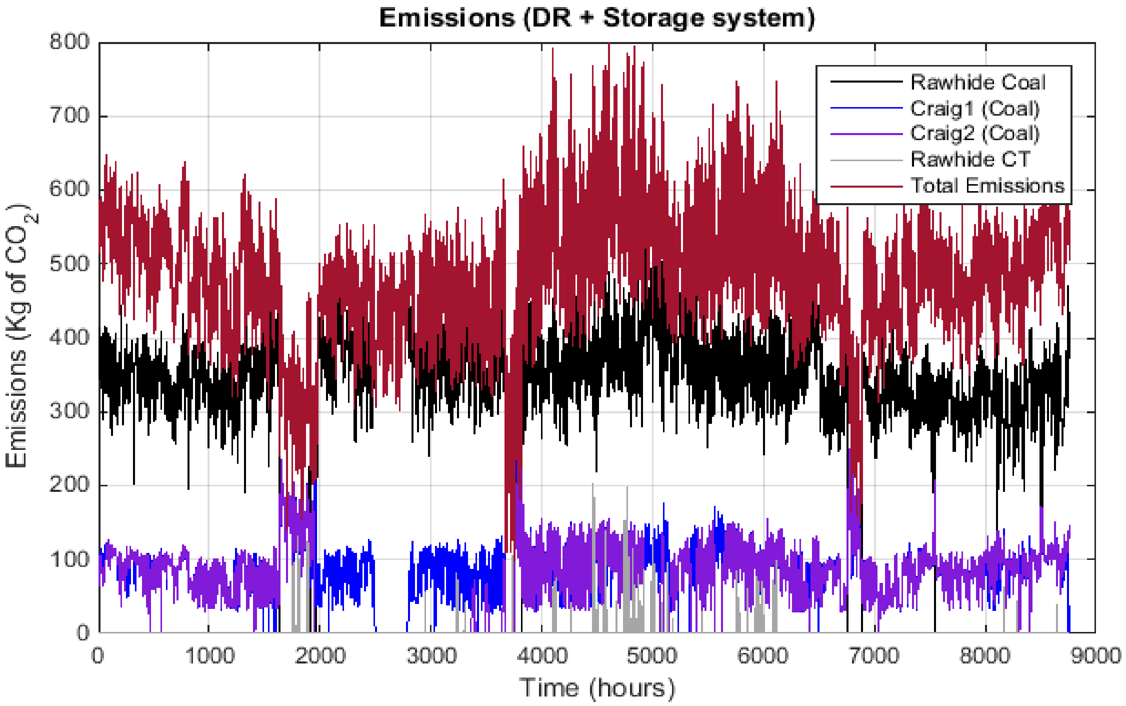

Figure 6-18: Emissions from the electricity residential sector, from the IEEE test system, for 2017 after using Residential DR with ESS

6.3.7 Communication and intelligence with energy conservation

In order to examine all the potential options that could reduce the carbon footprints from the electric sector, this scenario takes into account merging residential DR with energy conservation programs. In fact, energy conservation can play a major role toward attaining the goal when it is integrated with residential DR. In Figure 6-19, we realize a reduction in the demand curve due to the aggressive curtailment in energy use. Figure 6-20 depicts the emissions from the electric residential sector for 2017. It shows that this combination resulted in more than 18% emission reduction, dropping from 5,069 CO_2 tons in 2005 to 4,151 CO_2 tons. Table 6-6 highlights where this reduction comes from.

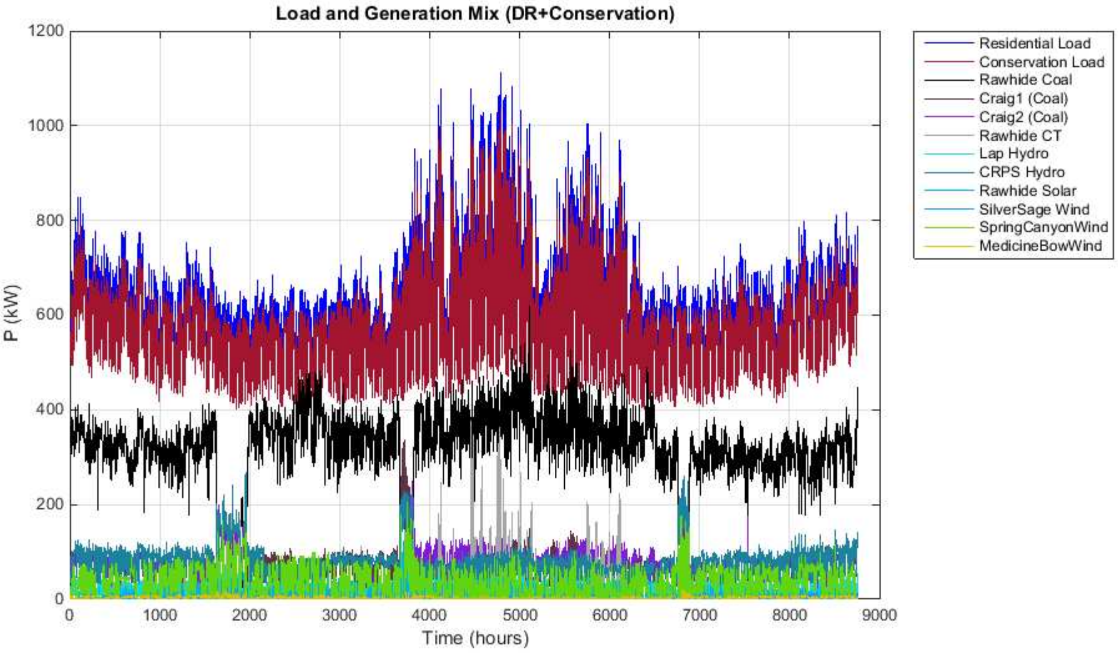

Figure 6-19: Residential load profile and generation mix, from the IEEE test system, for 2017 after using residential DR with energy conservation

Table 6-6: Emissions, from the IEEE Test System, after using Residential DR with Energy Conservation

	Residential Base Case (tons of CO_2)	After Residential DR with Energy Conservation (tons of CO_2)	Emissions Reduction (%)
Rawhide coal	2,972	2,818	5.18
Craig coal (unit 1)	755	716	5.22
Craig coal (unit 2)	613	581	5.22
Rawhide CTs	41	38	6.09

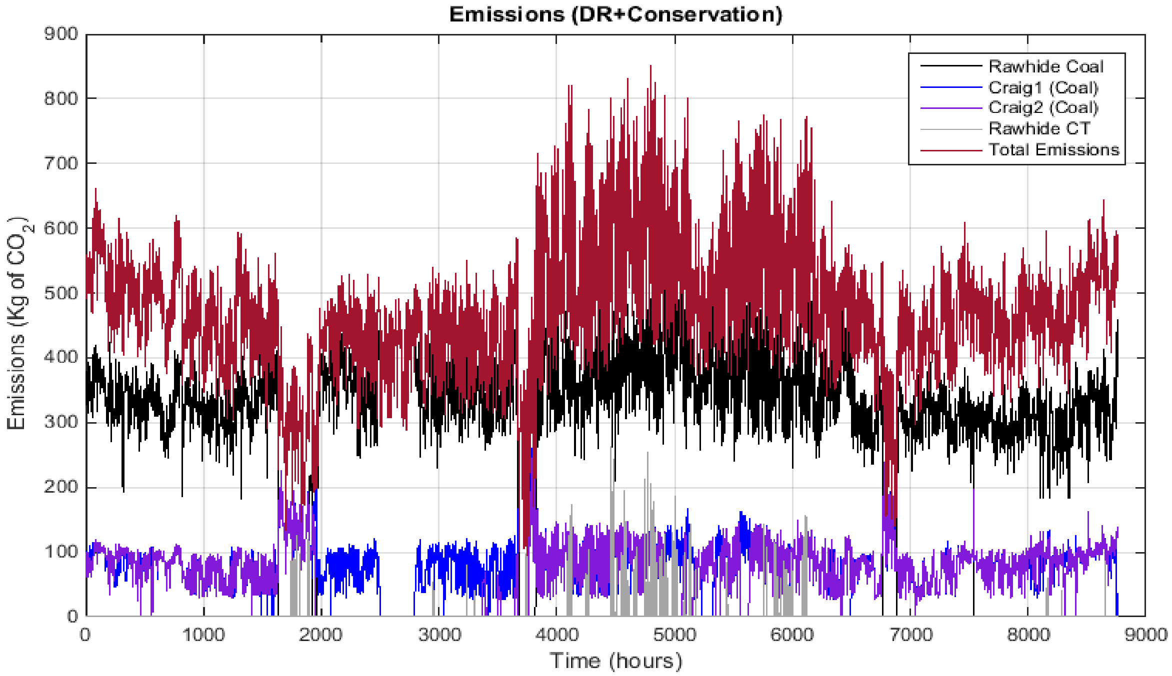

Figure 6-20: Emissions from the electricity residential sector, from the IEEE test system, for 2017 after using residential DR with energy conservation

6.3.8 Communication and intelligence with ESS and energy conservation

The last scenario is to examine all the three options together, i.e., we combine residential DR, ESS, and energy conservation in one scenario and then analyze their contribution to emissions reduction. Each scenario is applied with its designed methodology that is explained in the above-subsections. This scenario provides more options and flexibility during the year and in turn achieves more reduction in associated pollution. The obtained results show significant energy saving after integrating such options. It is notable from Figure 6-21 that this scenario minimized the total energy used in 2017 from the residential sector from 5.36 GWh for the base case to 4.97 GWh. Therefore, this scenario successfully reduces emissions, from the 2005 level, by about 19.72%. Table 6-7 presents the emissions from each source, and Figure 6-22 represents the emissions for the entire year.

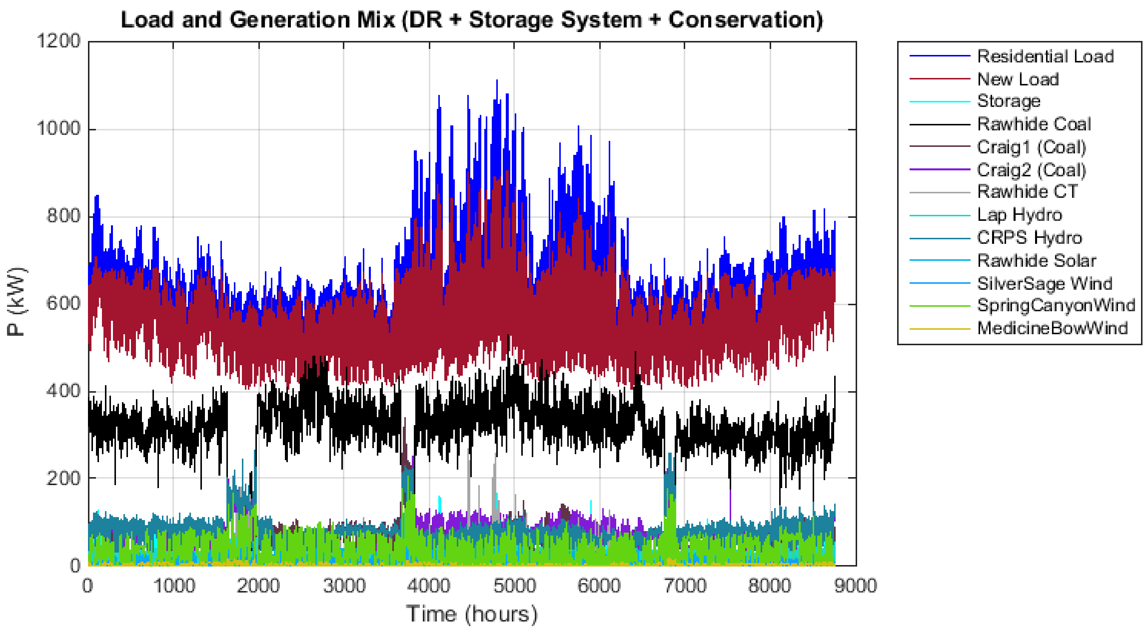

Figure 6-21: Residential load profile and generation mix, from the IEEE test system, for 2017 after combining all options

Table 6-7: Emissions, from the IEEE Test System, after combining all options

	Residential Base Case (tons of CO_2)	After combining All options (tons of CO_2)	Emissions Reduction (%)
Rawhide coal	2,972	2,753	7.38
Craig coal (unit 1)	755	716	5.24
Craig coal (unit 2)	613	581	5.22
Rawhide CTs	41	19	53.91

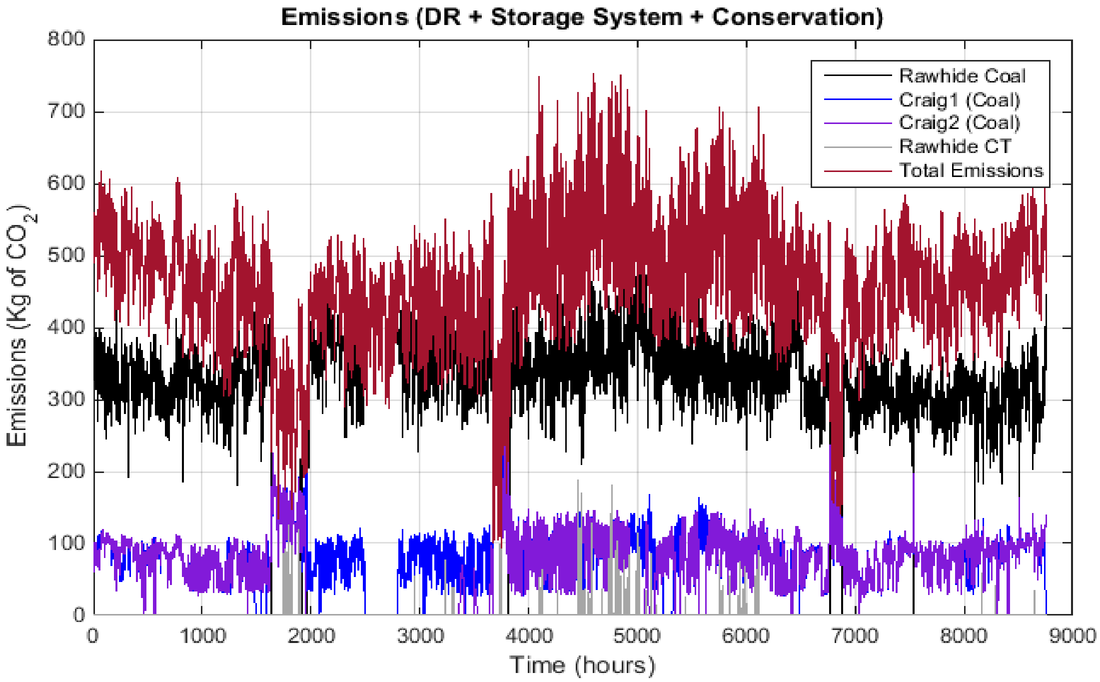

Figure 6-22: Emissions from the electricity residential sector, from the IEEE test system, for 2017 after combining all options

6.4 Results

This section discusses the demand curve and total emissions reduction for each scenario. The figures in this section make a comparison between all the scenarios and then quantify the progress of each scenario in achieving the goal. In that regard, Figure 6-23 shows the demand curve from the IEEE test system for 2017 after examining the first-three scenarios; ESS, energy conservation, and the scenario that combines ESS with energy conservation. Figure 6-24 illustrates the residential demand curve from the test system after considering communication and intelligence alternative and then merging it with other scenarios.

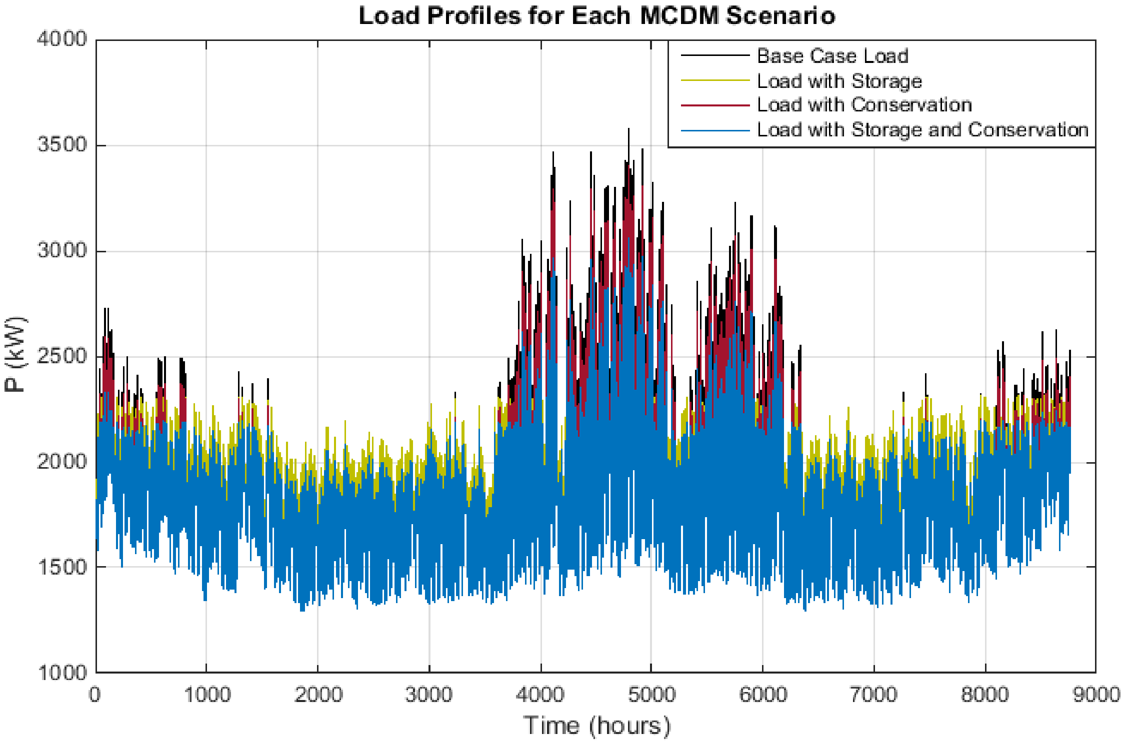

Figure 6-23: Load profile and generation mix, from the IEEE test system, for 2017 after considering ESS and energy conservation

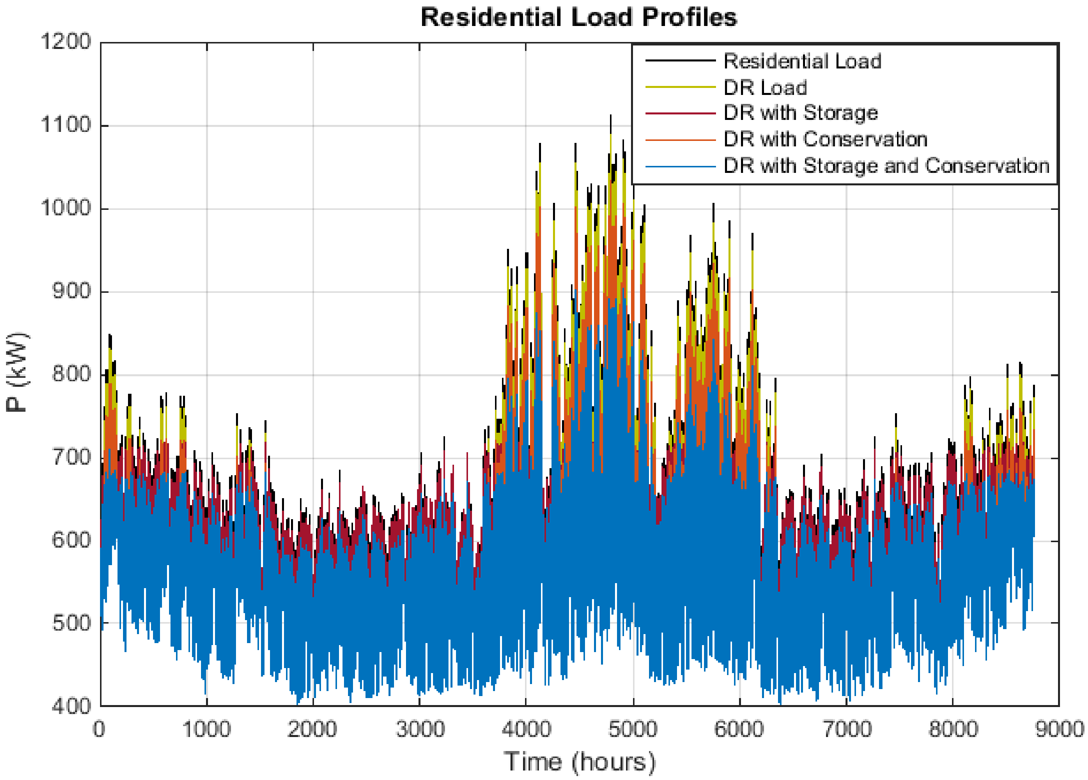

Figure 6-24: Residential Load profile and generation mix, from the IEEE test system, for 2017 for all MCDM alternatives

The results also show the environmental footprints is different for each scenario. Table 6-8 demonstrates the emissions from the emitted sources after integrating ESS and energy conservation while the behavior of each source is explained in Figure 6-25.

Table 6-8: Emissions, from the IEEE Test System, after using ESS and Energy Conservation

	Base Case (tons of CO_2)	After ESS (tons of CO_2)	After Energy Conservation (tons of CO_2)	After ESS and Energy Conservation (tons of CO_2)
Rawhide coal	9,284	9,046	8,826	8,600
Craig coal (unit 1)	2,361	2,361	2,244	2,244
Craig coal (unit 2)	1,916	1,916	1,821	1,821
Rawhide CTs	130	130	123	123

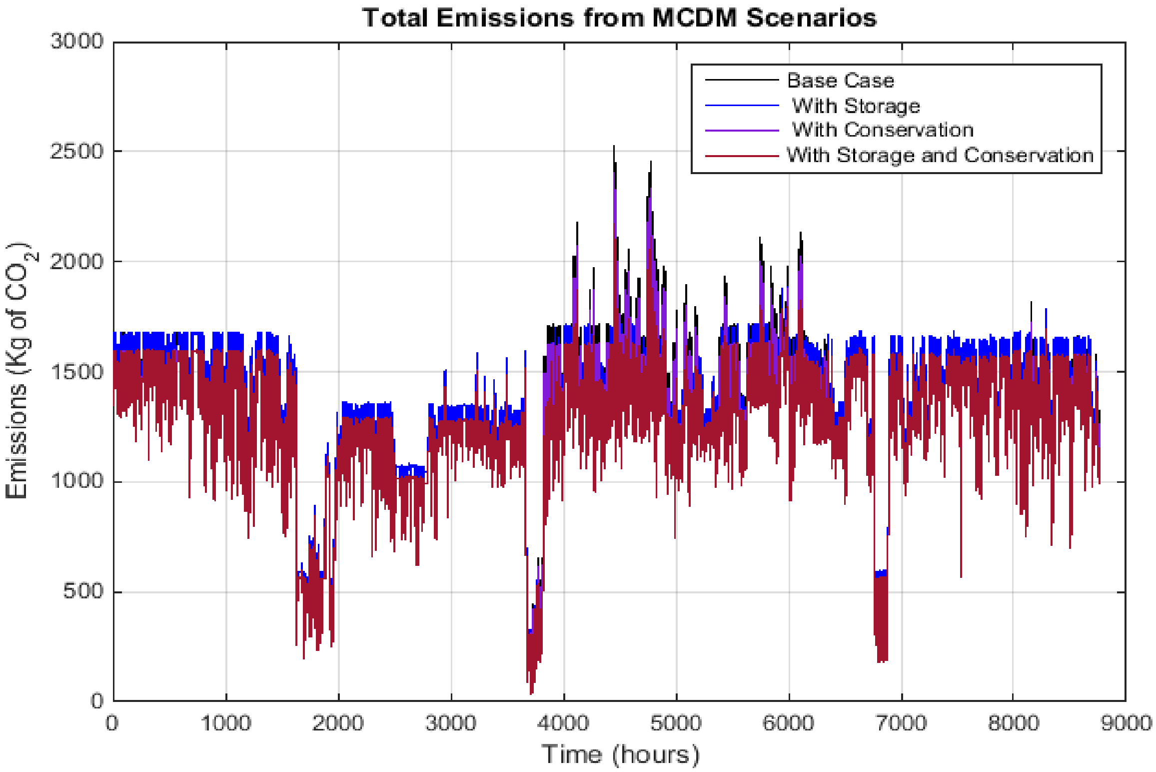

Figure 6-25: Emissions from electricity sector, from the IEEE test system, for 2017 after ESS and energy conservation

Table 6-9 shows the percentage of emissions reduction from each scenario. The values indicate that the MCDM options can help in a meaningful reduction in total emissions. It is obvious that merging ESS with energy conservation provides more improvement in environmental footprints.

Table 6-9: Emissions reduction, from the IEEE Test System, after integrating ESS and Energy Conservation

Scenario	Emissions (tons of CO_2)	Reduction from 2005 Level (%)
2005 level	16,350	--
Base case	13,692	16.26%
ESS	13,385	18.13%
Energy conservation	13,016	20.39%
ESS and energy conservation	12,725	22.17%

By including residential DR as a representing technique for communication and intelligence, the residential sector can save up to 20% of 2005 electric residential sector emissions. Table 6-10 explains the emissions per source from electric residential sector. Further, Figure 6-26 illustrates the hourly emissions in 2017 per source.

Table 6-10: Emissions, from the IEEE Test System, for all MCDM alternatives

Scenario	Residential Base Case (tons of CO_2)	After Residential DR (tons of CO_2)	After Residential DR with ESS (tons of CO_2)	After Residential DR with Energy Conservation (tons of CO_2)	After combining All options (tons of CO_2)
Rawhide coal	2,972	2,960	2,891	2,818	2,753
Craig coal (unit 1)	755	750	752	716	716
Craig coal (unit 2)	613	610	610	581	581
Rawhide CTs	41	40	20	38	19

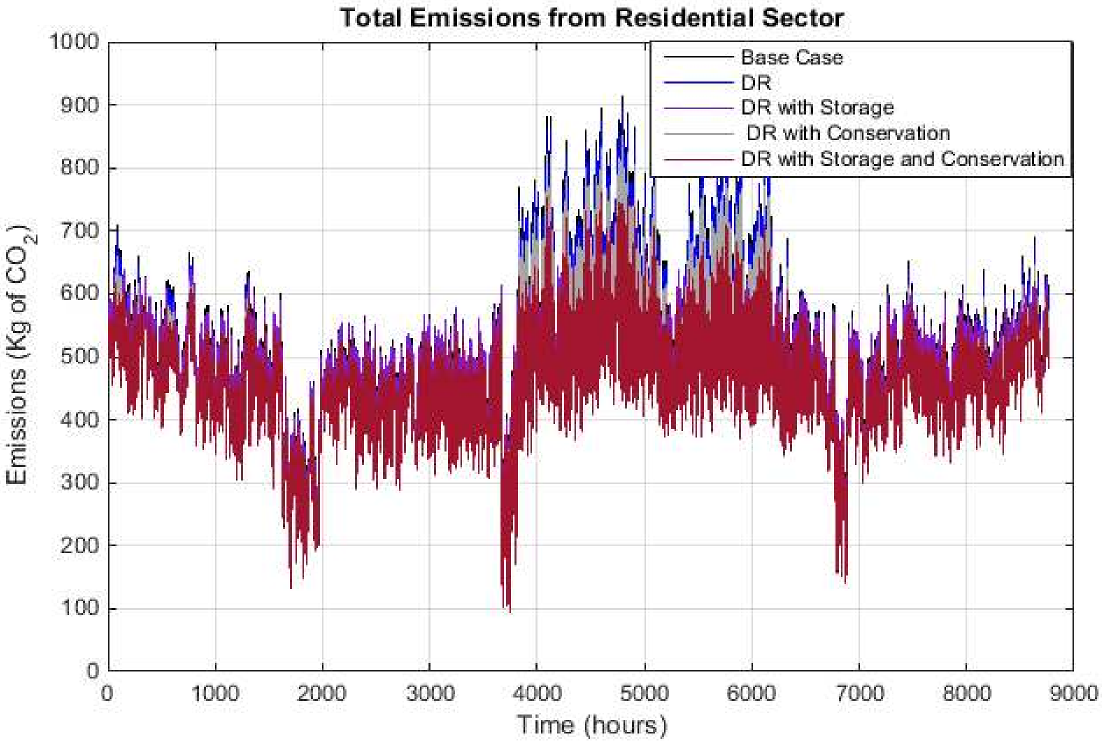

Figure 6-26: Emissions from the electricity residential sector, from the IEEE test system, for 2017 for all MCDM alternatives

The results indicate that applying all the MCDM options together in the electricity residential sector can provide the highest reduction in emissions as shown in Table 6-11.

Table 6-11: Emissions from the electricity residential sector, from the IEEE Test System, for all MCDM alternatives

Scenario	Emissions (tons of CO_2)	Reduction from 2005 Level (%)
2005 level	5,068	--
Base case	4,382	13.54%
Residential DR	4,363	13.91%
Residential DR and ESS	4,274	15.68%
Residential DR and energy conservation	4,154	18.04%
Residential DR with ESS and energy conservation	4,069	19.72%

6.5 Conclusion

This chapter presented a simulation study on the IEEE 13-node system through OpenDSS. The analysis includes examining the behavior of the demand curve for the first-three MCDM alternatives; communication and intelligence, ESS, and energy conservation. It also quantifies the impact of the proposed alternatives in reducing environmental footprints. The results show combining ESS and conservation programs can achieve a meaningful impact on the entire system. Moreover, employing communicating and intelligence in the residential sector helps in achieving the city's target for emissions reduction. The analysis on the residential sector shows merging all the MCDM options can help Fort Collins in meeting their 2020 goal. However, this analysis is implemented based on environmental evaluation only and other factors can affect this ranking. Thus, it is important to investigate those alternatives from another perspective. In that regard, the next chapter will perform economic evaluation for all alternatives. Hence, Chapter 7 will conduct a CBA to study economic, technical, and environmental cost and benefits associated with each alternative.

CHAPTER 7

ECONOMIC EVALUATION[6]

7.1 Introduction

This chapter presents an economic analysis, using CBA, on the MCDM alternatives. CBA is an analytical tool used to help decision-makers justify different options by making judgments and evaluating the available options in turn. CBA is an economic tool that assists in determining the worth of a project or resource. Hence, it identifies and evaluates the benefits and costs associated with investing in such decisions. This chapter employs a CBA to calculate the expected costs and the estimated benefits in given alternatives to determine options that maximize benefits and reduce costs [99].

7.2 CBA process

The aim of using CBA is to make an assessment for each scenario and to quantify the net benefit to the system. This analysis evaluates the costs and benefits associated with each solution proposed to reduce emissions. The analysis quantifies environmental, technical, and economic costs and benefits. This evaluation should explain all costs associated with each alternative such as fixed costs, operating and maintenance costs, and customer dropout and removal costs. Benefits can be a reduction in the costs of generation, transmission, and distribution. Additionally, there can be customer benefits such as reducing the cost of electricity bill or utility benefits such as lowering cost of services or improving operation and efficiency. Social benefits such as reducing environmental degradation, conserving resources, or protecting the global environment are also considered. A key issue is the monetization of environmental and social impacts. A social cost of carbon emissions and a carbon price resulted from climate policies are two proposed approaches to establish monetary values for emissions [100, 101].

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[6] Part of this chapter is verbatim reproduced from [37], and it is submitted to the Journal of Energy Transitions at the time of writing this dissertation

CBA follows several steps to select the potential optimal alternative. The first step is to specify the set of alternative options. The next step is to define the boundaries of the analysis to explain which benefits and costs are included. Step three is to select indicators before measuring all costs and benefits of the selected measurements. Then, we monetize all costs and benefits before applying a discount rate to calculate the Net Present Value (NPV). The last step is to calculate NPV, Internal Rate of Return (IRR), the payback period, and Benefit to Cost Ratio (BCR) to select the most economically beneficial alternative for reducing emissions in this particular distribution system. The NPV computes all expected cash flows associated with the project and subtracts it from the capital cost [65, 102, 103]. Thus, the NPV of any project is

$$\text{NPV}= \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - CF_0 \tag{6}$$

where T is the period of the project, *r* is the discount rate, CF_0 is investment cost, CF_t is the net cash flow at time *t*. The project is accepted if NPV $>$ 0 while the decision maker rejects the project when NPV $<$ 0. IRR is another metric that measures the profitability of the project. So, the IRR is the discount rate that makes the NPV equals zero.

$$\text{IRR}= \text{NPV} = \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t} - CF_0=0 \tag{7}$$

The payback period is the time required to recover the capital investment in a project. The cash flow is summed until it equals the initial investment in the project. Benefit to cost ratio, BCR, is another useful measure that summarizes the relationship between the related costs and benefits of the project. The benefits exceed the costs when BCR $>$ 1 and the project should be accepted. When BCR=1, the project indicates that the costs and benefits are equal, and the project can be accepted with little viability. If BCR $<$ 1, it means the costs are higher than the benefits, and the project should be rejected [65, 102, 103].

$$\text{BCR}= \frac{Present\ value\ of\ benefits}{Present\ value\ of\ costs} \tag{8}$$

The next section deploys CBA to estimate all costs and benefits which determine the best approach to achieving the goal.

7.3 Economic analysis of MCDM alternatives

This section investigates the benefits and costs of integrating DSM alternatives programs to the distribution system. Such analysis quantifies all the associated costs, and measures the estimated benefits for each scenario. Since each scenario has its own costs parameters, the costs vary based on the specified alternative. Further, the benefits obtained from every scenario take into account the revenue from the avoided operating and maintenance costs or bill reduction. It also monetizes the impact of every scenario on power quality, reliability, environmental collateral, and socioeconomic equity. Final results will show a rank the weighted value for each scenario to choose the one that gives the highest benefit over cost. It also allows the participant to trade off the proposed scenarios to choose the option with the best environmental impact for economic output and vice versa.

7.3.1 ESS

As explained in Section 6.3, ESS is dispatched during peak hours to shave the demand and avoid running resources like coal. While ESS has a capacity of 50 MW, 200 MWh, and serving for 4-hour peak load, this capacity is adjusted to match the IEEE 13-node system capacity. The new size of ESS is scaled down to 270.98 kW for 4-hour peak shaving (i.e. 1083.93 kWh). In that regard, PRPA proposes the estimated cost range of ESS for peak shaving. According to [93], the battery cost ranges between $340 and $450 per kWh. Power Conversion System (PCS) costs $150 to $350 per kW while power control system starts from $80 to $120/kW. Balance of plant could cost $90 up to $120 per kW, and procurement construction costs $150 to $180/kWh. Further, this study adjusts the cost of recycling to the size of the ESS used in the test system [104]. Since this is an economic evaluation for a new technology in the system, we take into account the worst-case scenario.

Hence, the analysis considers the highest price for each parameter. The prices for installing ESS are explained in Table 7-1, taken from [105].

Table 7-1: ESS Estimated Prices

Item	Price
Battery ($/kWh)	450
Power conversion system ($/kW)	350
Power control system ($/kW)	120
Balance of plant ($/kW)	120
Procurement construction ($/kWh)	180
Fixed O&M cost ($/kW year)	14
Variable cost ($/kWh)	0.0703

A research study in [105] estimates the discount rate for a storage system project is 5.09% while PRPA expects a 10 years lifetime for the ESS project. Further, EIA estimates the average load growth is 0.2% which is the load growth assumed in this calculation [106]. As PRPA proposes ESS to relief the stress on the system, all the costs and outcomes are studies based on the utility perspective. After performing a CBA, Table 7-2 illustrates all associated costs for installing ESS.

Table 7-2: Associated Costs of ESS Project

	Battery ($)	PCS ($)	Power Control System ($)	Balance of Plant ($)	Procurement Construction ($)	Recycling ($)	Fixed O&M Cost ($)	Variable Cost ($)	Total Cost ($)
Investment	487,773	94,845	32,518	130,073	48,777				793,986
1Y							3,794	23,640	27,433
2Y							3,801	23,687	27,488
3Y							3,809	23,734	27,543
4Y							3,817	23,782	27,598
5Y							3,824	23,829	27,654
6Y							3,832	23,877	27,709
7Y							3,840	23,925	27,764
8Y							3,847	23,973	27,820
9Y							3,855	24,021	27,876
10Y						125,000	3,863	24,069	152,931
Total	487,773	94,845	32,518	130,073	48,777	125,000	38,281	238,536	1,195,803

The benefits of installing ESS can be measured as a fuel saving cost, network support, or environmental benefits. The work in [105] concludes that integrating a storage system in the grid would improve DG integration by increasing electricity utilization. EIA determines a levelized avoided cost for resources like coal and natural gas. This calculation uses a \$0.082 and \$0.080 per kWh for coal and natural gas, respectively, to estimate the cost of fuel saving [107]. According to [108], there is a social cost of using fossil fueled generating units in which the environmental cost is \$11 per Kg of CO_2 and the cost will increase to reach \$26 per Kg of CO_2 by 2050. Thus, the avoided emissions, as a result of enabling ESS, is multiplied by \$11 to quantify the environmental benefits. According to [105], the benefit of utilizing DG is \$52.28/MWh, avoided from conventional resources. Maintaining acceptable limits of power quality and reliability could save up to \$62.71 per kW. The estimated benefits of integrating ESS in the distribution system is shown in Table 7-3.

Table 7-3: Estimated Benefits of ESS Project

	Fuel Saving ($)	Environmental benefit ($)	DG Integration ($)	Network Support ($)	Total Benefit ($)
1Y	26,860	3,373	175,801	16,993	223,028
2Y	26,914	3,379	176,153	16,993	223,440
3Y	26,968	3,386	176,505	16,993	223,853
4Y	27,022	3,393	176,858	16,993	224,267
5Y	27,076	3,400	177,212	16,993	224,681
6Y	27,130	3,406	177,566	16,993	225,097
7Y	27,185	3,413	177,922	16,993	225,513
8Y	27,239	3,420	178,277	16,993	225,930
9Y	27,293	3,427	178,634	16,993	226,348
10Y	27,348	3,434	178,991	16,993	226,767
Total	271,037	34,031	1,773,920	169,935	2,248,923

Table 7-4 summarizes the findings from the economic evaluation. The project is beneficial since BCR is greater than 1, and the project will pay its capital cost after about 4 years.

Table 7-4: Economic Results for ESS Project

NPV ($)	644,975
IRR	20.40%
Payback (years)	4.05
BCR	1.392

Figure 7-1 shows cash flow and cumulative cash flow for ESS. In Figure 7-2, the project starts getting positive cash flow after the fourth year.

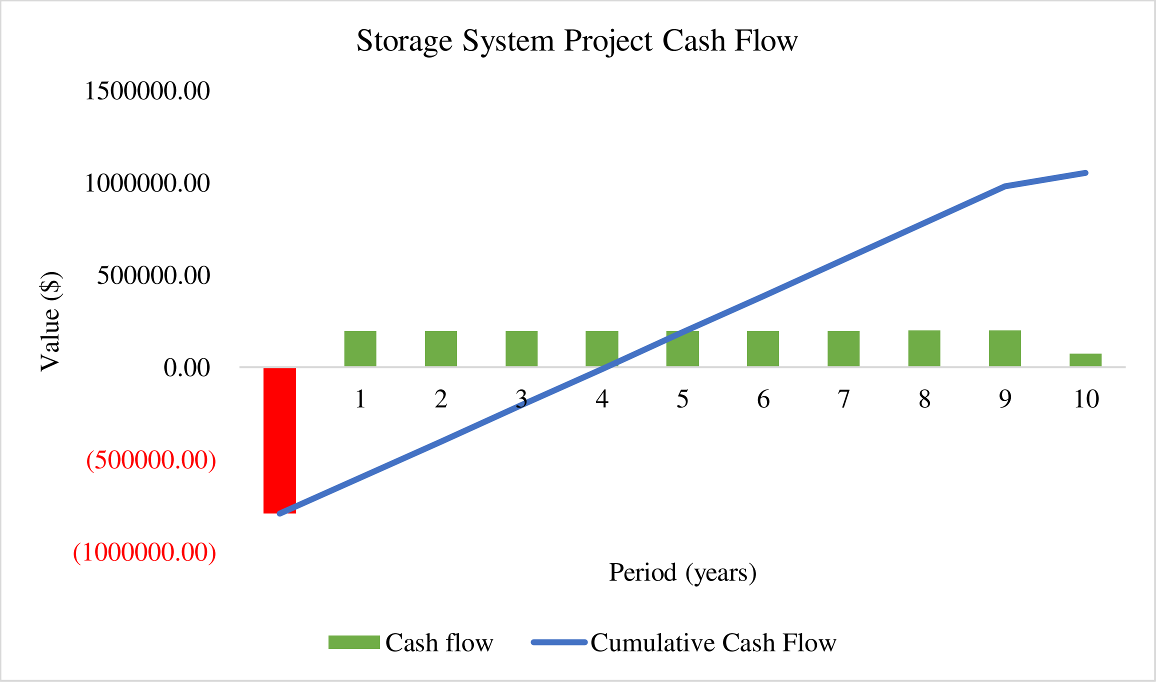

Figure 7-1: Cash Flow for ESS project

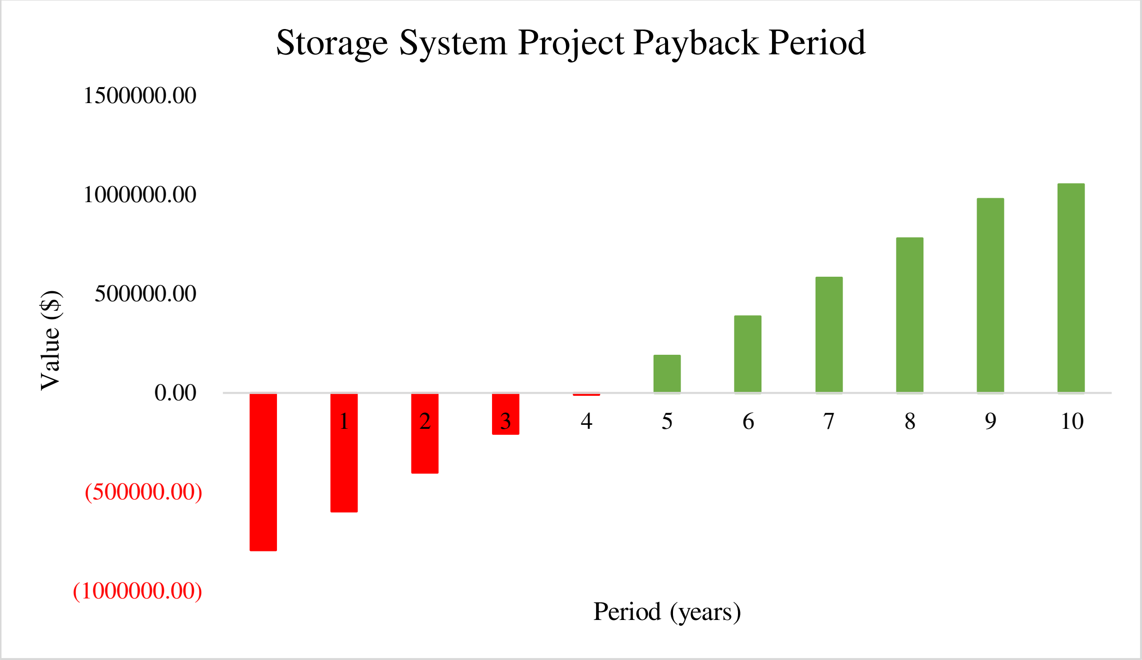

Figure 7-2: Payback period for ESS project

7.3.2 Energy conservation

The DOE explains the cost of implementing a conservation program in Fort Collins in [109]. This includes installing about 85,328 smart meters, 2,347 programmable communicating thermostats, and 1,710 direct load control devices. The investment cost of this energy conservation project is adjusted to the test system. Further, there is an operating cost to deploy such a project which is $0.035 per kWh saved [110]. Implementing energy conservation programs can cause inconvenience for the participants. Therefore, this analysis defines socioeconomic cost as a societal cost. EPA estimates socioeconomic cost as $0.214 per kWh [111]. Moreover, Fort Collins has a rebate program to replace the low efficient equipment with higher efficiency appliances [112]. Table 7-5 illustrates the utility costs of deploying energy conservation project.

Table 7-5: Associated Costs of Energy Conservation Project

	Capital Cost ($)	Program Cost ($)	Socioeconomic Cost ($)	Rebate ($)	Total Cost ($)
Investment	216,188				217,532
1Y		30,165	184,437		214,602
2Y		30,225	184,806		215,031
3Y		30,286	185,175		215,461
4Y		30,346	185,546		215,892
5Y		30,407	185,917		216,324
6Y		30,468	186,289		216,756
7Y		30,529	186,661		217,190
8Y		30,590	187,034		217,624
9Y		30,651	187,408		218,059
10Y		30,712	187,783	1,344	218,496
Total	216,188	304,378	1,861,056	1,344	2,382,966

The benefits obtained from reducing the energy demand and mitigating environmental footprints are calculated as explained in subsection 7.3.1. The report from [109] shows the utility avoided and deferred costs after implementing the conservation project while the socioeconomic benefit is obtained, from [111] after excluding avoided carbon cost. Table 7-6 presents the benefits yielding the utility uses the conservation program.

Table 7-6: Estimated Benefits for Energy Conservation Project

	Fuel Saving ($)	Reduced O&M Cost ($)	Environmental Benefit ($)	Deferred Investment ($)	Network Support ($)	Socioeconomic Benefit ($)	Total Benefit ($)
1Y	96,709	4,811	7,431	1,626	2,168	142,206	254,951
2Y	96,902	4,821	7,446	1,629	2,172	142,490	255,461
3Y	97,096	4,830	7,461	1,632	2,177	142,775	255,972
4Y	97,290	4,840	7,476	1,636	2,181	143,061	256,484
5Y	97,485	4,850	7,491	1,639	2,185	143,347	256,997
6Y	97,680	4,859	7,506	1,642	2,190	143,634	257,511
7Y	97,875	4,869	7,521	1,646	2,194	143,921	258,026
8Y	98,071	4,879	7,536	1,649	2,198	144,209	258,542
9Y	98,267	4,889	7,551	1,652	2,203	144,497	259,059
10Y	98,463	4,898	7,566	1,655	2,207	144,786	259,577
Total	975,837	48,546	74,987	16,406	21,875	1,434,926	2,572,578

Table 7-7 demonstrates the final calculation for the energy conservation project. Although the project is acceptable, the project takes a longer time than ESS to recover its expenses.

Table 7-7: Economic Results for Energy Conservation Project

NPV ($)	95,229
IRR	13.34%
Payback (years)	5.37
BCR	1.051

The economic behavior of this project is shown in Figure 7-3, and Figure 7-4 clarifies that the project requires half its lifetime to recover its expenses.

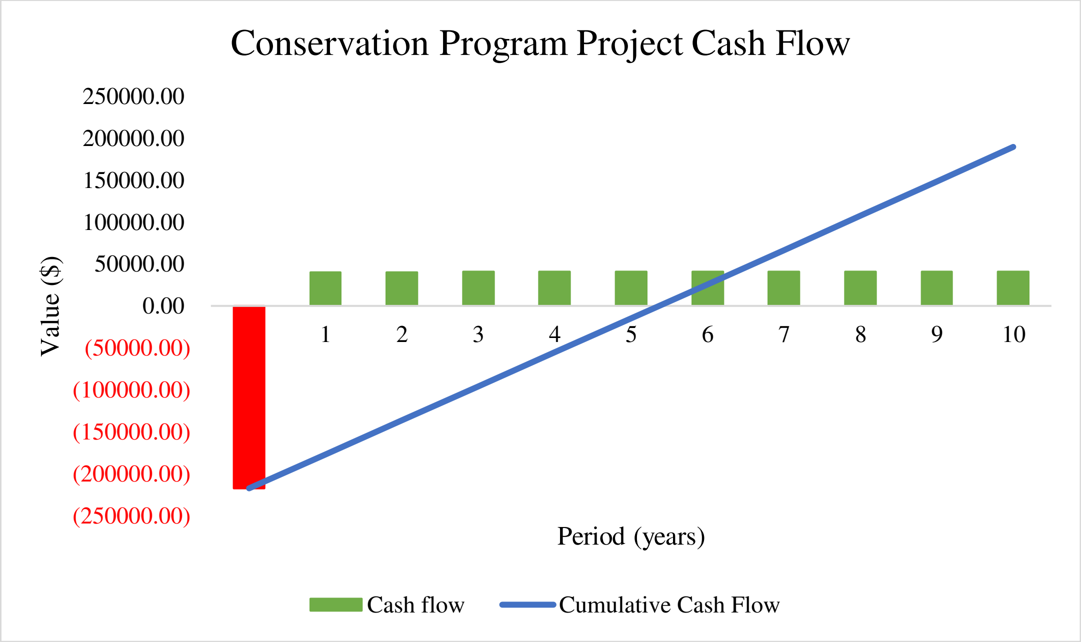

Figure 7-3: Cash Flow for energy conservation project

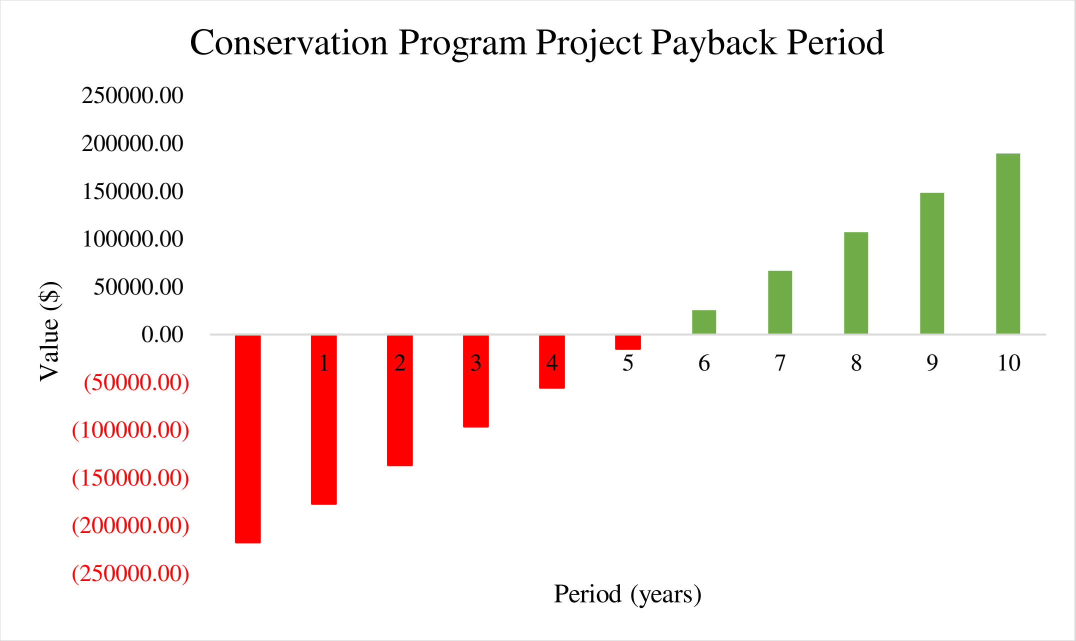

Figure 7-4: Payback period for energy conservation project

7.3.3 ESS with energy conservation

The economic analysis of this scenario includes all the expected costs from ESS and energy conservation. Table 7-8 states all the expenses needed to deploy this project. We notice that the final cost after 10 years is higher than expected. This is reasonable since this scenario has a capital cost and higher operating costs. After calculating the outcomes of this scenario, it saves energy more than expected since ESS and efficient appliances are displacing the energy needed from other resources. Table 7-9 shows all the expected benefits from this scenario.

Table 7-8: Estimated Costs of combining ESS with Energy Conservation

	Battery ($)	PCS ($)	Power Control System ($)	Balance of plant ($)	Procurement Construction ($)	Conservation Capital cost ($)	Socioeconomic Cost	Fixed O&M Cost ($)	Variable Cost ($)	Conservation Program Cost ($)	Recycling ($)	Rebate ($)	Total Cost ($)
Investment	439,898	85,453	29,298	117,306	43,947	216,188							932,089
1Y							184,437	3,598	22,458	30,165			240,657
2Y							184,806	3,605	22,503	30,225			241,139
3Y							185,175	3,612	22,548	30,286			241,621
4Y							185,546	3,620	22,593	30,346			242,104
5Y							185,917	3,627	22,638	30,407			242,588
6Y							186,289	3,634	22,683	30,468			243,074
7Y							186,661	3,641	22,729	30,529			243,560
8Y							187,034	3,649	22,774	30,590			244,047
9Y							187,409	3,656	22,820	30,651			244,535
10Y							187,783	3,663	22,865	30,712	125,000	1,344	371,368
Total	439,898	85,453	29,298	117,306	43,947	216,188	1,861,056	36,306	226,609	304,378	125,000	1,344	3,486,782

Table 7-9: Estimated Benefits of combining ESS with Energy Conservation Project

	Fuel Saving ($)	Reduced O&M Cost ($)	Environmental Benefit ($)	Deferred Investment ($)	DG Integration ($)	Network Support ($)	Socioeconomic Benefit ($)	Total Benefit ($)
1Y	42,699	4,811	10,635	1,626	167,011	19,161	135,600	381,544
2Y	42,785	4,821	10,657	1,629	167,345	19,166	135,871	382,273
3Y	42,870	4,830	10,678	1,632	167,680	19,204	136,143	383,038
4Y	42,956	4,840	10,699	1,636	168,015	19,242	136,415	383,804
5Y	43,042	4,850	10,721	1,639	168,351	19,281	136,688	384,571
6Y	43,128	4,859	10,742	1,642	168,688	19,319	136,961	385,340
7Y	43,214	4,869	10,764	1,646	169,025	19,358	137,235	386,111
8Y	43,301	4,879	10,785	1,649	169,363	19,397	137,510	386,883
9Y	43,387	4,889	10,807	1,652	169,702	19,436	137,785	387,657
10Y	43,474	4,898	10,828	1,655	170,042	19,474	138,060	388,432
Total	430,856	48,546	107,317	16,406	1,685,224	193,039	1,368,266	3,849,654

The results are not surprising since this scenario incorporates more cost. The project requires more than 6 years and 6 months to pay its investment cost. However, it is still economically acceptable. Table 7-10 gives an economic summary about merging ESS and conservation programs. Figure 7-5 and 7-6 represents the project's cash flow and the payback period, respectively.

Table 7-10: Economic Results after using ESS and Energy Conservation Project

NPV ($)	82,837
IRR	7.02%
Payback (years)	6.58
BCR	1.027

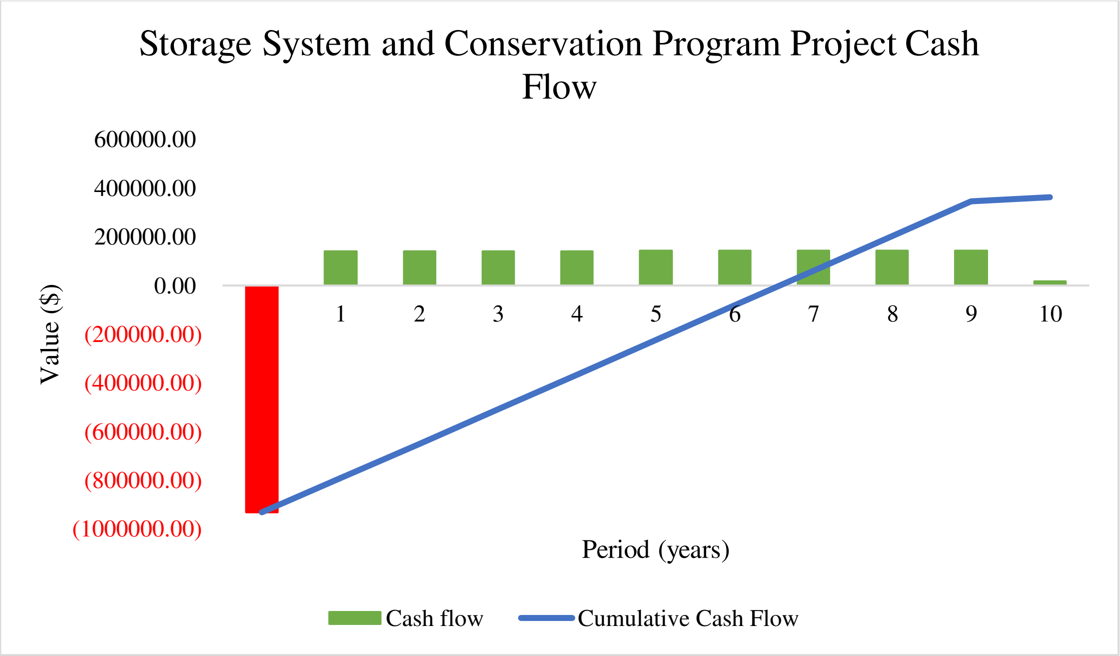

Figure 7-5: Cash Flow for the project of ESS with energy conservation

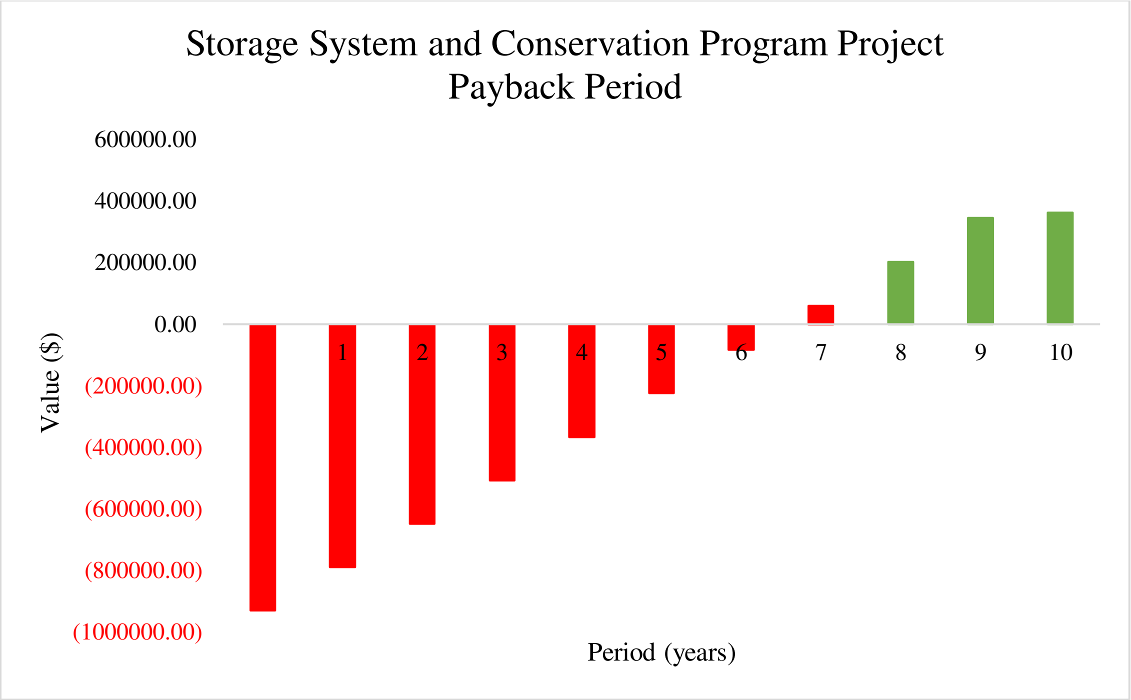

Figure 7-6: Payback period for the project of ESS with energy conservation

7.3.4 Communication and intelligence

As explained in Chapter 6, the residential DR program represents communication and intelligence since this alternative leads to change the end-use demand curve. The economic evaluation of this option is implemented according the DR model in [65], which studies the system from the utility point of view. Since this alternative is deployed in the residential sector, the capital cost is excluded and scaled down from [109]. The energy cost, energy sales, and peak demand cost for the base case are calculated as follows [65]:

$$\text{Energy cost} = Q * \pi_r \tag{9}$$

where Q is the energy consumption and π_r is the retail price. PRPA determines the energy charges as \$0.04282/kWh for summer season and \$0.04109/kWh for winter season [113]. The energy sales before DR can be calculated from:

$$\text{Energy sales} = D * \pi_{wh} \tag{10}$$

Where *D* is the demand curve and π_{wh} is the wholesale price. The utility charges the customers for energy usage based on the old electric rates for residential energy use, before DR. Table 7-11 shows the usage charge per kWh, regenerated from [114].

Table 7-11: Residential Energy Rate before DR Program

Usage Charge	Summer Season	Non-Summer Season
First 500 kWh	\$0.09582	\$0.09031
Next 500 kWh	\$0.11448	\$0.09487
All additional kWh	\$0.15158	\$0.10494

Monthly peak demand is the user’s demand during the hour that coincides with the system’s monthly peak. An \$11.56 charge is applied per kW as a demand charge for summer season and this charge decreases to \$8.81/kW for non-summer times [113]. The utility applies a 60-minute charge on coincident demand using:

$$\text{PCD}= \sum_{m=1}^{12} \pi_{DC} * P_m \qquad (11)$$

where PCD is the peak demand charge, P_m is the coincident peak demand, and π_{DC} is the demand charge. The energy cost, energy sales, and peak demand cost for the DR are calculated for the modified energy consumption, Q':

$$\text{Energy cost}= \text{Q'}*\pi_r \qquad (12)$$

The electricity sold after DR depends on the new demand curve, D', and the pricing mechanism, explained in Figure 6-10 and Figure 6-11:

$$\text{Energy sales}= \text{D'}*\pi_{wh} \qquad (13)$$

While the peak demand charge, PCD', changes according to the new coincident peak demand, P_m', the monthly peak demand rates remains the same during coincident demand:

$$\text{PCD'}= \sum_{m=1}^{12} \pi_{DC} * P_m{}' \qquad (14)$$

The cost of incorporating such a technique requires evaluating the capital cost and the variable costs. According to [115], the variable cost of applying DR is adjusted, $28 per kW, to match the size of the test system. The operating and maintenance costs can be communications labor cost or controls labor cost [115]. The following equation shows all the associated costs of DR where DR_{inv} is the investment cost of DR and $C_{O\&M}$ is the annual operating and maintenance cost.

$$\text{Total cost}= DR_{inv} + C_{O\&M} \qquad (15)$$

This alternative incurs a yearly financial benefit by obtaining the difference between the energy sales and the peak demand charges. Table 7-12 illustrates the first-year financial impact.

$$\text{Total benefits}= \sum_{t=1}^{8760}(PCD' - PCD) + (\, D'*\pi_{wh} - D * \pi_{wh}) \qquad (16)$$

Table 7-12: The First Year Financial Impact

	Energy Sales ($)	Energy Cost ($)	Demand Charge ($)	DR Cost ($)
Base case	492,378	224,074	105,930	
DR	595,012	221,440	103,694	67,018

After performing a CBA, the economic analysis in Table 7-13 shows the cost of residential DR for 10 years.

Table 7-13: Associated Costs of Residential DR Project

	Fixed Cost ($)	Variable Cost ($)	Total Cost ($)
Investment	67,018		67,018
1Y		100,156	100,156
2Y		100,356	100,356
3Y		100,557	100,557
4Y		100,758	100,758
5Y		100,960	100,960
6Y		101,162	101,162
7Y		101,364	101,364
8Y		101,567	101,567
9Y		101,770	101,770
10Y		101,973	101,973
Total	67,018	1,010,622	1,077,640

The analysis shows several benefits from the program. As smart meters and thermostat devices are the enablers of residential DR, the analysis adjusted the expected benefits such as reduced cost and investment deferral from [109]. Table 7-14 summarizes the expected benefits after using residential DR.

Table 7-14: Estimated Benefits of Applying Residential DR Project

	Sold Electricity ($)	Fuel Saving ($)	Reduced O&M Cost ($)	Environmental Benefit ($)	Deferred Investment ($)	Network Support ($)	Total Benefit ($)
1Y	104,226	6,516	1,491	209	504	672	113,618
2Y	106,662	6,529	1,494	209	505	673	116,073
3Y	106,875	6,542	1,497	210	506	675	116,305
4Y	107,089	6,555	1,500	210	507	676	116,538
5Y	107,303	6,568	1,503	211	508	677	116,771
6Y	107,518	6,581	1,506	211	509	679	117,005
7Y	107,733	6,594	1,509	212	510	680	117,239
8Y	107,948	6,608	1,512	212	511	682	117,473
9Y	108,164	6,621	1,515	212	512	683	117,708
10Y	108,381	6,634	1,519	213	513	684	117,944
Total	1,071,900	65,749	15,049	2,109	5,086	6,781	1,166,674

The economic evaluation shows the project in economically beneficial in order to reduce the environmental impact. Table 7-15 explains the economic outcomes of this alternative.

Table 7-15: Economic Results for Residential DR Project

NPV ($)	52,450
IRR	18.83%
Payback (years)	4.40
BCR	1.062

Figure 7-7 and Figure 7-8 demonstrate that the project pays the investment after the fourth year. Although the project requires annual expenses to implement the program, it takes less time to recover the capital cost with less benefit.

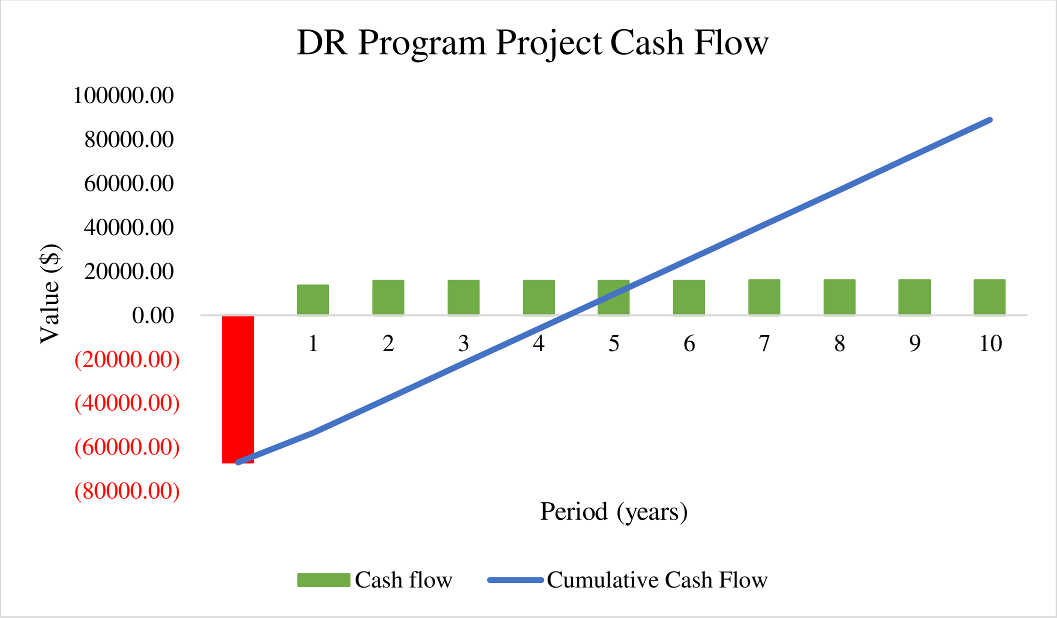

Figure 7-7: Cash Flow for residential DR project

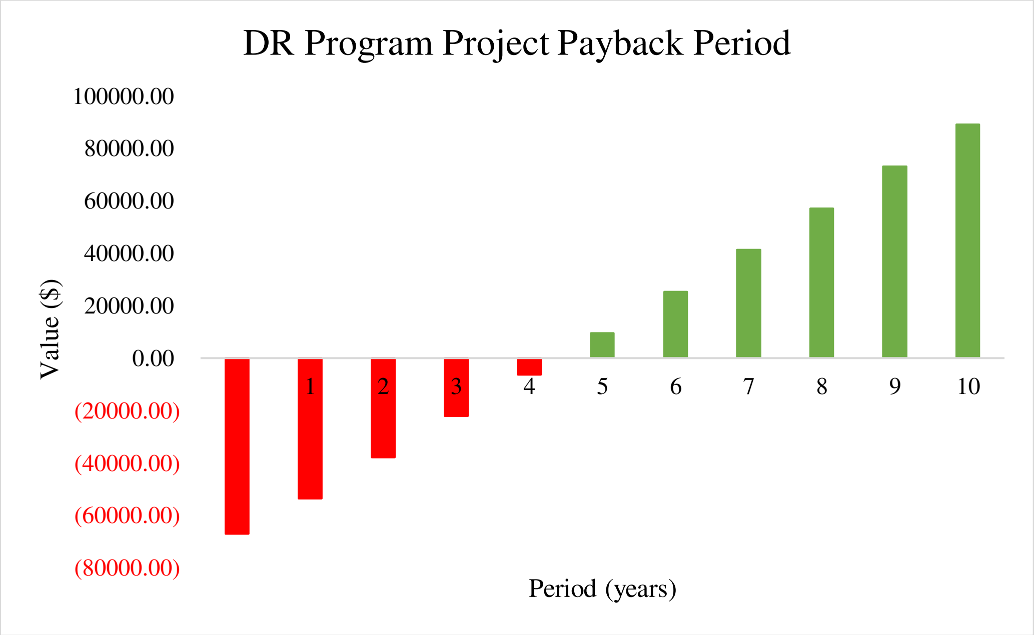

Figure 7-8: Payback period for residential DR project

7.3.5 Communication and intelligence with ESS

This subsection investigates the economic approach of combining residential DR and ESS. All the utility costs and benefits follow the methodologies explained in subsections 7.3.1 and 7.3.4. Since ESS is integrated in the residential electricity sector, the investment cost in Table 7-2 is extracted for the residential sector only, and the DR framework model is the same. Table 7-16 shows the financial year impact of merging residential DR and ESS.

Table 7-16: The First Year Financial Impact for Residential DR with ESS Project

	Energy Sales ($)	Energy Cost ($)	Demand Charge ($)	DR Cost ($)
Base case	492,378	224,074	105,930	
DR with ESS	578,846	217,432	95,899	67,018

All the costs relevant to the residential DR or ESS are discussed and adapted to the size of the test system as stated in Table 7-17. In Table 7-18, all the expected benefits from this type of combination are investigated. It shows how DR and ESS work together to achieve such benefits. The results are not surprising since the main goal of these alternatives is shaving the peak during high demand for electricity. Even this scenario takes a longer time than the residential DR project to pay the capital cost, Table 7-19 shows this option is more beneficial than the previous alternative.

Table 7-17: Costs of deploying Residential DR with ESS Project

	DR Capital Cost ($)	Battery ($)	PCS ($)	Power Control System Cost ($)	Balance of Plant ($)	EPC ($)	Recycling ($)	Fixed O&M Cost ($)	Variable Cost ($)	Total Cost ($)
Investment	67,018	151,210	29,402	10,081	40,323	15,121				313,154
1Y								101,332	6,929	108,261
2Y								101,535	6,943	108,478
3Y								101,738	6,957	108,695
4Y								101,941	6,971	108,912
5Y								102,145	6,985	109,130
6Y								102,349	6,999	109,348
7Y								102,554	7,013	109,567
8Y								102,759	7,027	109,786
9Y								102,965	7,041	110,005
10Y							38,750	103,171	7,055	148,975
Total	67,018	151,210	29,402	10,081	40,323	15,121	38,750	1,022,489	69,918	1,444,310

Table 7-18: Estimated Benefits of using Residential DR with ESS Project

	Sold Electricity ($)	Fuel Saving ($)	Reduced O&M Cost ($)	Environmental Benefit ($)	Deferred Investment ($)	DG Integration ($)	Network Support ($)	Total Benefit ($)
1Y	87,870	22,682	1,491	1,195	504	51,530	5,940	171,213
2Y	89,894	22,728	1,494	1,197	505	51,633	5,952	173,403
3Y	90,074	22,773	1,497	1,199	506	51,736	5,963	173,750
4Y	90,254	22,819	1,500	1,202	507	51,840	5,975	174,097
5Y	90,434	22,864	1,503	1,204	508	51,944	5,987	174,445
6Y	90,615	22,910	1,506	1,207	509	52,048	5,999	174,794
7Y	90,797	22,956	1,509	1,209	510	52,152	6,011	175,144
8Y	90,978	23,002	1,512	1,211	511	52,256	6,023	175,494
9Y	91,160	23,048	1,515	1,214	512	52,360	6,035	175,845
10Y	91,342	23,094	1,519	1,216	513	52,465	6,047	176,197
Total	903,419	228,876	15,049	12,054	5,086	519,964	59,934	1,744,383

Table 7-19: Economic Results after Combining Residential DR and ESS Project

NPV ($)	163,759
IRR	15.27%
Payback (years)	4.84
BCR	1.139

To track the financial behavior for each year, Figures 7-9 and 7-10 shows cash flow, cumulative cash flow, and the payback period.

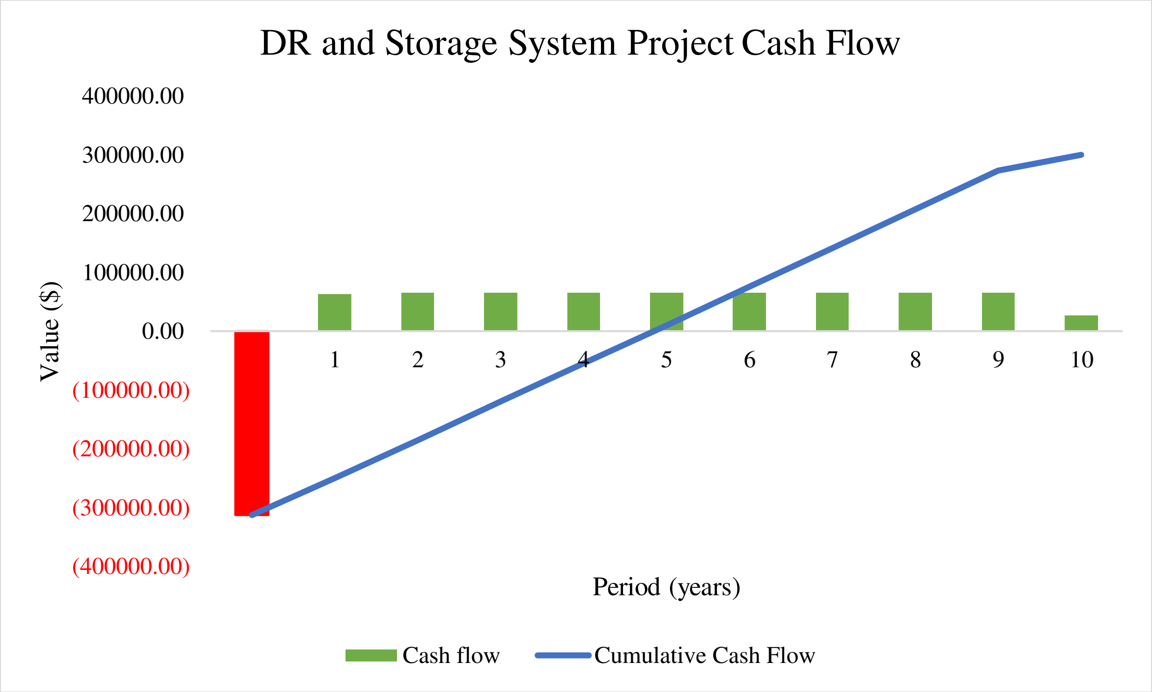

Figure 7-9: Cash flow for residential DR and ESS project

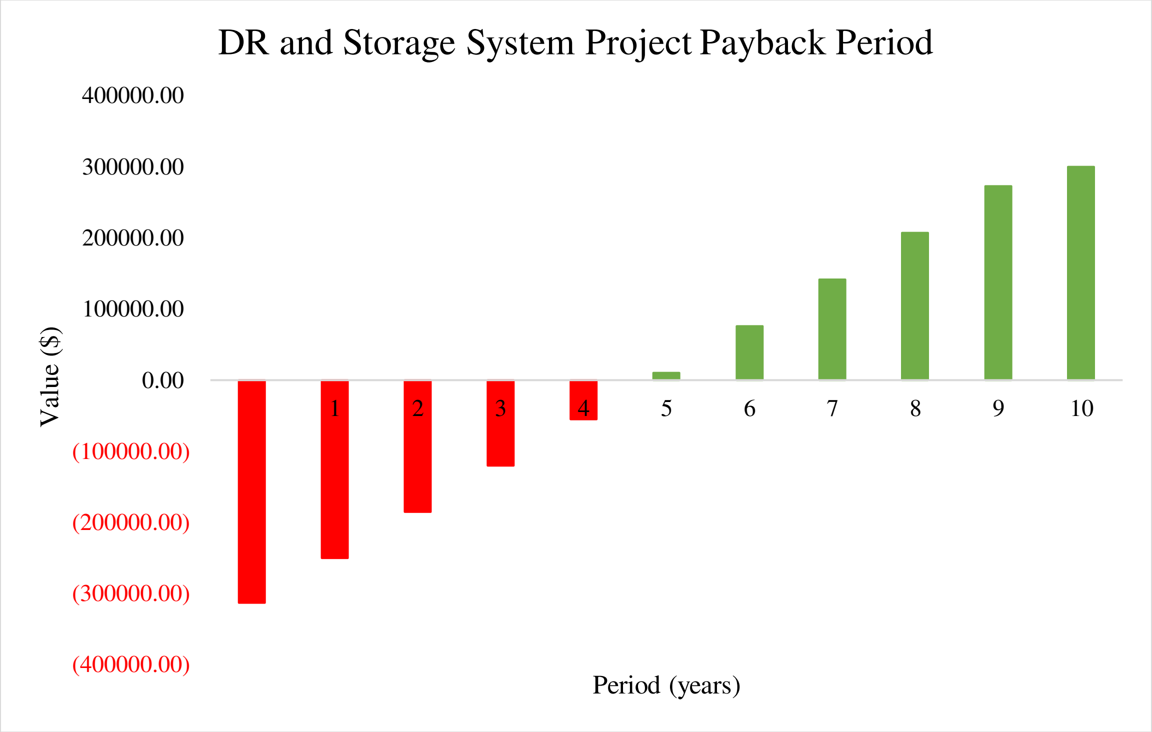

Figure 7-10: Payback period for residential DR and ESS project

7.3.6 Communication and intelligence with energy conservation

This scenario assumes applying conservation programs along with the residential DR. Conservation program uses the same model in subsection 7.3.2. The cost of implementing such a scenario might be higher since there is an effect on the convenience of the participants. After the first year, the residential DR increased the energy sales and reduced the costs of purchasing electricity as shown in Table 7-20. However, the total cost increases with incorporating energy conservation programs as stated in table 7-21.

Table 7-20: The First Year Financial Impact after incorporating Energy Conservation with Residential DR Project

	Energy Sales ($)	Energy Cost ($)	Demand Charge ($)	DR Cost ($)
Base case	492,378	224,074	105,930	
DR with energy conservation	565,262	210,368	98,509	67,018

Table 7-21: Costs of applying Residential DR with Energy Conservation Project

	Capital Cost ($)	Program Cost ($)	Socioeconomic Cost ($)	Variable Cost ($)	Recycling ($)	Total Cost ($)
Investment	134,036					134,036
1Y		10,205	54,232	100,156		164,593
2Y		10,225	54,340	100,356		164,922
3Y		10,246	54,449	100,557		165,252
4Y		10,266	54,558	100,758		165,582
5Y		10,287	54,667	100,960		165,913
6Y		10,307	54,776	101,162		166,245
7Y		10,328	54,886	101,364		166,578
8Y		10,349	54,996	101,567		166,911
9Y		10,369	55,106	101,770		167,245
10Y		10,390	55,216	101,973	1,222	167,579
Total	134,036	102,973	547,225	1,010,622	1,222	1,794,856

The benefit pertaining to this scenario ranges from reducing electricity bills and decreasing dependency on fossil-fueled generators. Table 7-22 illustrates the potential outcomes of using energy conservation with the residential DR.

Table 7-22: Expected Benefit of merging Energy Conservation with Residential DR

	Sold Electricity ($)	Fuel Saving ($)	Reduced O&M Cost ($)	Environmental Benefit ($)	Deferred Investment ($)	Network Support ($)	Socioeconomic Benefit ($)	Total Benefit ($)
1Y	74,343	36,267	2,983	2,509	1,008	1,344	64,145	182,598
2Y	76,029	36,339	2,989	2,514	1,010	1,347	64,273	184,502
3Y	76,181	36,412	2,995	2,519	1,012	1,349	64,402	184,871
4Y	76,334	36,485	3,001	2,524	1,014	1,352	64,531	185,240
5Y	76,486	36,558	3,007	2,529	1,016	1,355	64,660	185,611
6Y	76,639	36,631	3,013	2,534	1,018	1,358	64,789	185,982
7Y	76,793	36,704	3,019	2,539	1,020	1,360	64,919	186,354
8Y	76,946	36,777	3,025	2,544	1,022	1,363	65,049	186,727
9Y	77,100	36,851	3,031	2,550	1,024	1,366	65,179	187,100
10Y	77,254	36,925	3,037	2,555	1,026	1,368	65,309	187,474
Total	764,105	365,947	30,099	25,318	10,172	13,562	647,256	1,856,458

After specifying all the utility costs and benefits obtained from this partnership between conservation programs and DR, the findings demonstrate this project has the longest time among others to recover the cost and starts receiving profit. Also, Table 7-23 indicates that this project is accepted based on its BCR value with less benefit when compared to other alternatives. Figure 7-11 explains the incurred cash for each year while Figure 7-12 illustrates the payback period during the life of the project

Table 7-23: Economic Results for Residential DR with Energy Conservation Project

NPV ($)	14,746
IRR	7.26%
Payback (years)	6.96
BCR	1.010

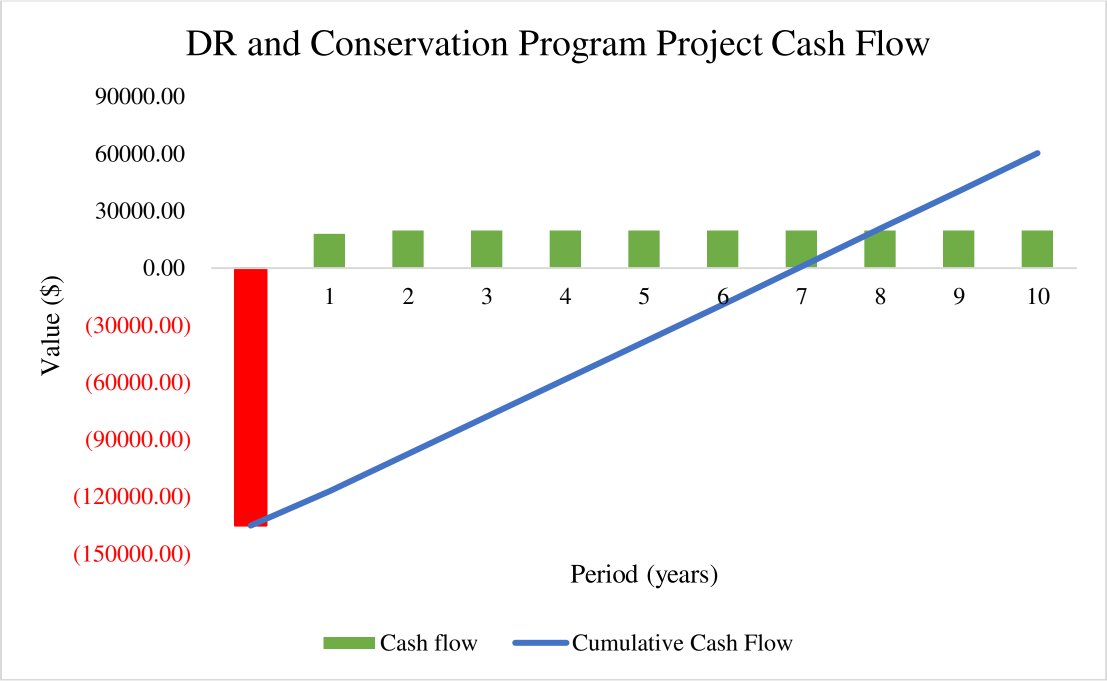

Figure 7-11: Cash Flow for residential DR with energy conservation project

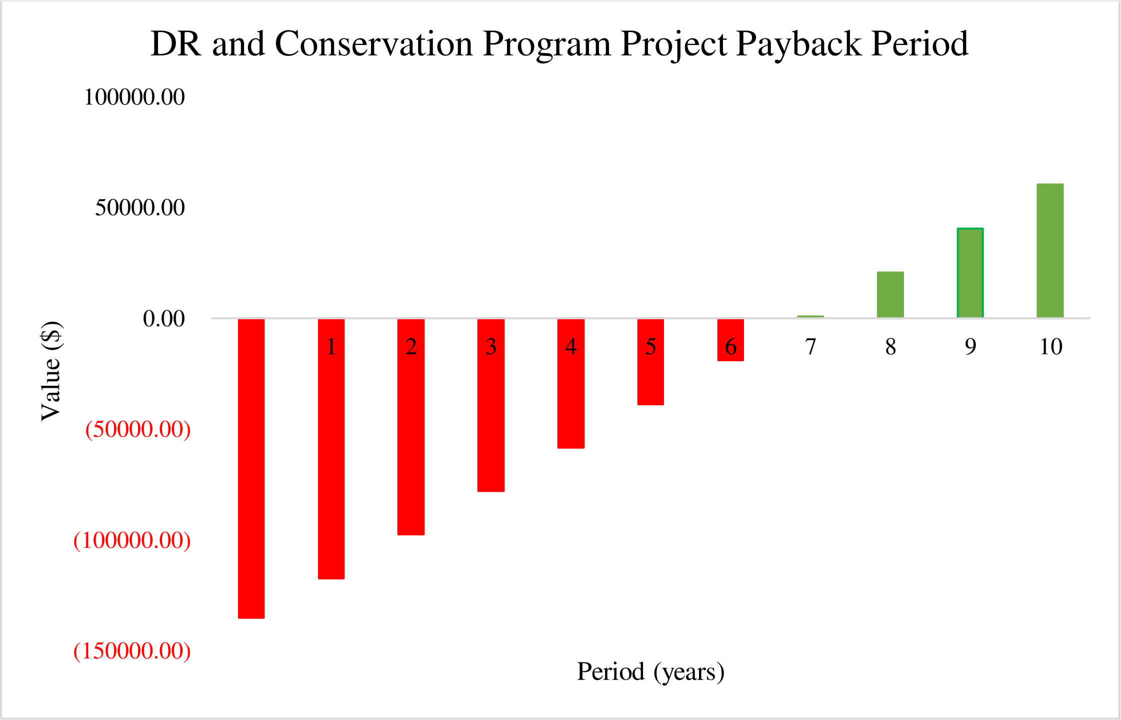

Figure 7-12: Payback period from residential DR with energy conservation project

7.3.7 Communication and intelligence with ESS and energy conservation

Last scenario is to investigate the economic approach of combining all the proposed alternatives on the electricity residential sector. Environmentally, this option successfully achieved about 20% reduction in total emissions from the electricity residential sector. However, this subsection studies the utility economic viability of this approach. In that regard, the analysis takes into consideration the methodologies in subsections 7.3.4, 7.3.5, and 7.3.6. The results demonstrate that this scenario performs better than the base case. Table 7-24 shows the first financial year for the DR program with ESS and energy conservation. The costs needed to perform such a project is explained in Table 7-25.

Table 7-24: The First Year Financial Impact after combining All MCDM Alternatives

	Energy Sales ($)	Energy Cost ($)	Demand Charge ($)	DR Cost ($)
Base case	492,378	224,074	105,930	
DR with ESS and energy conservation	549,903	206,560	91,105	67,018

Including ESS with DR and energy conservation increased the predicted benefits since ESS discharge the stored energy during peaking demand and in turn increased the convenience level for the participants. Table 7-26 described all the expected benefits

Table 7-25: Costs of combining All MCDM Alternatives

	DR & Con Capital Cost ($)	Battery ($)	PCS ($)	Power Control System Cost ($)	Balance of Plant ($)	EPC ($)	Program Cost ($)	Socioeconomic Cost ($)	Fixed O&M Cost ($)	Variable Cost ($)	Recycling ($)	Total Cost ($)
Investment	134,036	143,649	27,932	9,577	38,306	14,365						367,865
1Y							10,205	54,232	101,273	6,583		172,293
2Y							10,225	54,340	101,476	6,596		172,637
3Y							10,246	54,449	101,679	6,609		172,983
4Y							10,266	54,558	101,882	6,622		173,328
5Y							10,287	54,667	102,086	6,636		173,675
6Y							10,307	54,776	102,290	6,649		174,022
7Y							10,328	54,886	102,495	6,662		174,371
8Y							10,349	54,996	102,700	6,675		174,719
9Y							10,369	55,106	102,905	6,689		175,069
10Y							10,390	55,216	103,111	6,702	1,222	175,419
Total	134,036	143,649	27,932	9,577	38,306	14,365	102,973	547,225	1,021,895	66,423	1,222	2,106,381

Table 7-26: Benefits of combining All MCDM Alternatives

	Sold Electricity ($)	Fuel Saving ($)	Reduced O&M Cost ($)	Environmental Benefit ($)	Deferred Investment ($)	DG Integration ($)	Network Support ($)	Socioeconomic Benefit ($)	Total Benefit ($)
1Y	58,805	51,625	2,983	3,453	1,008	51,530	5,940	64,145	239,489
2Y	60,111	51,728	2,989	3,460	1,010	51,633	5,952	64,273	241,156
3Y	60,231	51,831	2,995	3,467	1,012	51,736	5,963	64,402	241,638
4Y	60,352	51,935	3,001	3,474	1,014	51,840	5,975	64,531	242,122
5Y	60,473	52,039	3,007	3,481	1,016	51,944	5,987	64,660	242,606
6Y	60,594	52,143	3,013	3,488	1,018	52,048	5,999	64,789	243,091
7Y	60,715	52,247	3,019	3,495	1,020	52,152	6,011	64,919	243,577
8Y	60,836	52,352	3,025	3,502	1,022	52,256	6,023	65,049	244,065
9Y	60,958	52,456	3,031	3,509	1,024	52,360	6,035	65,179	244,553
10Y	61,080	52,561	3,037	3,516	1,026	52,465	6,047	65,309	245,042
Total	604,154	520,918	30,099	34,841	10,172	519,964	59,934	647,256	2,427,338

The economic results show the improvement after integrating ESS with the two remaining alternatives. The NPV has been increased as well as BCR while the payback period decreased as stated in Table 7-27. Figure 7-13 explains the cash flow for each year, and Figure 7-14 illustrates the required years for the project to pay its capital cost.

Table 7-27: Economic Results for combining All MCDM Alternatives

NPV ($)	160,315
IRR	13.30%
Payback (years)	5.37
BCR	1.094

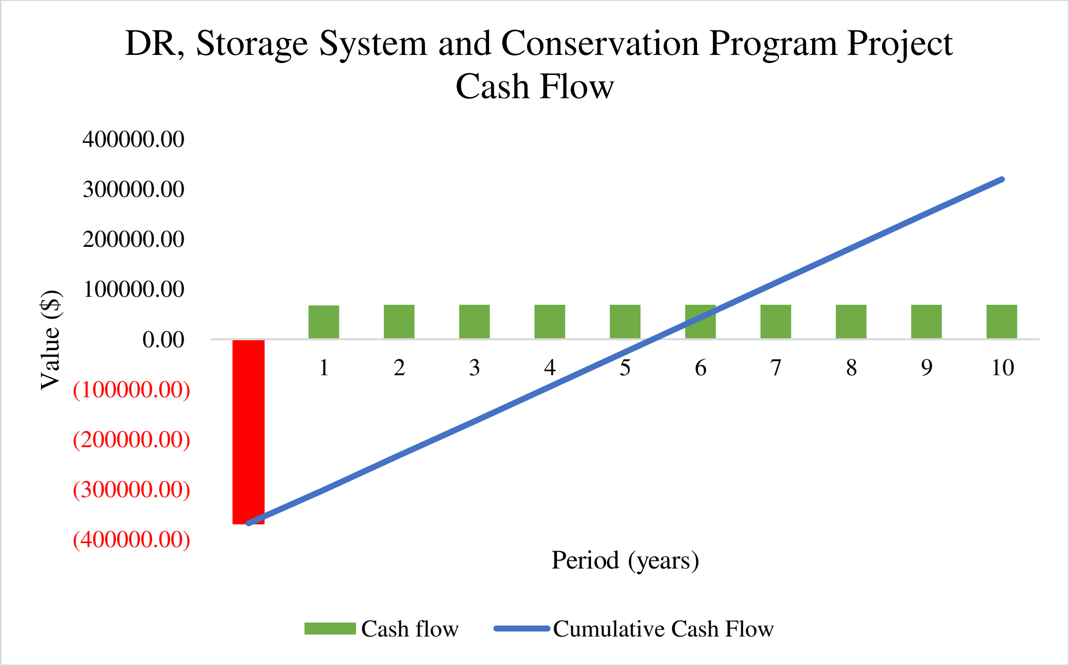

Figure 7-13: Cash flow after combining all MCDM alternatives

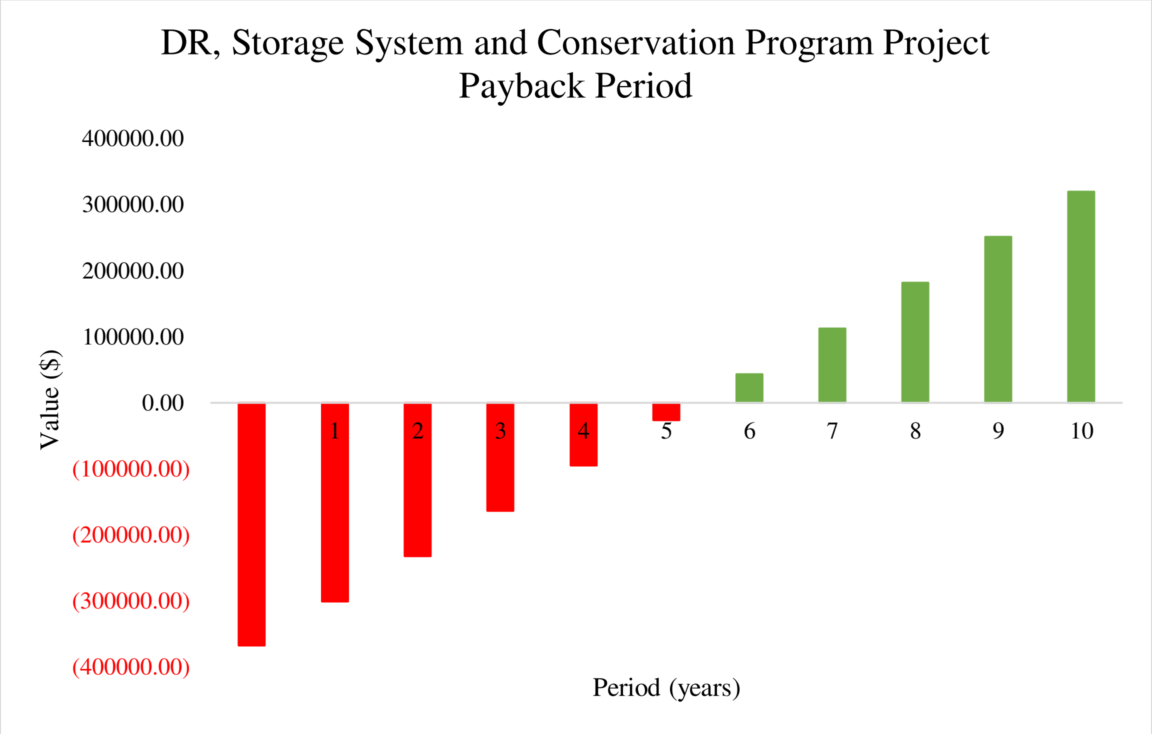

Figure 7-14: Payback period after combining all MCDM alternatives

7.4 Results

This section discusses the final economic evaluation among the proposed alternatives. The pertinent results to the above studied scenarios show that all the projects are economically accepted. They provide a positive NPVs, pay their costs during the life of the project, and their BCRs are greater than one. Table 7-28 illustrates the cash flow for each project for 10 years. Further, Table 7-29 explains the cumulative cash flow of the projects. To clearly justify all alternatives, we compare all the projects by obtaining the NPVs, the IRRs, the payback period, the BCRs, and the total expected emissions reduction for each alternative. Table 7-30 makes a comparison between all available options.

Table 7-28: Cash Flow for All Projects

Year	ESS ($)	Energy Conservation ($)	ESS and Energy Conservation ($)	Residential DR ($)	Residential DR and ESS ($)	Residential DR and Energy Conversation ($)	Residential DR, ESS and Energy Conversation ($)
Investment	(793,986)	(217,532)	(932,089)	(67,018)	(313,154)	(135,258)	(367,865)
1	195,595	40,349	140,887	13,462	62,952	18,006	67,196
2	195,952	40,430	141,134	15,717	64,925	19,580	68,519
3	196,310	40,511	141,417	15,748	65,055	19,619	68,656
4	196,668	40,592	141,699	15,780	65,185	19,658	68,793
5	197,028	40,673	141,983	15,811	65,316	19,697	68,931
6	197,388	40,754	142,267	15,843	65,446	19,737	69,069
7	197,749	40,836	142,551	15,875	65,577	19,776	69,207
8	198,110	40,918	142,836	15,907	65,708	19,816	69,345
9	198,472	40,999	143,122	15,938	65,840	19,855	69,484
10	73,835	41,081	17,064	15,970	27,221	19,895	68,401

Table 7-29: Cumulative Cash Flow for All Projects

Year	ESS ($)	Energy Conservation ($)	ESS and Energy Conservation ($)	Residential DR ($)	Residential DR and ESS ($)	Residential DR and Energy Conversation ($)	Residential DR, ESS and Energy Conversation ($)
	(793,986)	(217,532)	(932,089)	(67,018)	(313,154)	(135,258)	(367,865)
1	(598,391)	(177,183)	(791,202)	(53,556)	(250,202)	(117,253)	(300,669)
2	(402,439)	(136,753)	(650,068)	(37,839)	(185,277)	(97,673)	(232,150)
3	(206,130)	(96,242)	(508,651)	(22,091)	(120,221)	(78,054)	(163,494)
4	(9,461)	(55,650)	(366,951)	(6,311)	(55,036)	(58,396)	(94,701)
5	187,566	(14,977)	(224,969)	9,501	10,280	(38,699)	(25,770)
6	384,954	25,778	(82,702)	25,344	75,726	(18,962)	43,299
7	582,703	66,614	59,850	41,218	141,303	814	112,505
8	780,813	107,531	202,686	57,125	207,012	20,629	181,851
9	979,285	148,531	345,808	73,063	272,851	40,485	251,335
10	1,053,120	189,612	362,872	89,034	300,073	60,380	319,735

Table 7-30: Comparison between All Projects

	ESS ($)	Energy Conservation ($)	ESS and Energy Conservation ($)	Residential DR ($)	Residential DR and ESS ($)	Residential DR and Energy Conversation ($)	Residential DR, ESS and Energy Conversation ($)
NPV ($)	644,975	95,229	82,838	52,450	163,759	14,746	160,316
IRR	20.40%	13.34%	7.02%	18.83%	15.27%	7.26%	13.30%
Payback (years)	4.05	5.37	6.58	4.40	4.84	6.96	5.37
BCR	1.600	1.051	1.027	1.062	1.139	1.010	1.094
Emissions Reduction	18.13%	20.39%	22.17%	13.91%	15.68%	18.04%	19.72%

Figure 7-15 presents the combination between the environmental impact and the economic outputs for the alternatives. The findings show that ESS has the highest rank among other alternatives. This is reasonable since ESS charges during lower electricity prices and discharge during peaking demand. Thus, the customers can avoid the high electricity charges, and the utility is not required to run more generating units. The second option is residential DR combined with ESS. This alternative comes after ESS due to its flexibility in shifting the loads to off-peak periods. Combining all the MCDM alternatives in one option is the third ranked scenario. This alternative provides more emissions reduction than the previous ones. While energy conservation project and ESS with energy conservation project provide less economic impact than residential DR, they take the fourth and fifth place, respectively, due to their environmental impact. The penultimate alternative is residential DR because it is designed to shift the peak load, and it has socioeconomic cost. The last alternative is combining residential DR with energy conservation. Although the option performs environmentally better than residential DR, its socioeconomic cost plays a major role in selecting this alternative.

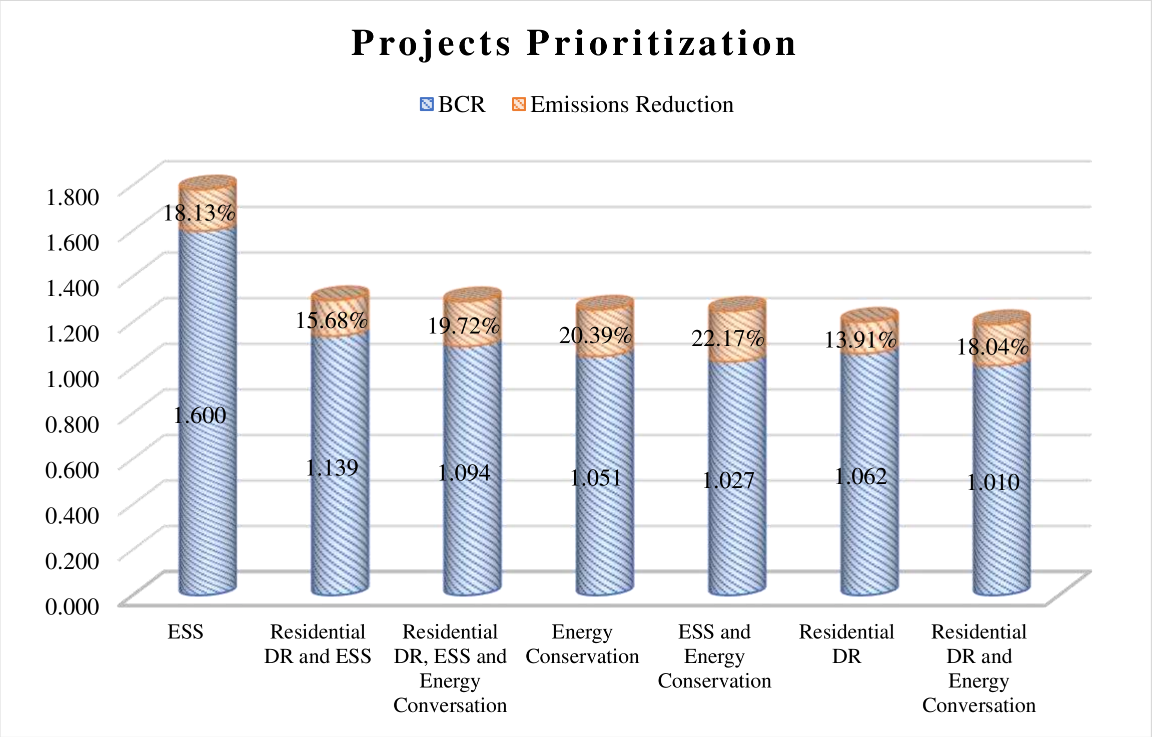

Figure 7-15: Projects ranking after combining environmental and economic impact

The finding in Figure 7-15 are weighted based on environmental and economic impact of each project. However, priorities might change according to the preference. One can prefer environmental impact over economic output and vice versa. Therefore, a trade-off between the options is a strategic decision that takes into consideration the advantages and disadvantages of each project. In this analysis, there are two factors that can affect the prioritization: environment impact and economic output. Thus, the final result is presented in Figure 7-16 in a trade-off setup, so the decision-makers can tradeoff between the alternatives to select the most suitable option.

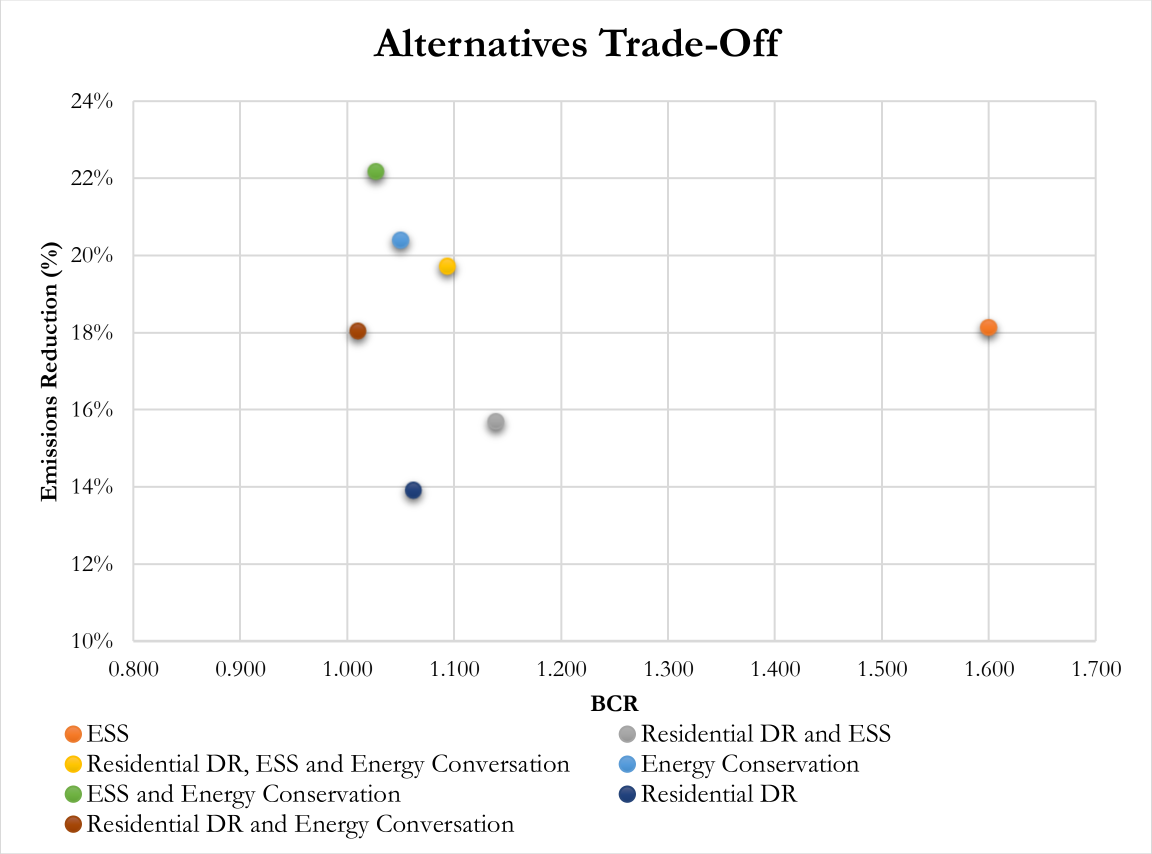

Figure 7-16: A trade-off between the alternatives

7.5 Conclusion

This chapter investigated the economic consequences of the MCDM options. It studied each alternative based on its associated costs and the expected benefits. The economic evaluation obtains the NPV, the IRR, the payback period, and the BCR for every scenario. Since this work examines the potential emissions reduction from the proposed alternatives, it ensured those solutions are economically accepted. The preliminary result shows that investing in ESS is the best option followed by combining residential DR with ESS. The third choice is merging all the MCDM options since they provide high emissions reduction. The remaining choices are energy conservation project, ESS with energy conservation, residential DR, and residential DR with energy conservation. Further, this chapter presents a trade-off chart to allow the participant to select the alternatives based on their environmental or economic preference. However, this analysis is particularly based on Fort Collins distribution system data. The result might change based on the location, data, or the distribution system structure.

From the previous analysis, we notice that the ranking on DSM options has changed. The AHP findings show that communication and intelligence (residential DR) is on the top of the list followed by ESS and energy conservation, respectively. The result from the ANP model explains the effect of alternatives on criteria. The ANP approach ranks the DSM options as follows: communication and intelligence (residential DR), energy conservation, and ESS, respectively. The simulation result based on the environmental impact shows the prioritization is different from the MCDM ranking as energy conservation provides the biggest emissions reduction in the distribution system. ESS comes in the second rank as it is integrated to the system for load shaving. Communication and intelligence (residential DR) alternative is in the third place based on the environmental simulation. Further, the simulation analysis allows us to merge several options in one scenario. This combination provides the flexibility of using the MCDM alternatives and helps in achieving cumulative emissions reduction. Economically, ESS is the best alternative as it has the highest BCR and requires less time to recover the investment cost. Communication and intelligence (residential DR) project is the second place followed by energy conservation project. However, this work presents a trade-off chart between the environmental impact and the economic outcomes of the DSM options.

CHAPTER 8

CONCLUSION AND FUTURE WORK[7]

8.1 Introduction

This dissertation illustrated the impact of GHG emissions, especially of the electricity sector. This work discussed some climate action plans and their benefits and challenges in reducing the emissions from power plants. DSM is a technique that is used as an option to diminish the environmental footprints.

8.2 Conclusion

The increased use of energy leads to increased energy-related emissions. It is important to keep the produced emissions under control by regulating carbon footprints. Therefore, this work discussed some government-directed plans that can mitigate GHG. The CPP is the most comprehensive and largest climate protection plan in the U.S. until its proposed repeal in 2017. The plan provides several approaches and options to meet the targeted reduction of emissions from power plants. The CPP includes several scenarios that can lead to achieving the goal with less impact on electricity generation. Another plan in the CAP of Fort Collins. It is a climate plan in Fort Collins, Colorado, U.S. that aims to mitigate the emissions in the city by 20% in 2020, 80% by 2030, and carbon neutral by 2050.

DSM was considered as a potential solution to mitigate the emissions from EGUs. In fact, DSM can make a significant impact in reducing the emissions and providing economic and reliability benefits. This work presented some DSM techniques such as loads shifting, energy conservation, and valley filing. Further, the work explained the most common DSM programs such as DR, energy management, and DG.

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[7] This chapter is verbatim reproduced from [37], and it is submitted to the Journal of Energy Transitions at the time of writing this dissertation

In order to prioritize the DSM options based on their impact on reducing the environmental footprints, the research deployed a MCDM model, AHP, to calculate the final ranking of the DSM alternatives. In fact, AHP uses a framework for problem solving that organizes judgments into a hierarchy of criteria that influence decisions. Therefore, the fourth chapter of this dissertation established a problem framework corresponding to the goal of the CAP of Fort Collins, Colorado, U.S. to study the importance of each alternative in achieving the target. The results show that "communication and intelligence" has the highest priority in meeting the goal followed by "electric stationary storage" and "energy conservation". However, AHP evaluates the decision elements in a hierarchical way while ignoring the impact of alternatives on the weight of criteria and this can affect the final ranking.

ANP in another model in MCDM that allows interdependencies, outerdependencies and feedback connections among decision elements in the network structure to effectively rank alternatives. Hence, Chapter 5 constructed an ANP DSM-based framework to precisely calculate the important available options in reducing carbon footprint. The results pertaining to Fort Collins' electric distribution system indicate the final ranking changes when interdependence relationships are taken into consideration. The results show "communication and intelligence" is the most preferred alternative followed by "energy conservation". Also, "electric stationary storage" moved back to the third option while it was the second alternative in AHP. Indeed, "solar PV" and "combustion generation" are flipped while "load side management" and "electric water heater" maintain the same rank.

After prioritizing the most suitable options, from the DSM alternatives, in reducing the produced emissions from power plants, Chapter 6 presented environmental analysis by creating several scenarios based on the first-three options from the MCDM alternatives. The simulation in this chapter considers studying each alternative individually and then merge an alternative with another alternative. The IEEE 13-node test system was used through the OpenDSS simulation tool to analyze year 2017 hourly load data, corresponding to Fort Collins, Colorado area. Each scenario shows different CO_2

curves based on the change in supply and demand. The base case simulation for the 2017 data indicates the emissions were reduced by 16.26% from 2005 level and this comply with the results released by the city. The results obtained for the 2017 load profile demonstrated that “electric stationary storage” can contribute a more than 18% emission reduction from the 2005 level. While “energy conservation” can meet the city’s goal by achieving a 20.39% reduction in emissions, merging both alternatives in one scenario could increase the emissions mitigation up to 22.17%. “communication and intelligence” in applied only to the residential sector and shows about a 14% emission reduction from the 2005 level. Integrating “electric stationary storage” with “communication and intelligence” can provide a more than 15% decrease while combining “communication and intelligence” with “energy conservation” may diminish the environmental footprint by 18.04%. The last scenario examined combines all MCDM alternatives into one option. The result finds that this option can reach a 19.72% emissions reduction.

The previous results are obtained based on environmental assessment while other factors can affect this ranking. CBA is conducted to study economic, technical, and environmental costs and benefits associated with each alternative. After evaluation all the costs and benefits of each scenario, the preliminary results rank the alternatives according to their environmental impact and the economic outputs. The results show that “electric stationary storage” is on the top of the list followed by “communication and intelligence” combined with “electric stationary storage”. The scenario that includes all the MCDM options came in third place since it provides almost 20% emissions reduction and the BCR is 1.094. The rest of the list is; “energy conservation”, “electric stationary storage” with “energy conservation”, “communication and intelligence”, and “communication and intelligence” with “energy conservation”, respectively. However, the ranking might change according to the participant’s choice. One can prefer environmental impact over economic output and vice versa. Therefore, this work presented a trade-off chart, so the decision maker can select the alternative based on their preference.

This analysis is mainly based on Fort Collins distribution system data and is not a general assessment. There are several factors that might affect the result such as the location, data, or the distribution system structure.

8.3 Future work

The results presented in this dissertation rank the alternatives based on the simulation from the IEEE 13-node distribution system. But, studying this case from a test system would not be sufficient in ranking the potential solutions for minimizing environmental footprints through DSM. Future path should consider the real electric distribution system of Fort Collins. As the city has a plan to reduce its dependence on conventional generation and to increase the penetration of renewable energy, analyzing the real system can obtain results that are more accurate. The future use of the test system doesn't constrain the results of the current studies as the future work will investigate reliability, and power quality, sizing and siting of ESS in the electric distribution system. This can increase the benefits of ESS by decreasing the system loss and increasing reliability and power quality. Our future path is also considering coordinated energy storage charging with available renewable energy generation. This dispatch will increase the utility utilization by smoothing energy output from intermittent resources and increase reliability and resilience of the system. It can also reduce the electricity bill, defer investment, and offset the emissions from dirty generating units.

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APPENDIX

AHP questions for reducing GHG emissions with an electric distribution system

The answers are provided by the former chair of the city energy advisory board who served from 2011 through 2017. He chaired the board for the last three years of this period and led the extensive five-year revision of the city's energy policy document that was adopted by City Council in early 2016. During his period of service on the Energy Board, Fort Collins developed and adopted an aggressive Climate Action plan that seeks to reduce net city GHG emissions from a 2005 baseline by 20% by 2020 (achieved in 2018), 80% by 2030, and 100% by 2050. The Energy Board worked closely with the municipal electric distribution utility, environmental service department, other city staff, and outside experts like Rocky Mountain Institute to develop and evaluate plans to implement the Climate Action Plan and to meet other city goals related to energy production and consumption. Among those plans are a time-of-use electric rate that went into effect in October 2018; WiFi thermostat and electric water heater demand-response programs; and a major shift in the city's bulk generation supplier, Platte River Power Authority, from coal to wind, solar, and even battery storage.

Though Mr. O'Neill's entire professional career has been spent in the semiconductor industry, he has been interested in energy technology and policy for decades, following the development of both and experimenting on his own house. He has built two very energy-efficient houses, installed two PV systems, and built an extensive home automation system a major objective of which is energy optimization.

Mr. O'Neill was awarded the MSEE degree in 1978 and the BSEE in 1977, both from Purdue University.

Objective: reduce GHG emissions with an electric distribution system

Which criterion do you think is more significant in achieving the objective?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, and CAIDI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

1. 1	Cost	Equal	Reliability
2. 1	Cost	Equal	Power quality
3. 1	Cost	Equal	Environmental collateral
4. 1	Cost	Equal	Socio-economic equity
5. 1	Reliability	Equal	Power quality
6. 1	Reliability	Equal	Environmental collateral
7. 1	Reliability	Equal	Socio-economic equity
8. 1	Power quality	Equal	Environmental collateral
9. 1	Power quality	Equal	Socio-economic equity
10. 1	Environmental collateral	Equal	Socio-economic equity

Which of the following alternatives is more important in achieving the goal WRT?

Note:

1- The closer to the option, the better in achieving the goal with lower cost
2- The closer to the option, the better in achieving the goal with high reliability
3- The closer to the option, the better in achieving the goal with acceptable levels of power quality
4- The closer to the option, the better in achieving the goal with lower environmental impact
5- The closer to the option, the better in achieving the goal with equal socio-economic status

11. Cost

Energy consumption Equal Communication & intelligence

12. Cost

Energy consumption Equal Electrification of heating & transportation

13. Cost

Energy consumption Equal Distributed generation

14. Cost

Communication & intelligence Equal Electrification of heating & transportation

15. Cost

Communication & intelligence Equal Distributed generation

16. Cost

Electrification of heating & transportation Equal Distributed generation

17. Reliability

Energy consumption Equal Communication & intelligence

18. Reliability

Energy consumption Equal Electrification of heating & transportation

19. Reliability

Energy consumption Equal Distributed generation

20. Reliability

Communication & intelligence Equal Electrification of heating & transportation

21. Reliability

Communication & intelligence Equal Distributed generation

22. Reliability

Electrification of heating & transportation Equal Distributed generation

23. Power quality

Energy consumption Equal Communication & intelligence

24. Power quality

Energy consumption Equal Electrification of heating & transportation

25. Power quality

Energy consumption Equal Distributed generation

26. Power quality

Communication & intelligence Equal Electrification of heating & transportation

27. Power quality

Communication & intelligence	Equal	Distributed generation
28. Power quality		
Electrification of heating & transportation	Equal	Distributed generation
29. Environmental collateral		
Energy consumption	Equal	Communication & intelligence
30. Environmental collateral		
Energy consumption	Equal	Electrification of heating & transportation
31. Environmental collateral		
Energy consumption	Equal	Distributed generation
32. Environmental collateral		
Communication & intelligence	Equal	Electrification of heating & transportation
33. Environmental collateral		
Communication & intelligence	Equal	Distributed generation
34. Environmental collateral		
Electrification of heating & transportation	Equal	Distributed generation
35. Socio-economic equity		
Energy consumption	Equal	Communication & intelligence
36. Socio-economic equity		

Energy consumption Equal Electrification of heating & transportation

37. Socio-economic equity

Energy consumption Equal Distributed generation

38. Socio-economic equity

Communication & intelligence Equal Electrification of heating & transportation

39. Socio-economic equity

Communication & intelligence Equal Distributed generation

40. Socio-economic equity

Electrification of heating & transportation Equal Distributed generation

Which energy consumption option is more important in achieving the goal WRT?

Reducing energy consumption is an alternative to achieve the goal, and it consists of three investment options: energy conservation, load side management (demand response) and stationary electric energy storage. In this page, we make a comparison between the three options of energy consumption with respect to each criterion

Note:

1- The closer to the option, the better in achieving the goal with lower cost

2- The closer to the option, the better in achieving the goal with high reliability

3- The closer to the option, the better in achieving the goal with acceptable levels of power quality

4- The closer to the option, the better in achieving the goal with lower environmental impact

5- The closer to the option, the better in achieving the goal with equal socio-economic status

41. Cost

Energy conservation Equal Load side management

42. Cost

Energy conservation Equal Stationary electric energy storage

43. Cost

Load side management Equal Stationary electric energy storage

44. Reliability

Energy conservation Equal Load side management

45. Reliability

Energy conservation Equal Stationary electric energy storage

46. Reliability

Load side management Equal Stationary electric energy storage

47. Power quality

Energy conservation Equal Load side management

48. Power quality

Energy conservation Equal Stationary electric energy storage

49. Power quality

Load side management Equal Stationary electric energy storage

50. Environmental collateral

Energy conservation Equal Load side management

51. Environmental collateral

Energy conservation Equal Stationary electric energy storage

52. Environmental collateral

Load side management Equal Stationary electric energy storage

53. Socio-economic equity

Energy conservation Equal Load side management

54. Socio-economic equity

Energy conservation Equal Stationary electric energy storage

55. Socio-economic equity

Load side management Equal Stationary electric energy storage

Which of the following alternatives is more important in achieving the goal WRT?

Communication and intelligence infrastructure is an alternative to achieve the goal, and it consists of four investment options; Internet of Things (IoT), smart meters and Advanced Metering Infrastructure (AMI), real-time pricing and smart appliances. In this page, we make a comparison between the four options of communication and intelligence with respect to each criterion . . Note: 1- The closer to the option, the better in achieving the goal with lower cost

2- The closer to the option, the better in achieving the goal with high reliability

3- The closer to the option, the better in achieving the goal with acceptable levels of power quality

4- The closer to the option, the better in achieving the goal with lower environmental impact

5- The closer to the option, the better in achieving the goal with equal socio-economic status

Question Title

56. Cost

IoT Equal Smart meters and AMI

57. Cost

IoT Equal Real-time pricing

58. Cost

IoT Equal Smart appliances

59. Cost

Smart meters Equal Real-time pricing

60. Cost

Smart meters Equal Smart appliances

61. Cost

Real-time pricing Equal Smart appliances

62. Reliability

IoT Equal Smart meters and AMI

63. Reliability

IoT Equal Real-time pricing

64. Reliability

IoT Equal Smart appliances

65. Reliability

Smart meters Equal Real-time pricing

66. Reliability

Smart meters Equal Smart appliances

67. Reliability

Real-time pricing Equal Smart appliances

68. Power quality

IoT Equal Smart meters and AMI

69. Power quality		
IoT	Equal	Real-time pricing
70. Power quality		
IoT	Equal	Smart appliances
71. Power quality		
Smart meters	Equal	Real-time pricing
72. Power quality		
Smart meters and AMI	Equal	Smart appliances
73. Power quality		
Real-time pricing	Equal	Smart appliances
74. Environmental collateral		
IoT	Equal	Smart meters and AMI
75. Environmental collateral		
IoT	Equal	Real-time pricing
76. Environmental collateral		
IoT	Equal	Smart appliances
77. Environmental collateral		
Smart meters and AMI	Equal	Real-time pricing
78. Environmental collateral		
Smart meters and AMI	Equal	Smart appliances
79. Environmental collateral		
Real-time pricing	Equal	Smart appliances
80. Socio-economic equity		
IoT	Equal	Smart meters and AMI
81. Socio-economic equity		
IoT	Equal	Real-time pricing

82. Socio-economic equity

IoT	Equal	Smart appliances

83. Socio-economic equity

Smart meters and AMI	Equal	Real-time pricing

84. Socio-economic equity

Smart meters and AMI	Equal	Smart appliances

85. Socio-economic equity

Real-time pricing	Equal	Smart appliances

Which of the following alternatives is more important in achieving the goal WRT

Electrification of heating and transportation is an alternative to achieve the goal, and it consists of three options: geo-exchange heat pump, electric water heater, and electric vehicles. In this page, we make a comparison between the three options of electrification of heating and transportation with respect to each criterion

Note:

1- The closer to the option, the better in achieving the goal with lower cost

2- The closer to the option, the better in achieving the goal with high reliability

3- The closer to the option, the better in achieving the goal with acceptable levels of power quality

4- The closer to the option, the better in achieving the goal with lower environmental impact

5- The closer to the option, the better in achieving the goal with equal socio-economic status

86. Cost

Geo-exchange heat pump	Equal	Electric water heater

87. Cost

Geo-exchange heat pump Equal Electric vehicles

88. Cost

Electric water heater Equal Electric vehicles

89. Reliability

Geo-exchange heat pump Equal Electric water heater

90. Reliability

Geo-exchange heat pump Equal Electric vehicles

91. Reliability

Electric water heater Equal Electric vehicles

92. Power quality

Geo-exchange heat pump Equal Electric water heater

93. Power quality

Geo-exchange heat pump Equal Electric vehicles

94. Power quality

Electric water heater Equal Electric vehicles

95. Environmental collateral

Geo-exchange heat pump Equal Electric water heater

96. Environmental collateral

Geo-exchange heat pump Equal Electric vehicles

97. Environmental collateral

Electric water heater Equal Electric vehicles

98. Socio-economic equity

Geo-exchange heat pump Equal Electric water heater

99. Socio-economic equity

Geo-exchange heat pump Equal Electric vehicles

100. Socio-economic equity

Electric water heater Equal Electric vehicles

Which distributed generation alternatives is more important in achieving the goal WRT

Distributed generation is an alternative to achieve the goal, and it consists of two options: solar PV and combustion generation. In this page, we make a comparison between the two options of distributed generation with respect to each criterion

Note:

1- The closer to the option, the better in achieving the goal with lower cost

2- The closer to the option, the better in achieving the goal with high reliability

3- The closer to the option, the better in achieving the goal with acceptable levels of power quality

4- The closer to the option, the better in achieving the goal with lower environmental impact

5- The closer to the option, the better in achieving the goal with equal socio-economic status

101. Cost

Solar PV Equal Combustion generation

102. Reliability

Solar PV Equal Combustion generation

103. Power quality

Solar PV	Equal	Combustion generation
104. Environmental collateral		
Solar PV	Equal	Combustion generation
105. Socio-economic equity		
Solar PV	Equal	Combustion generation

AHP questions for applying energy conservation to reduce GHG emissions with an electric distribution system

Objective: applying energy conservation to reduce GHG emissions with an electric distribution system

Which energy conservation option is more important in achieving the goal WRT

Applying energy conservation is one alternative, under energy consumption, to achieve the goal, and it consists of three investment options: efficient appliances, efficient buildings and behavior (educational programs). In this page, we make a comparison between the three options of energy conservation with respect to each criterion

Note:

1- The closer to the option, the better in achieving the goal with lower cost

2- The closer to the option, the better in achieving the goal with high reliability

3- The closer to the option, the better in achieving the goal with acceptable levels of power quality

4- The closer to the option, the better in achieving the goal with lower environmental impact

5- The closer to the option, the better in achieving the goal with equal socio-economic status

Question Title

1. Cost

Efficient appliances Equal Efficient buildings

2. Cost

Efficient appliances Equal Behavior

3. Cost

Efficient buildings Equal Behavior

4. Reliability

Efficient appliances Equal Efficient buildings

5. Reliability

Efficient appliances	Equal	Behavior
6. Reliability		
Efficient buildings	Equal	Behavior
7. Power quality		
Efficient appliances	Equal	Efficient buildings
8. Power quality		
Efficient appliances	Equal	Behavior
9. Power quality		
Efficient buildings	Equal	Behavior
10. Environmental collateral		
Efficient appliances	Equal	Efficient buildings
11. Environmental collateral		
Efficient appliances	Equal	Behavior
12. Environmental collateral		
Efficient buildings	Equal	Behavior
13. Socio-economic equity		
Efficient appliances	Equal	Efficient buildings
14. Socio-economic equity		
Efficient appliances	Equal	Behavior
15. Socio-economic equity		
Efficient buildings	Equal	Behavior

ANP questions for reducing GHG emissions with an electric distribution system

Objective: reduce GHG emissions with an electric distribution system using Analytic Network Process

For energy conservation, which criterion do you think is more important?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, CAIDI, CAIFI, and ASAI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations
4- Environmental collateral considers the footprint of the whole system, e.g. fuel extraction in addition to fuel consumption
5- Socio-economic equity means the fairness in the access to and the benefit from the alternatives among social and economic groups

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

Question Title

1. 1

Cost Equal Reliability

2. 1

Cost Equal Power quality

3. 1

Cost Equal Environmental collateral

4. 1

Cost Equal Socio-economic equity

5. 1

Reliability Equal Power quality

6. 1

Reliability Equal Environmental collateral

7. 1

Reliability Equal Socio-economic equity

8. 1

Power quality Equal Environmental collateral

9. 1

Power quality Equal Socio-economic equity

10. 1

Environmental collateral Equal Socio-economic equity

For load side management (DR), which criterion do you think is more important?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, CAIDI, CAIFI, and ASAI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations
4- Environmental collateral considers the footprint of the whole system, e.g. fuel extraction in addition to fuel consumption
5- Socio-economic equity means the fairness in the access to and the benefit from the alternatives among social and economic groups

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

Question Title

11. 1

Cost Equal Reliability

12. 1

Cost Equal Power quality

13. 1

Cost Equal Environmental collateral

14. 1

Cost Equal Socio-economic equity

15. 1

Reliability Equal Power quality

16. 1

Reliability Equal Environmental collateral

17. 1

Reliability Equal Socio-economic equity

18. 1

Power quality Equal Environmental collateral

19. 1

Power quality Equal Socio-economic equity

20. 1

Environmental collateral Equal Socio-economic equity

For electric stationary storage, which criterion do you think is more important?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, CAIDI, CAIFI, and ASAI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations
4- Environmental collateral considers the footprint of the whole system, e.g. fuel extraction in addition to fuel consumption
5- Socio-economic equity means the fairness in the access to and the benefit from the alternatives among social and economic groups

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

21. 1	Cost	Equal	Reliability
22. 1	Cost	Equal	Power quality
23. 1	Cost	Equal	Environmental collateral
24. 1	Cost	Equal	Socio-economic equity
25. 1	Reliability	Equal	Power quality
26. 1	Reliability	Equal	Environmental collateral
27. 1	Reliability	Equal	Socio-economic equity
28. 1	Power quality	Equal	Environmental collateral
29. 1	Power quality	Equal	Socio-economic equity
30. 1	Environmental collateral	Equal	Socio-economic equity

For communication and intelligence, which criterion do you think is more important?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, CAIDI, CAIFI, and ASAI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations

4- Environmental collateral considers the footprint of the whole system, e.g. fuel extraction in addition to fuel consumption
5- Socio-economic equity means the fairness in the access to and the benefit from the alternatives among social and economic groups

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

31. 1

Cost Equal Reliability

32. 1

Cost Equal Power quality

33. 1

Cost Equal Environmental collateral

34. 1

Cost Equal Socio-economic equity

35. 1

Reliability Equal Power quality

36. 1

Reliability Equal Environmental collateral

37. 1

Reliability Equal Socio-economic equity

38. 1

Power quality Equal Environmental collateral

39. 1

Power quality Equal Socio-economic equity

40. 1

Environmental collateral Equal Socio-economic equity

For geo-exchange heat pump space heat, which criterion do you think is more important?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, CAIDI, CAIFI, and ASAI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations
4- Environmental collateral considers the footprint of the whole system, e.g. fuel extraction in addition to fuel consumption
5- Socio-economic equity means the fairness in the access to and the benefit from the alternatives among social and economic groups

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

41. 1

Cost Equal Reliability

42. 1

Cost Equal Power quality

43. 1

Cost Equal Environmental collateral

44. 1

Cost Equal Socio-economic equity

45. 1

Reliability Equal Power quality

46. 1

Reliability Equal Environmental collateral

47. 1

Reliability Equal Socio-economic equity

48. 1

Power quality Equal Environmental collateral

49. 1

Power quality Equal Socio-economic equity

50. 1

Environmental collateral Equal Socio-economic equity

For electric water heater, which criterion do you think is more important?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, CAIDI, CAIFI, and ASAI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations
4- Environmental collateral considers the footprint of the whole system, e.g. fuel extraction in addition to fuel consumption
5- Socio-economic equity means the fairness in the access to and the benefit from the alternatives among social and economic groups

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

51. 1

Cost Equal Reliability

52. 1

Cost Equal Power quality

53. 1

Cost Equal Environmental collateral

54. 1

Cost Equal Socio-economic equity

55. 1

Reliability Equal Power quality

56. 1

Reliability Equal Environmental collateral

57. 1

Reliability Equal Socio-economic equity

58. 1

Power quality Equal Environmental collateral

59. 1

Power quality Equal Socio-economic equity

60. 1

Environmental collateral Equal Socio-economic equity

For electric vehicles, which criterion do you think is more important?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, CAIDI, CAIFI, and ASAI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations
4- Environmental collateral considers the footprint of the whole system, e.g. fuel extraction in addition to fuel consumption
5- Socio-economic equity means the fairness in the access to and the benefit from the alternatives among social and economic groups

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

61. 1

Cost Equal Reliability

62. 1

Cost Equal Power quality

63. 1

Cost Equal Environmental collateral

64. 1

Cost Equal Socio-economic equity

65. 1

Reliability Equal Power quality

66. 1

Reliability Equal Environmental collateral

67. 1

Reliability Equal Socio-economic equity

68. 1

Power quality Equal Environmental collateral

69. 1

Power quality Equal Socio-economic equity

70. 1

Environmental collateral Equal Socio-economic equity

For solar PV, which criterion do you think is more important?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, CAIDI, CAIFI, and ASAI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations
4- Environmental collateral considers the footprint of the whole system, e.g. fuel extraction in addition to fuel consumption
5- Socio-economic equity means the fairness in the access to and the benefit from the alternatives among social and economic groups

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

71. 1

Cost Equal Reliability

72. 1

Cost Equal Power quality

73. 1

Cost Equal Environmental collateral

74. 1

Cost Equal Socio-economic equity

75. 1

Reliability Equal Power quality

76. 1

Reliability Equal Environmental collateral

77. 1

Reliability Equal Socio-economic equity

78. 1

Power quality Equal Environmental collateral

79. 1

Power quality Equal Socio-economic equity

80. 1

Environmental collateral Equal Socio-economic equity

For combustion generation, which criterion do you think is more important?

1- Cost includes the following: fixed cost, operating and maintenance cost, and avoided cost
2- Reliability is quantified by indices: SAIFI, SAIDI, CAIDI, CAIFI, and ASAI
3- Power quality includes acceptable levels of the following: harmonics, flicker, voltage deviations, and frequency variations
4- Environmental collateral considers the footprint of the whole system, e.g. fuel extraction in addition to fuel consumption
5- Socio-economic equity means the fairness in the access to and the benefit from the alternatives among social and economic groups

Note: slider scale includes 17 steps. Equal means the options are equally important, and the closer the slider to the option the more important

81. 1

Cost Equal Reliability

82. 1

Cost Equal Power quality

83. 1

Cost Equal Environmental collateral

84. 1

Cost Equal Socio-economic equity

85. 1

Reliability Equal Power quality

86. 1

Reliability Equal Environmental collateral

87. 1

Reliability Equal Socio-economic equity

88. 1

Power quality Equal Environmental collateral

89. 1

Power quality Equal Socio-economic equity

90. 1

Environmental collateral Equal Socio-economic equity

This test feeder includes data for lines, transformers, capacitors, spot loads, and distributed loads.

Transformer Data

	kVA	kV-high	kV-low	R (%)	X (%)
Substation:	5,000	115 (Δ)	4.16 (Y)	1	8
XFM -1	500	4.16 – (Y)	0.48 – (Y)	1.1	2

Line Segment Data

Node A	Node B	Length(ft.)
632	645	500
632	633	500
633	634	0

645	646	300
650	632	2000
684	652	800
632	671	2000
671	684	300
671	680	1000
671	692	0
684	611	300
692	675	500

Capacitor Data (kVAr)

Node	Ph-A	Ph-B	Ph-C
675	200	200	200
611			100
Total	200	200	300

Regulator Data

Line Segment	650 - 632	
Phases	A - B -C	
Connection	3-Ph, LG	
Monitoring Phase	A-B-C	
Bandwidth	2.0 volts	
PT Ratio	20	
Primary CT Rating	700	

Compensator Settings	Ph-A	Ph-B	Ph-C
R - Setting	3	3	3
X - Setting	9	9	9
Voltage Level	122	122	122

Distributed Load Data

Node A	Node B	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
		Model	kW	kVAr	kW	kVAr	kW	kVAr
632	671	Y-PQ	17	10	66	38	117	68

Spot Load Data

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
	Model	kW	kVAr	kW	kVAr	kW	kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	Total	1158	606	973	627	1135	753