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Optimizing the Operation of Bulk Energy Storage Devices to Find the Trade-offs Between Revenue and CO2 Emissions.

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OPTIMIZING THE OPERATION OF BULK ENERGY STORAGE DEVICES TO FIND THE TRADE-OFFS BETWEEN REVENUE AND CO_2 EMISSIONS.

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Department of Public Policy

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DEDICATION

I would like to thank my mother, Lucy, for her endless love and dedication to her two children. I would like to thank my brother, Carlos, for always being there to support and believe in me. Although we are only three, we have always been there for each other, and always will be. Finally, I would like to acknowledge that our small family is expanding to include three wonderful individuals. Mike, Lauren, and Mario you are all welcomed with open arms and boundless love as new members to nuestra familia.

Abstract

Name: Laura M. Arciniegas

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Title of Study: Optimizing the Operation of Bulk Energy Storage Devices to Find the Trade-Offs Between Revenue and CO_2 Emissions.

Major Field: Science, Technology, and Public Policy

Abstract: The purpose of this research is to encourage policy makers to craft policies that support environmentally sound design practices while integrating bulk energy storage into the electricity grid. Bulk energy storage technology can regulate electricity coming into the grid from different energy sources. Grid flexibility is a powerful tool to empower the clean energy movement because it enables the integration of renewable energy into the electrical grid. However, storage technology has the potential to become another one of the many "tragedy of commons", considering that there are no regulations forcing storage companies to pursue environmental-friendly operation. Bulk energy storage devices which earn income through arbitrage, have the potential to increase grid emissions. Both energy losses and the variety of energy grid resources, largely damper the environmental advantages of bulk energy storage devices. By using a linear programming formulation that considers both revenue and emissions, this thesis proposes operational solutions where bulk energy storage technologies can retain a high revenue while simultaneously reducing their emissions from the current eGRID sub-regions. These results can be achieved by explicitly demanding small inexpensive changes in the operation of the system. Usually, only a few companies will follow sustainable practices by themselves. Therefore, a variety of policy implementations are suggested to support environmentally sound design principals for bulk energy storage technology.

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CHAPTER I

INTRODUCTION

This thesis applied a linear programing formulation to provide specific operating schedules in which bulk energy storage technology could have earned a profit while reducing storage induced emissions from the current electricity grid. Bulk energy storage refers to various methods such as pumped-hydro, compressed air energy storage (CAES), and batteries used to store electrical energy on a large scale. Bulk Energy storage has many advantages like reliability and fast response regulation but it is best acknowledged for increasing grid flexibility. Other less pronounced ways of increasing grid flexibility include demand responses and forecasting. However, bulk energy storage is expected to have a much higher ability of increasing grid flexibility. Grid flexibility is necessary for the integration of renewable energy onto the current electricity grid. Bulk energy storage is a promising solution to modernize the energy grid to include cleaner energy sources such as wind and solar power.

The introduction of bulk energy storage into energy grids has both advantages and disadvantages. Energy storage offers many benefits to electricity systems, often providing several services at once [1]. Storage can reduce the need for peaker plants, optimize congested transmission, provide frequency regulation service, or manage electricity demand. In the case of a natural disaster, distributed energy storage can provide power while system operations are restored. Finally, and perhaps most prominent in the popular imagination, a broad literature describes the ability of bulk energy storage to integrate renewable energy into any grid [2]–[8]. Storage technologies can earn a profit due to arbitrage, the different pricing of electricity per unit of time. However, using storage to seek the maximum possible revenue from the electricity market will likely increase emissions [9]. Both energy losses and the variety of energy sources largely damper the environmental advantages of bulk energy storage. However, alternative operation options exist which reduce bulk energy storage emissions while retaining high revenue. The establishment of bulk energy storage does not have to be purely based on economics, more environmental transitional methods exist to integrate this new technology into the electricity market.

The first part of this thesis presents the political and scientific perspectives of the environmental effectiveness of bulk energy storage. All storage related policy that has been passed throughout the entire United States is identified. The purpose for this search is to find the societal return on investment that lawmakers expect, from funding startup storage companies. Within these policies, an emphasis was placed on the metrics which are used to measure environmental gains. After a historical policy analysis, the thesis presents academic literature pertaining to the environmental practicality of bulk energy storage. Preexisting academic literature concludes that bulk energy storage has the potential to be environmentally harmful. Scientific evidence which defends how storage does not behave like a green technology is thoroughly examined and discussed.

Complete elimination of bulk energy storage emissions is difficult to achieve due to the nature of the technology and the current grid infrastructure, however, operational modes exist that significantly reduce the relative change in emissions while having little effect on annual revenue. This thesis presents a computational model that investigated operational opportunities where a bulk energy storage device could reduce the amount of storage emissions while making profitable annual revenue. The optimization model used electricity prices, along with emission rates, and average storage constraints to find optimal operating schedules for storage in different regions throughout the United States. The strengths and limitations of the simulation are explained as well as the meaning of the results. Lastly, a critical analysis of how the results could be used to renovate current policies is presented.

In conclusion, the lever chosen by governments to enable renewable energy onto electricity grids was not adopted with sufficient scientific background. Bulk energy storage has the potential to be very impactful in the transition to a clean energy grid, dominated by renewables. However, politicians need to be very careful in how they introduce new technologies into open markets. As of 2016, bulk energy storage has entered the electricity market without any environmental precautions. In 2015 and 2016 alone, approximately 400 MW of energy storage was deployed onto the electricity grid [10]. As more states and utilities attempt to innovate creative ways to utilize energy storage on the electricity grid, we will learn much more about the costs and benefits of the technology and about which policy strategy is the most effective. The objective of this thesis is to encourage policies that are both environmentally friendly and economically sound while increasing the flexibility of the electricity grid through bulk energy storage.

CHAPTER II

BACKGROUND

The increase of atmospheric greenhouse gases demonstrates the need for more sustainable energy sources. The planet is experiencing permanent changes to its natural ecology due to human influence in the form of greenhouse gas emissions. The Intergovernmental Panel in Climate Change has declared that "since the 1950's, many of the observed changes are unprecedented over decades to millennia" [11]. These irreversible impacts include the warming of the atmosphere and oceans, the melting of ice, a decrease in snowfall, and the rising of sea levels. As the stresses from climate change bear increasingly unfavorable consequences, the development of socio-economic, clean energy policy becomes vital.

Energy is a vital resource in the development of any society, and even more critical in societies that have entered a technological realm, so the pursuit of energy will always exist within humankind. In the past, energy sourcing for electricity production has only been considered using the economic principle of minimizing expenses. However, since the start of this century, research groups began to study the environmental effects of incumbent energy extracting technologies. The Environmental Protection Agency (EPA) speculated in 2015 that primary resources extraction such as natural gas, coal, and gasoline are 89% of the primary causes for climate change [12]. Although fossil fuel energy is unlikely to disappear, integrating cleaner fuels into the energy grid has progressed rapidly [13]. Renewable energy is a promising solution because it provides the necessary power to keep society afloat while tackling climate change challenges.

Renewable energy alone will not solve climate change, yet the renewable industry is expected to make up a significant percentage of the global energy demand in the next half century [14]. Unfortunately, the addition of new sources, such as wind power and solar energy, into the current energy mix is complicated. The main obstacle with universal use of wind and solar energy is reliability during demand hours and the fact that renewable energy resources are usually unpredictable and sporadic. Thus, the integration of sporadic energy from renewables into established energy grids is a very difficult problem throughout the world [15]. It has been suggested that bulk energy storage is the 'holy grail' solution to store renewable energy and to mitigate multiple power sources into the electricity grid [16].

Besides facilitating renewable technologies onto almost every electricity grid, bulk energy storage also provides other advantages, such as higher grid flexibility and revenue from arbitrage [17] , [18] , [19]. Moreover, bulk energy storage can be used to replace peak power plants or create more efficient combined hybrid natural gas plants [7]. Storage technologies expand the realm of possibilities for the combination of energy sources, but they are best recognized for their ability to assimilate renewables into the electricity grid. The US government has presumed that bulk energy storage and renewables are both green technologies and must go together, therefore, many environmental policies include integration of both. Bulk energy storage can be used as a powerful tool to empower the clean energy movement, but this technology also has the potential to make vast amounts of money at the expense of the environment [9]. It has become more evident that the scheduling of storage technology could result in greater emissions if not regulated. Before implementing massive storage reforms, it is essential to examine how the electrical grid behaves when energy storage is incorporated under different scenarios. Bulk energy storage can be viewed from many perspectives, but during a climate change crisis, any energy infrastructure change needs to incorporate the sustainability demands of the future. Thus, the environmental impacts of storage have the most priority when incorporating bulk energy storage into the energy system.

CHAPTER III

REVIEW OF POLICY

This chapter presents the investigation of the environmental effects of bulk energy storage policy. It first conducts a historical search on the renewable policy that has been passed throughout the entire United States. The purpose for this is to find how bulk energy storage was first introduced and what the initial intended goal of storage was. Then the chapter focuses on the bulk energy storage polices found at the state level, since the states took it upon themselves to support their own storage market. California bulk energy policy originated the policy movement, but many other states have passed policies as well. Lastly, this chapter will end with federal storage policies that have been attempted. The federal government has not officially passed any policies relating to bulk energy storage but there have been several attempts. With the numerous polices involving bulk energy story, this chapter investigates the environmental impacts that lawmakers expect to find and the metrics that are used to measure environmental success from funding bulk energy storage.

Federal Renewable Energy Policy

The United States has been pursuing the development of a bulk energy storage market through renewable energy policy. Majority of bulk energy storage policies are found in small clauses under renewable policy, therefore, policy that includes renewable integration is the starting point for conducting research on the US energy storage agenda. The United States failed to manifest interest in the first global attempt to reduce emissions and implement renewable policies, by not recognizing the Kyoto Protocol [20] in 1997 and by not ratifying the Doha Amendment in 2012. If the US government had approved the treaty, it is very plausible that storage policies would have been created sooner. A stronger US policy push for clean energy and bulk energy storage occurred after the Pairs Agreement, a universal effort to reduce the effects of climate change [21].

For over a decade, branches within the scientific community warned repeatedly of the environmental harm caused by fossil fuels [22]. After published scientific research provided evidence for climate change, the United States government felt obligated to pass clean energy policies to generate cleaner production of electricity. Table 1 has such policies which commenced the “Sustainability Era” within the United States. The Clean Air Act [23] , the Energy Policy Act [24], and the Energy Independence and Security Act [25] made strides to get the country on an environmental track, but the movement was not very stern. None of these policies placed enough emphasis to boost the renewable technology industry nor the storage technology industry. Figure 1 shows the gradual growth of consumption for renewable energy over the span of ten years, from 2005 to

2015, during the time that the environmental policies were passed. Using the downloaded data from Figure 1 (US energy consumption from the Energy Information Agency (EIA)), Renewable energy has increased by 3.5% while fossil fuel consumption has decreased by 4.1% since 2005, when the Energy Policy act was passed. Although the energy grid has become cleaner, the first three US environmental policies cannot be perceived as having made an impactful difference. As seen in Figure 1, fossil fuels have continued to dominate 80% of the energy market for over a hundred years in the US. It was not until 2015, when much more rigorous renewables policies were made to combat the fossil fuel dominated energy industry.

Table 1. History of United States renewable energy policy.

US Federal Policy	***Main Objective***	***Additional Goals***	***Renewables Significance***
Clean Air Act 1963 [23]	Controls air pollution and emissions from stationary and mobile sources at a national level. Section 112, requires the EPA to establish emissions standards with "maximum achievable control technology" for any major source.	National Ambient Air Quality Standards (NAAQS) were created. The Office of Air and Radiation (OAR) was established.	Commenced the beginning of air pollution research.
Energy Policy Act 2005 [24]	Provides loans and tax cuts for technologies that reduce the by-product of greenhouse gases. The act also required an increased percent of biofuel in gasoline.	The Office of Underground Storage Tanks (OUST) was established.	Loans and tax credits for renewable technology.

US Federal Policy	***Main Objective***	***Additional Goals***	***Renewables Significance***
Energy Independence and Security Act 2007 [25]	Reinforces cleaner energy goals through the Average Fuel Economy Standards, the Renewable Fuel Standard. Increased the production of renewable sources, promoted greenhouse gas capture, and aimed to increase the efficiency of vehicles and buildings within the federal government.	Infrastructure for carbon capture and sequestration of bio-fuels was established.	Renewable integration into buildings was promoted.
Clean Power Plan 2015 [26]	Provides emissions standards for each power plant of 2.5 GW or larger, and customized goals for states to lower greenhouse gas emissions.	Promotes a 20% nuclear power energy mix.	Renewables are promoted to aid power production, maintaining the allowable emissions standards.
Renewable Electricity Production Tax Credit (PTC) 2016 [27]	Provides a tax break for each kWh of renewable electricity production for the first ten years of the operation, construction must be completed by 2019.	Wind projects have a higher tax cut but other sources like biomass and waste are included.	Huge incentive to construct more renewable farms.
Business Energy Investment Tax Credit (ITC) 2017 [28]	Provides a 30% tax credit for commercial solar roof installations and large wind production. This amount decreases annually but construction will be rewarded until 2021.	Doubles the current number of solar jobs by 2020.	Huge incentive to construct more rooftop and utility-scale solar energy.

It was not until 2015 that the United States got another opportunity to join the rest of the world to develop a global emissions reduction agenda. This new global treaty, known as *L'accord de Paris* or the Paris Agreement [21], included more countries and was considered a more serious attempt to combat climate change than the Kyoto Protocol [20]. Per this treaty, the world was expected to meet an overall 80% emissions reduction by the year 2050, using the 2005 carbon dioxide equivalent levels as a baseline. The United States, ratified the Paris Agreement on September 3, 2016, and accepted rigorous emissions standards, along with other large polluting countries like China and India. The US will remain a party to the accord at least until 2020, because, any consideration to pull out will not be considered until 2019, three years after the agreement came into force [29].

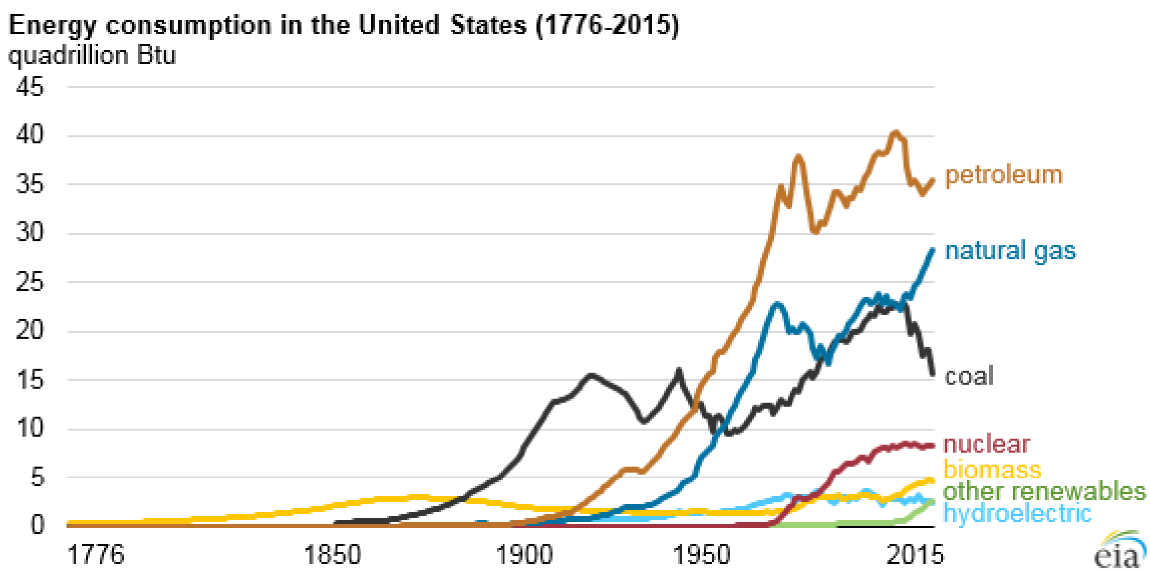

Figure 1. A comparison between US renewable energy consumption to US fossil fuel energy consumption from 1776 to 2015, as found by the EIA [30].

To meet the goals set forth by the Paris Agreement, the 44th president of United States created more strategic and innovative emissions reduction policies and regulations. On August 3, 2015, President Obama and EPA announced the first piece of national policy aimed to significantly reduce greenhouse gases. The Clean Power Plan [31] was an aggressive order, which assigned each state emissions targets, previously researched and carefully analyzed by the EPA. The plan reported mass-based pollution standards for each power plant in the United States using data from industry practices, as seen in Table 1. The Clean Power Plan was a massive step to tackling a main source of climate change.

At first, the clean energy movement in the United States was very resented, but after a year of debating the Clean Power Plan, the entire country was in support of reducing pollution. When the Clean Power Plan was first passed two dozen states joined legal actions to block the clean energy resolution [32]. Many states felt the propositions were unjust and they did not agree that emissions control needed federal authority. The states were forced to accept the Clean Power Plan because the Supreme Court of the United States ordered a stay. Meaning, that until further notice the Clean Power Plan will remain legal. The Clean Power Plan [26] gave each state an enormous amount of flexibility in choosing how to meet the new emissions regulations. The most favorable alternative option recommended by the Clean Power Plan was renewable technology. Many states accepted the challenge of integrating cleaner technologies into eGRID sub-regions.

In 2017, the perseverance of state governments to meet environmental standards was tested. The new commander in chief made an announcement on June 1, 2017 that he intends to repeal the United States from the Paris Agreement [33]. President Trump cannot submit a request to leave the treaty until November 4, 2019 [29]. However, his intentions in dismantling US environmental climate change policy are quite clear. In response to his capricious actions, states have independently agreed to sign the Paris Agreement and stand firm to their environmental obligations. Washington, Hawaii, New York, and California were the first to sing the agreement, followed by Connecticut, Delaware, Massachusetts, Minnesota, Oregon, Rhode Island, Vermont, and Virginia [34]. These 12 states make up approximately a third of the population and increasingly more states have started to show interest. Although the federal government refuses to lead on environmental issues, the states have taken up the responsibility. It is very likely that even if the Clean Power Plan gets annulled, that the states will continue to abide by it and generate organizations to keep the United States present in the Paris Agreement and future climate change world policy.

Although the Clean Power Plan promoted the advancement of renewable technology more than previous policies had, further challenges arose. Implementation of renewable technology into the electricity grid is mentioned in the "State Measures Plan" section of the Clean Power Plan [26]. This policy option allows states to utilize energy efficient technology in residential areas and within the energy industry to reach new emissions standards. The idea is to promote the use of new cleaner technology and the discarding of old, high emitting, coal generators. To further help the establishment of the new renewable energy market, the federal government passed tax incentives. As seen in Table 1, PTC [19] and ITC [20] are previously amended renewable energy tax cuts that were reinstated to promote wind and solar energy production. The US government saw renewable energy as a practical solution to reduce greenhouse gas emissions and air pollution, however, the integration of wind and solar power became very challenging. To overcome the obstacle of interlacing renewable technology into the current multi-source electricity grid, individual states passed policies to expand grid flexibility.

State Bulk Energy Storage Policy

A growing number of bulk energy storage policies are being drafted at the state level. Energy storage is just one way to increase grid flexibility; other methods include forecasting and demand response. The state bills presented in this thesis focus on the stationing of storage technology throughout individual eGRID sub-regions within the United States. California, a leading state in the clean energy industry, started drafting storage implementation laws sooner than any other state and even before the federal government. As early as 2010, a state act (AB2514) gave California Public Utilities Commission the responsibility of finding the appropriate storage limits for the entire state [35]. In 2013, the commission mandated that 1.325 GW of storage capacity needs to be built in the electricity grid of California by 2020. This amount of storage would hold about 3.8% of the daily electricity consumption of California in 2015 [36]. This mandate initiated the wave of state policies, drafted to expand eGRID sub-region flexibility for renewable energy integration.

Table 2. History of California energy storage bills.

Assembly Bill	***Objective***
AB 2514 [35]	A 1.325 GW of energy storage mandate needs to be in place by the Public Utilities Commission (PUC) of California by the year 2020.
AB 2861 [21]	Aimed to reduce conflicts of interconnection applications between utilities and storage companies by establishing a way to bring jurisdictions forward. PUC will even provide legal guidance for utilities and storage entrepreneurs if necessary.
AB 2868 [22]	Mandated that PUC passes more distributed energy storage programs for the public sector and low-income customers.

Assembly Bill	Objective
AB 33 [26]	Demanded that PUC evaluate each bulk energy storage project in its long-term effectiveness to intergrade renewables into the electricity grid.
AB 1637 [24]	Gave the PUC financial support to expand upon distributed energy by providing incentives for individuals interested in electrical fuel cells. This law required that PUC monitor the customer generated emissions and only provide funding if emissions are being reduced.

Following the energy storage mandate of California (AB2514), four more bills were passed to redefine the goals of the Public Utilities Commission (PUC) of California in September 2016. These bills, namely AB2861, AB2868, AB33, and AB1637, regulated and promoted the storage market [21]-[24]. A more detailed description of each law can be seen in Table 2. This set of policies indicated the foundation of the bulk energy storage industry within California. Investments of several million dollars in storage technology from California urged other states to pass policies that include storage technology subsidies and programs. In 2015, Oregon passed HB 2193, mandating 5 MWh of energy storage by 2020 [41]. Massachusetts also approved the idea of an energy storage mandate into the 2016 Act Relative to Energy Diversity, demanding 100 MWh of energy storage by 2020 [9]. Nevada passed a renewable portfolio standard which awards up to 10% of energy to come through energy storage [10]. Maryland passed a tax incentive to help stimulate the distributed energy storage industry [44]. Figure 2, along with Table 3, show the development of storage policies through other fast-moving states.

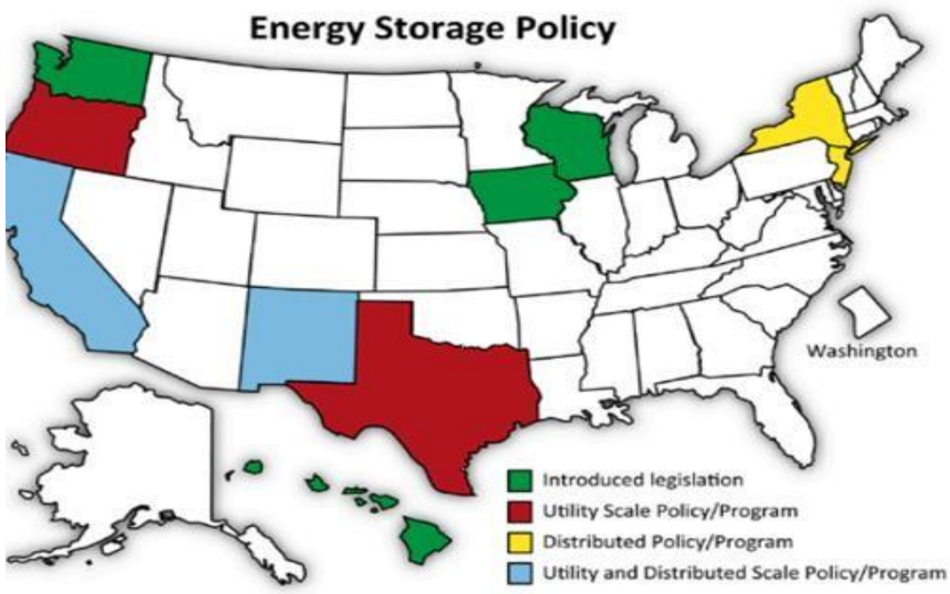

Figure 2. States with energy storage policy as of 2013, as found in P. Denholm et al. [19].

As shown in Table 3, there were approximately 13 states with policies, programs, or introduced legislation for storage technology in 2016. Most states have delegated the responsibility of storage implementation to utility companies, and some states have even funded third party contractors to take care of it [19]. Other states preferred to distribute storage technology among residents, and award initial investment relief [19]. Either way, almost all storage laws were written descriptively about technical specifications of the technology and the financial support awarded [45]. Many states failed to address environmental regulation for bulk energy storage implementation. Nevada, Washington and California were the only states that rewarded fueling storage infrastructure with clean, low emitting fuels. However, even these states failed to quantify true emissions reduction standards. The lack of emissions reduction metrics within storage polices could allow for misuse in an economic-driven electricity market [9].

Table 3. History of energy storage bills that are being passed at the state level.

State, Date [Policies]	***Type of Project***	***Objective***	***2017 Update***
California, 2010- 2015 [SB 350] [AB 327] [SB 697]	Utility-scale and distributed energy	The bill required PUC to find cost-effective storage targets. They found that 1.325 GW mandate would be the best policy agenda for storage. In 2014, a revision which eliminated storage electricity from interconnecting fees, review fees, distribution upgrades, and standby chargers was made. The revision also put in place metering systems to ensure that storage energy was coming from clean sources.	Made distributed and bulk energy storage financial support available.
Hawaii, 2014 -2016 [HB 2618], [SB 2932], [SB 2739]	Utility-scale and distributed energy policy	The senate bill proposed the establishment of a storage portfolio standard. Hawaiian Electric must submit a rate review every three years. Hawaii Integrated Resource Planning Report of 2013 deemed storage as necessary. In 2016, SB2739 mandate storage for long term duration in case of emergency.	Seeking approval on long-duration mandate.
Texas, 2011 [SB943]	Utility-scale	ERCOT utilities infrastructure is being changed to allow variable resources. The senate bills stated that The Electric Reliability Council of Texas cannot charge storage entities to interconnect, nor to transmit services, nor to sell electricity. Utility may not charge storage as transition costs nor ancillary charges because those burdens will not be paid by the customers.	Oncor plan continues to be debated
Florida, 2014 [SunSmart]	Distributed energy	The Department of Agriculture and Consumer Services has installed solar photovoltaics with battery storage in 115 emergency shelter schools.	Emergency storage installed.

State, Date [Policies]	***Type of Project***	***Objective***	***2017 Update***
Washington, 2013 [HB 1289], [HB 1296], [HB 1826], [HB 1115], [SB 6052]	Utility-scale and distributed energy	Energy storage and other techniques were assessed by how well they integrated renewable resources. Storage technology must be a resource for renewable technologies. HB 1826 gives the Washington Clean Energy Fund financial support for green storage technology. Around $14.3 million have been awarded. HB 1115 authorized $10 million for research to aid renewable integration through energy storage. SB 6052 authorized $6 million for research on clean energy integration including storage.	Research funding has been awarded to pilot storage integration.
New York, 2010-2015 [NY-BEST]	Distributed energy	The New York Battery and Energy Storage Consortium was created in 2010 for research, and to promote policy incentives. The New York Research and Development Program (NYSERDA) and ConEdison plan to provid subsidies for distributed thermal and battery storage. The technology must provide peak reduction of at least 50 kW and will receive a bonus if it meets 500 kW of peak reduction.	ConEdison plan continues to be debated.
New Jersey, 2012-2014 [NJCEP]	Distributed energy	In 2012, the New Jersey Board of Public Utilities made the New Jersey Clean Energy Program, which allocated $10 million for storage for four years. Nine MW of storage has been deployed to improve grid resilience. In 2014, the Energy Resilience Bank was created, which holds $200 million dollars for solar photovoltaics coupled with storage.	Seeking approval on Renewable Electric Storage Program.

State, Date [Policies]	***Type of Project***	***Objective***	***2017 Update***
New Mexico, 2013 [H Joint Memorial10], [S Joint Memorial 43]	Utility-scale and distributed energy	Congress asked the Energy, Minerals, and Natural Resources Department to study storage deployment in New Mexico. In 2013, the recommendations included financing large scale energy storage.	Seeking approval.
Oregon, 2014 [HB 4036] [HB 2193]	Utility-scale	The Public Utility Commission held a storage workshop, where policy incentives were drafted appropriately for utility companies. $300,000 was set aside to research the value of storage and on the deployment of storage to take place in 2018. In 2016, HB 4036 requires 50% renewable energy generation for retailers. Cost recovery for energy storage project is authorized. Requires a total of 5 MWh by 2020.	Mandate approved in 2016.
Connecticut, 2015 [Public Act 1115] [SB 1078] [SB 1502]	Utility-scale and distributed energy	Demanded that Connecticut Department of Energy & Environment Protection (DEEP) research the value of direct response and bulk energy storage. SB 1078 allowed the commissioner of DEEP to solicit long term contracts with energy storage companies. The bill also allocated for interstate collaboration to meet Comprehensive Energy Strategy. SB 1502 request for construction plans for energy storage both distributed and grid-side.	Passed law to allow formation of long term energy storage contracts.
Minnesota, 2015 [HB 3a]	Utility-scale	Requires utilities to invest in the modernization of distribution and transition, includes energy storage as a suggestion.	Request proposal for energy storage plans.
Vermont, 2015 [HB 40]	Utility-scale	Requires renewable energy generation to make up 75% of electricity sales by 2032. 12% of final project can consist of energy storage or other transformation technologies.	Renewable energy requirement with storage suggestions.

State, Date [Policies]	***Type of Project***	***Objective***	***2017 Update***
Rhode Island, 2015 [HB 5900]	Utility-scale	Calls for plans for a more reliable, efficient, and conservative energy grid, construction plans range between 2017 to 2024.	Requires plans for modern energy grid.
Massachusetts 2015 [HB 4568]	Utility-scale	Awarded a $10 million dollars investment to Department of Energy Resources (DOER) and Massachusetts Clean Energy Center to analyze storage opportunities. Demands 100 MWh of energy storage by 2020.	Requires incentives for storage by 2017 and mandates by 2020.
Maryland 2017 [HB 773] [SB 758]	Utility-scale and distributed energy	Awards a 30% tax incentive for storage capped at $5,000 for residential projects and $75,000 for bulk storage.	Incentive approved.
Nevada 2017 [AB 206]	Utility-scale	Storage is a big part of the renewable portfolio standard (RPS). Credits energy from storage only if it is used as a renewable energy asset or to reduce peak demand.	Incentive approved.

Federal Bulk Energy Storage Policy

The federal government attempted to develop laws explicitly for energy storage, but has had limited success in implementing storage technology policies. Table 4 shows the development of attempts from the federal government. Originally, the federal government fused storage technology laws with renewable energy laws. Since 2009, storage policies have been made self-standing. The federal government has been cautious with incentivizing bulk energy storage because the effects are not well known. Instead, the government chose to limit resources to monitoring the effectiveness of these polices at the state level. Having proposed the 2009, 2010, and 2013 Storage Bills, but not being able to pass any of the three polices, shows that the federal government is either not convinced that bulk energy storage is the best option for grid flexibility or that the bulk energy storage market is thriving on its own. In either case, continuous attempts signify that the government agrees with the states in that storage could resolve many of the disadvantages of renewable energy. Unfortunately, none of the three federal bills demanded emissions reduction regulations for the tax credit awarded. Similar to the storage policies written by individual states, no environmental metric was put in place to safeguard the cleanliness of the funded storage technology. This situation sparked the interest of many research groups in the environmental community to model the possible outcomes of greenhouse gas emissions from placing bulk energy storage into the electricity grid.

Table 4. Attempts summary of US federal policy and regulation of energy storage.

Policy	***Objectives***
2007 United States Energy Storage Competitiveness Act	Promoted the research, development, and application of energy storage. Established an Energy Storage Advisory Council.
2009 STORAGE Bill Attempt	Tried to create energy tax credits for investments in energy storage.
2010 STORAGE Bill Attempt	Second attempt to create energy tax credits for investments in energy storage.
2013 Storage Technology for Renewable and Green Energy Bill Attempt	Created additional tax credits for investments in energy storage.

Electricity grids throughout the United States have evolved to include more wind and solar energy. The increase in renewable energy is affecting the infrastructure of the energy grid. Many states have created versatile policy options that explore grid modernization. Techniques that are likely to have the most success in stabilizing the energy grid include bulk energy storage, demand response, and forecasting. Demand response and forecasting are value tools for fine tuning the efficiency of supply-demand within the electricity market, however, bulk energy storage shows more potential for expanding grid flexibility. Bulk energy storage investigation is occurring nationwide in efforts to integrate wind and solar resources. Many state and federal policies include both renewable and bulk energy storage grid integration. In theory, bulk energy storage could provide the balance needed to support electricity demand using a variety of renewable and non-renewable resources. The objective of bulk energy storage policy is to feasibly intermit wind and solar resources into established energy grids.

CHAPTER IV

ACADEMIC LITERATURE REVIEW

Understanding how the electricity grid behaves when it is coupled with energy storage is crucial to determining how accurately mathematical simulation can predict the electricity grid in the real-world. Mathematical programming is an effective and inexpensive way to analyze new additions to the electricity market, but modeling this complex system to get accurate outputs can be challenging. Regardless, several researchers have been able to accurately predict the effects of adding renewable energies and bulk energy storage into the electricity grid. For instance, Korpaas et al. published in 2003 one of the first works on how to clearly model the integration of wind energy and storage devices into the power grid [46]. The authors focused on finding the optimal scheduling of storage to make wind power feasible in the electricity market. Many works expanded on the technique proposed by Korpaas et al. to find the optimal economic outcomes of storage technology under different scenarios [4][20]–[24].

Origins of Bulk Energy Storage Review

After economic feasibility was well establish, the investigation of social and environmental outcomes became prevalent when studying the integration of bulk energy storage into grids. Initially, most bulk energy storage research focused on the economic feasibility, through arbitrage, in the electricity market. Then, reliability became a new metric for quantifying social welfare. Finally, more robust metrics for environmental outcomes were developed, in the form of greenhouse gas emissions derived from the application of diverse grid generators. The three fundamental sustainability metrics (i.e., social welfare, economic interest, and environmental impacts) have been widely used to identify the success of technological advancements for quite some time, therefore, they are also used to evaluate bulk energy storage. From these, environmental impacts should be a priority because of the future environmental consequences that will arise from continuous air pollution.

Given the multidisciplinary nature of environmental research, there is not a unique metric that can be considered as a standard to measure losses or gains. Environmental assessments may take many forms, like wells-to-wheels, life cycle assessments, and exhaust emissions. Most research that tries to quantify the environmental effects of the electricity grid usually focuses on greenhouse gas emissions from the energy production and efficiency losses in the transmission. In some cases, environmental storage research focuses on the mining of rare earth metals and the manufacturing of the technology [50]. Because of the advancements of renewable technology and bulk energy storage, more research groups have found ways to assess the environmental implications of these technologies [51]–[55]. Contrary to popular belief, bulk energy storage technologies do not always add environmental benefits because of the various deployment options that exist.

The speculation that bulk energy storage has the potential to increase grid emissions has been developing and strengthening over some time. Denholm and Kulcinski [56] suggested in 2004 that storage works better when it is integrated with renewable and nuclear energy, rather than with fossil fuels. Although this concept was expected, their work further implied that, even if the storage is charged with renewables or nuclear energy, emissions might still increase. In 2005, Hadley and Van Dyke [57] investigated the emissions resulting from bulk energy storage in different sets of electrical grids. They studied bulk energy storage in a grid with combined fuels and compared the emissions to when bulk energy storage is used in a grid with mostly advanced coal technologies. This study suggested that storage paired with advanced coal technologies will increase the overall emissions more than when storage is used with combined fuels. The same year, Denholm and Holloway [58] concluded that storage could be used to help shift harmful emissions, such as sulfur dioxide (SO_2), and nitrogen oxide (NO_x), from high peak hours to minimize the effect on human health from these local pollutants. In other words, storage could charge when the energy source creates lower amounts of particulate matter, and discharge when the energy source in place would have created higher amounts of particulate matter. The local emissions shift came at the expense of increasing carbon dioxide (CO_2) during low peak hours, since particulate matter and CO_2 are disproportional. Although the group was on to something, Denholm and Holloway [58] admitted that accurate emissions outcomes could not be predicted at the time, since studies were performed using imprecise emissions factors. Many of these studies hinted to increased emissions from the integration of bulk energy storage but could not demonstrate suffice evidence using average hourly emission factors.

The theory that bulk energy storage was not a green technology, could not be validated until the development of precise marginal emissions factors in 2012 (e.g. Siler-Evans *et al*. [59]), when the true emissions of the energy grid could be measured. Well-founded advancements to the sustainability of bulk energy storage came after the application of marginal emissions factors. The effectiveness of these marginal emissions factors was a key component to dispute the theory that energy storage is always clean. In 2012, Siler-Evans et al. [59] published their work on marginal emissions factors, revolutionizing the way in which systematic greenhouse emissions from the electricity grid are measured. The accuracy of these rates represented a valuable tool when considering different scenarios towards the reduction of greenhouse emissions, and are more reliable when compared to average emissions factors [59]. Having acquired a better understanding of the emission rates from the electricity grid, research groups have been able to predict the true environmental effects of integrating bulk energy storage technologies [9], [49], [60]–[63].

The work developed by Siler-Evans et al. was recognized by the National Academy of Science as having "the potential to stimulate additional research on benefits and on the interaction of different policy instruments" [64]. These factors reflect the emissions intensities of marginal generators per unit of energy, and their value changes as a function of both time and location. The difficulty of the data analysis relays on the fact that the Environmental Protection Agency publishes the greenhouse gas emissions of three major gases, CO_2, SO_2, and NO_x, from every power plant that produces 2.5 GW of power or higher. Then Siler-Evans et al. [65] assigns a pollution value to a hourly wattage of electricity consumed by specific eGRID sub-region. Such conclusions were not easy to draw, since advanced statistical regressions must be employed to sort through the data. More information about how these emissions rates were derived can be found in the Marginal Emissions Data section in Chapter VI, Methodology. The marginal emissions factors formulated by Siler-Evans et al. [65] are specific hourly rates for the last (marginal) electricity emissions, which are very effective metrics to study mix fuels on a given US eGRID sub-region.

Using marginal emissions techniques that accurately represent grid emissions, several studies have demonstrated that storage can hardly be considered a green technology. When comparing if a natural gas plant would be more beneficial for the variability of wind power than bulk energy storage, Hittinger et al. [66] found that wind integration had a very precise pollution-free window. Moreover, the study found that storage paired with wind power could increase emissions. A study done on the PJM system, developed by Lueken and Apt [67], found that 25 MW of storage would have vast welfare benefits such as lowering the cost of residential electricity in the market by 2.5 billion dollars annually. However, when they analyzed the life cycle of storage options for the electricity grid, the authors found that storage modestly increased greenhouse gas emissions. Similarly, while modeling the social benefits of storage technology in Texas, Carson and Novan [68] found that arbitrage will increase unregulated emissions, since renewables were not marginal sources of energy. This observation was true because the emission rates of peak generators were not sufficiently lower than the emission rates of generators used during off-peak periods in the Texas energy market. More research groups have begun to report the possible environmental flaws with storage integration in an open electricity market.

In 2015, Hittinger and Azevedo [9] confirmed that due to arbitrage, the market demand will drive the use of storage and increase emissions, instead of lowering them, as it was originally intended to. From the study, the three main factors which convoluted emissions from bulk energy storage were: the emissions from the generator that charged the device, the emissions associated with the displaced generator, and the roundtrip efficiency of the storage. Even with the most efficient technology, emissions might increase due to the large range of pricing between low cost carbon fuel and more expensive natural gas. The study warned against storage mandates and subsidies by providing concrete results of how much storage would increase emissions per eGRID sub-region. The value of the research originates from the accuracy of the marginal emissions factors used. The collaboration between the precise rates of pollution with energy grid systems modeling, resulted in alarming pollution amounts from bulk energy storage devices [9].

With this concept in mind, Figure 3 further demonstrates how shifting energy from one time of the day to another, is economically favorable but may increase grid emissions. Due to arbitrage, bulk energy storage is expected to increase the operation of electrical energy from cheaper, conventional fuel. Bulk energy storage would charge when electricity is cheap and abundant and discharge when electricity is most expensive, to make the most revenue. While doing so, storage would likely charge from baseload, dirtier generation and discharge during peak, cleaner generation. This results in the displacement of the cleaner peak fuels by increasing energy from the dirty off-peak fuels, as seen on Figure 3. Hittinger and Azevedo [9] systemically proved that this kind of pollution will occur even if the marginal emissions rates of the off-peak generators are near the marginal emissions rates of peak generators because of inefficiency losses.

Even eGRID sub-regions that do not follow the trend of conventional off-peak generation is dirtier than peak generation, are at risk of implementing bulk energy storage that will increase pollution. This is because off-peak generation needs to be significantly cleaner than the peak generation to account for the energy losses that will occur from charging and discharging the device (e.g. a 75% efficient storage device needs to charge with off-peak generation that is 25% or more cleaner than peak generation to prevent adding emissions to the grid). It is often the case that, in most eGRID sub-regions within the United States, conventional coal plants generate electricity throughout the day and are rarely turned off, while natural gas generators are often only turned on during peak hours to meet the demand of the customers. Even in other cleaner grids, combined natural gas energy, nuclear, or pumped-hydro produces baseload generation, but peak demand usually has similar marginal CO_2 emissions rates as the baseload. The cleanest of grids no dot have sufficiently clean off-peak energy to make up for energy losses in charging cycles. Some of the cleaner eGRID sub-regions include NYUP (Upstate New York) with off-peak emissions rates around 425-450 kg of CO_2/MWh and peak emissions rates around 543-575, CAMX (California) with off-peak emissions rates 402-429 kg of

CO_2/MWh around and peak emissions rates around 409-445 kg of CO_2/MWh, and NYCW (New York City) with off-peak emissions rates around 351-387 kg of CO_2/MWh and peak emissions rates around 354-419 kg of CO_2/MWh. Acronyms for eGRID sub-regions, established by the EPA and used throughout this thesis, can be found in Table 5 located under Pricing Data Section in Chapter VI, Methodology. While some of these cleaner grids have off-peak energy that is cleaner than peak energy, it continues to be environmentally unfavorable to implement bulk energy storage because of the inefficacy losses.

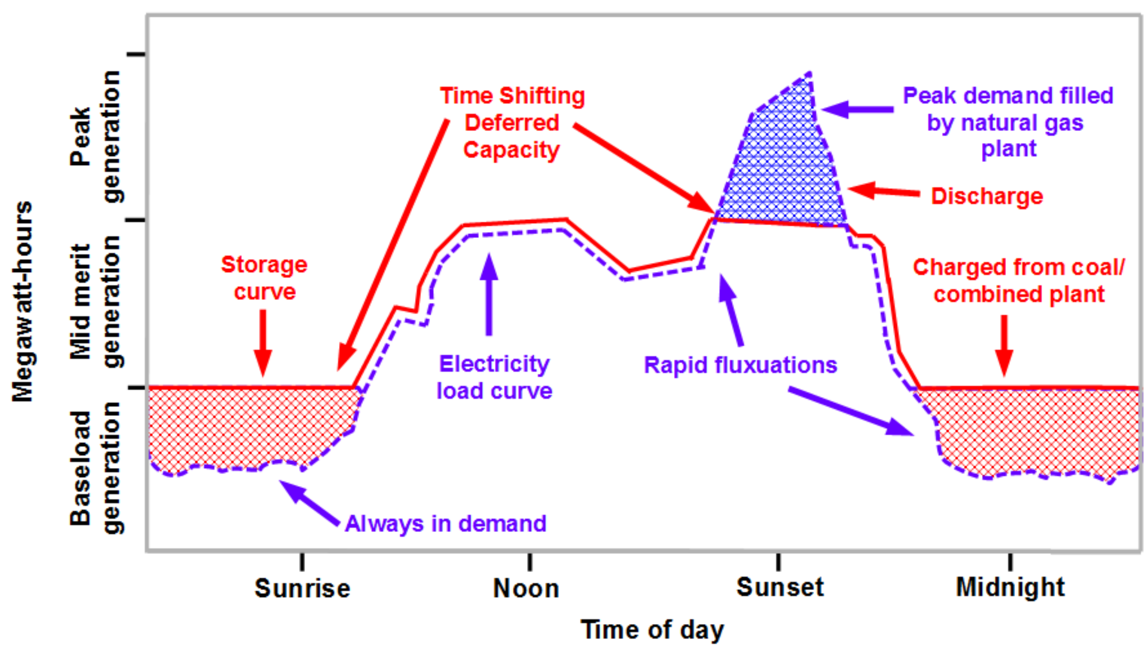

Figure 3. Electricity demand curve with (solid red line) and without (dashed purple line) bulk energy storage. Deferred capacity occurs as storage charges from off-peak generation and discharges during peak generation. For the system to be economical and emissions free, charging electricity needs to be significantly cheaper and cleaner than the displaced electricity to account for inefficiently losses.

The complication with storage inefficiency losses is portrayed in Figure 3 by the shaded regions. The red area symbolizing the energy charged from the bulk energy storage device, is purposely larger than the purple area symbolizing the energy displaced. This difference in areas, in Figure 3, illustrates the energy losses that occur when moving energy from one system to another, as explained by the second law of thermodynamics. The variety of generators used to power the United State electricity grid, as well as the energy losses, were the two main contributors for the increase of electricity grid emissions from bulk energy storage. Even with perfect efficiency, bulk energy storage pollution is inevitable, due to the dirtier or equally dirty baseload plants. Therefore, emissions will tend to increase with the natural market eagerness to make vast revenue.

The electricity grid is a very complex entity and it is challenging to predict the effects that storage technology will have on a large scale. Quantifying the effectiveness of bulk energy storage entails the consideration of revenue, reliability, and environmental-friendliness. Bulk energy storage has already proven to be economically profitable and reliable; however, to be accepted as a sustainable technology, bulk energy storage needs to reduce emissions. Investigation of clean storage deployment is critical to ensuring that bulk energy storage behaves desirably. It is important to find sustainable energy solutions that will reduce the output of harmful air pollution, while upholding the current energy demand at a reasonable price. This thesis investigates the instances within the US where bulk energy storage can be charged and discharged to yield high revenue and reduce excessive storage emissions.

Simulation of Bulk Energy Storage Review

It is likely that in many eGRID sub-regions, unregulated bulk energy storage will displace low emitting peak generation with high-emitting baseload generation, or at least displace equally clean generation to make a profit. In either case, CO_2 grid emissions will increase unless the entire energy grid infrastructure drastically changes. As this theory becomes more widely accepted, research groups have begun to build mathematical models to investigate alternatives to limit the amount of emissions resulting from the integration of storage systems. Sioshani [69] built a model to investigate the effects of competing bulk energy storage companies in the Texas electricity grid, and found that storage produces the least amount of emissions if owned by the renewable energy industry. The partnership of wind energy producers and storage facilities was crucial to limiting the amount of emitted air pollutants. In another wind energy study, Boer et al. [70] found that storage should only be implemented in areas where wind speeds range from medium to high, because storage systems could lose profit and create emissions if the renewable energy in the grid is not sufficient. Lamadrid et al. [71] found that the integration of wind, in any kind of energy grid, was less economical than the standard combined fuels grid. This often results in an insignificant reduction of emissions for the high cost spent in wind production. When wind and storage are integrated together, the results showed an even lower emissions reduction and a slightly higher cost, compared to the integration of wind only. Arbabzadeh et al. intensively investigated feasible storage characteristics to make predictions about which storage factors induce CO_2 emissions [72]. The authors found that round-trip efficiency, heat rate of the charging technology, and heat rate of the displaced technology had the strongest influence on CO_2 emissions from highly utilized energy storage devices. In another recent study, Fares and Webber found that sending solar energy back into the grid is more environmentally beneficial than storing the energy in household storage devices [73]. The study concluded that managing distributed storage under either the common interest or under the interests of the household owner would lead to increased grid emissions, mainly due to inefficiency losses. Many studies found that this concept of green energy storage is very difficult to achieve [1].

Since limiting the amount of additional emissions from storage systems would be ideal, and there is a lack of models that predict this effect, Lin et al. [74] developed a stochastic model which sets a coal emissions cap into a grid simulator. The study found that, with the coal emissions cap, storage would be forced to work excessively, increasing emissions from other fuels and from inefficiency losses. Without the coal emissions cap, storage still had the possibility of increasing emissions due to "reserve capacity." Lin et al. [74] used this term to describe storage space that is not filled by renewable energy, and is therefore free to be charged by another fuel. The amount of reserve capacity in a specific hour depends on the renewable energy production, the capacity of the storage device, and the charging device constraints set by outside sources. The authors concluded that the larger the amount of reserve capacity the more system emissions, due to the varied rates of marginal emissions factors of the charged and displaced energy [74]. It is evident that there are environmental risks associated with the integration of storage technology.

CHAPTER V

RESEARCH HYPOTHESIS

Operational modes exist for bulk energy storage that significantly reduce storage emissions while having little effect on annual revenue.

The accommodation of renewable technology into a fossil fuel foundation contains many obstacles for policy makers. Besides overcoming the initial investment of renewable technology, the sporadic bursts from renewables make it difficult to adjust every electricity resource on the grid simultaneously to meet demand. The United States implemented bulk energy storage policy to better operate the power generated from these renewable sources. Whether the storage is pumped hydro, compressed gas, or chemical storage, policy makers need to know if the integration of storage technology offers an environmentally sustainable system. Having profit as the main driving force for storage implementation, it is very feasible that bulk storage policy turns into a negative feedback loop, in which more emissions are created rather than reduced.

Usually, only a few companies will follow sustainable practices by themselves. Therefore, operational modes for bulk energy storage that significantly reduce storage emissions while having little effect on annual revenue were investigated. An operational linear optimization of bulk energy storage was formulated which can be simplified into a cost-benefit analysis of placing a 25 MW storage device into every continental eGRID sub-region in 2014. External expenses, such as initial investment, capital expenditure, and the degradation of the device, were not included in the bulk energy storage scheduling assessment. The benefit is the annual revenue that the addition of storage within the system, makes by selling electricity. The cost includes the purchased electricity. Pollution from the electricity to charge the device was considered an additional cost, while the displaced pollution from the delivered electricity was considered additional revenue. Electricity prices and marginal emissions factors for every eGRID sub-region accurately represented the cost and the pollution rates of any given hour, respectively. Discrepancies exist for the allowable pollution cost, because carbon emissions are not in units of currency. Therefore, several carbon values were explored using a scalarization technique, among these values was the Environmental Protection Agency, social cost of carbon equal to $36 per tonnes of CO_2 [75]. The solutions presented for bulk energy storage are very practical trade-offs between annual revenue and storage-induced emissions because empirical evidence from past research is used to justify the assumptions used in the optimization. Additionally, sensitivity analysis is used to back up any lingering uncertainties about the bulk energy storage optimization constraints. The solutions presented are Pareto efficient, meaning that they are all equally optimal and a decision maker is needed to identify the subjective trade-off. This thesis presents the trade-offs between annual revenue and induced emissions, to demonstrate that several sustainable methods exist to introduce bulk energy storage into the grid.

CHAPTER VI

METHODOLOGY

Using a linear programming formulation that simulates a bulk energy storage device, optimal schedules of charged and discharged energy within several electricity grids were found. The charging and discharging cycles were then used to find the earning potential of the storage technology. Moreover, marginal emissions factors were used to estimate the annual emissions from the energy shifted by the bulk energy storage. This procedure has been previously reported by Hittinger and Azevedo [9], whose objective function was to maximize revenue. The model proposed in this thesis considers a bi-objective function, where revenue and emissions are simultaneously considered into one equation. The proposed Pareto model requires two objective functions: revenue and reductions of emissions, to decide the amount of energy to displace and when to displace the energy. Hence, this thesis constructed on the method proposed by Hittinger and Azevedo [9].

The model presented in this thesis was solved using data from 2014, therefore, the results presented are the energy shifting schedules of a hypothetical storage device in that year. Figure 4 (A) introduces the multi-objective optimization procedure followed in this thesis. The inputs and outputs of the linear programming model, as well as the interpretation of results, are sequenced by arrows. The simulation inputs two sets of real-world data, electricity prices and emissions rates, and outputs an optimal energy shifting schedule that the storage should have followed to obtain the greatest revenue possible in 2014. Electricity prices can be found for every state in terms of USD per megawatt-hour (MWh). Marginal emissions factors for 22 eGRID sub-regions are formatted in terms of tonnes of CO2 per megawatt-hour. The objective of the formulation is to find the optimal schedule for the storage device that maximizes revenue. A scalarization carbon value was used to weight the importance of emissions. The carbon value assigns CO_2 emissions a dollar value, essentially acting as a unit converter from mass to currency. Several values of carbon were used because of the many discrepancies that exist about the cost of pollution; among these values was the EPA social cost of carbon equal to $36 per tonnes of CO_2 [75]. The output consisted of the charge and discharge of bulk energy storage for each hour of operation within the year 2014. After acquiring the optimal operational patterns, calculating annual revenue and storage-induced emissions is straightforward, Figure 4 (B) shows the logic behind the annual results. The decision variable summarizes whether electricity is being purchased or sold and how much of it, during each hour. This information is useful for determining the annual revenue and annual storage induced emissions.

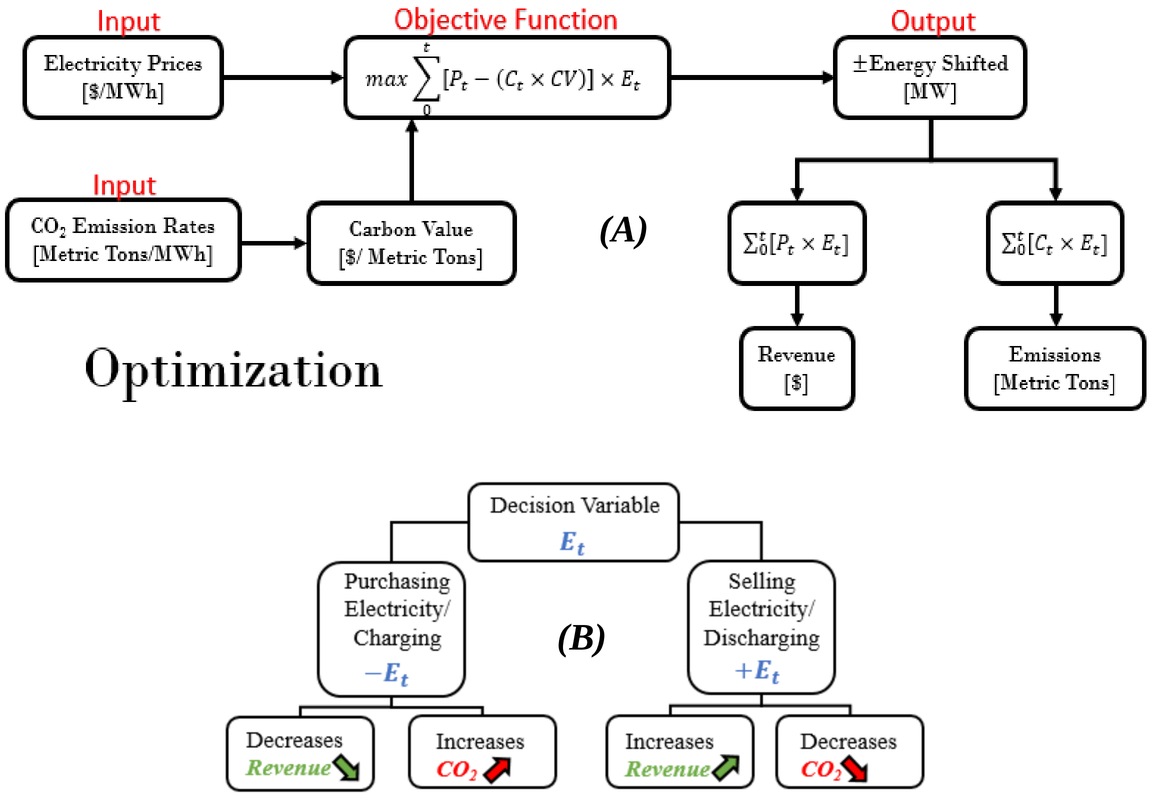

Figure 4. (A) Flow chart of optimization formulation for bulk energy storage operation. Two sets of real world data, electricity prices and emissions rates, were inputted into the objective function. The result was the energy charged or discharged which is then used to find the annual revenue and emissions form the bulk energy storage device. ***(B)*** The decision variable of the operational optimization of storage is the energy shifted from one hour to the other. Energy can be positive or negative depending on if the storage is charging or discharging. The sign of the decision variable will determine the results of revenue and storage induced CO2 emissions.

Storage Data

In this study, bulk energy storage was modeled using attributes of existing technologies such as pumped-hydro, compressed air (CAES), and battery technologies [76]. Using a technique proposed by Hittinger and Azevedo [9], approximate performance values for these technologies were found. Their study used the Global Energy Storage Database created by Sandia National Laboratory to find average values for pumped hydro, batteries, and compressed air energy storages in the following categories: number of installed devices, capacity, and charging rates. This thesis located the latest 2016 values from the Sandia National Laboratory National Energy Storage Database for the same categories, this information is displayed in Table 5. Number of installed devices refers to the register storage devices as of 2016 in each category. Capacity refers to the amount of energy that the device can hold. The charge rates are the length of time to fully charge or discharge the device. These values were self-registered and might have some discrepancies, however, they provided an estimate for characteristics for commonly used bulk energy storage devices. Values from Table 5 acted as a reference to decide system constraints for the hypothetical storage device studied in this thesis.

Table 5. Energy storage data and hypothetical device values used for computation [76].

Characteristic	***Pumped-Hydro***	***Batteries***	***CAES***	***Hypothetical Device***
Installed Devices	51	481	10	-
Capacity	578 MWh	2.8 MWh	82 MWh	100 MWh
Max Charge Rate	12 hours/cycle	1.1 hours/cycle	24 hours/cycle	4 hours/cycle
Max Discharge Rate	12 hours/cycle	1.1 hours/cycle	24 hours/cycle	4 hours/cycle
Round Trip Efficiency	65-85%	70-80%	40-65%	75%
Start Energy	0-100%	0%	0%	0 %

Additionally, a second source was used to find the round-trip efficiency for the same technologies [77], these efficiencies are also displayed in Table 5. Round-trip efficiency refers to the ratio of energy inputted to the energy retrieved from the storage system. The values for efficiencies for different storage technologies where gather from Figure 5 found in a study published in 2014. Using values from traditional energy storage technologies, a set of technical constraints was formulated to represent an overall common bulk energy storage system. The properties for the hypothetical storage device used in this computation can be seen in the last column of Table 5.

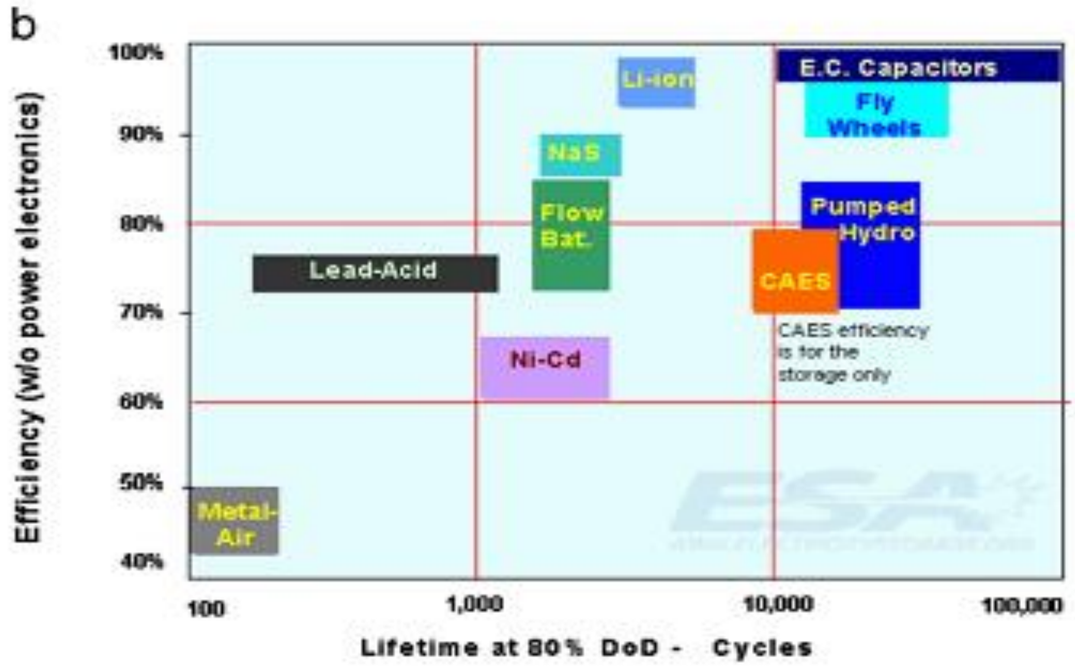

Fig. 14. (a) Storage systems as a function of investment costs per unit of power or unit of energy [108]. (b) Efficiency and lifetime at 80% DoD for each technology [108].

Figure 5. A 2014 comparison of lifetime and efficiencies of storage devices, as found in Suberu et al. [77].

Pricing Data

Optimal storage solutions for 22 regions within the United States were estimated. Regions were chosen from the 26 United States EPA eGRID sub-regions, as seen in Figure 6. The 22 chosen regions were selected because of the availability of eGRID sub-region emissions data [78]. Markets in Alaska and Hawaii were omitted from this study, but all other eGRID sub-regions within continental US were analyzed. Table 6 provides a list of all the eGRID sub-regions studied in this thesis. Pricing data for each chosen eGRID sub-region was convoluted using individual state pricing data, as reported by Horner et al. [79], [80]. All electricity price data for each state was indexed by hour, and represents real prices from 2014 [78]. For regions without an hourly electricity market, the nearest, most similar state node was used as the hourly prices. For regions with multiple electricity prices, the state with the largest population was used. For regions with Independent System Operator markets, the nearest state node was used as the hourly price. Hourly pricing data for each eGRID sub-region was inputted into the linear optimization model and was also used to find the results of annual revenue.

Table 6. EPA eGRID sub-region acronym, names, and states with respective state pricing data (price data from Horner et al. [79], [80]).

eGRID Sub-region	***eGRID Sub-region name***	***States within the eGRID sub-region***	***State electricity pricing used***
NEWE	NPCC New England	Massachusetts, New Hampshire, Vermont, Maine, Connecticut, and Rhode Island	Massachusetts
NYUP	NPCC Upstate New York	Upstate New York	New York
NYLI	NPCC Long Island	New York Long Island	New York
NYCW	NPCC New York City & Westchester	New York City, NY	New York
RFCE	RFC East	Pennsylvania, New Jersey, Maryland, and Delaware	Pennsylvania
RFCW	RFC West	Indiana, Ohio, and West Virginia	Ohio
SRVC	SERC Virginia/Carolina	North Carolina, South Carolina, and Virginia	North Carolina
SRTV	SERC Tennessee Valley	Tennessee and Kentucky	Tennessee
ERCT	ERCT all	Texas	Texas
SPSO	SPP South	Oklahoma	Oklahoma
SRMW	SERC West	Missouri and Illinois	Illinois
SRMV	SERC Mississippi Valley	Louisiana, Mississippi, and Arkansas	Louisiana
MROW	MRO West	North Dakota, South Dakota, Minnesota, Nebraska, and Iowa.	Minnesota
SPNO	SPP North	Kansas	Kansas
MROE	MRO East	Wisconsin	Wisconsin
RFCM	RFC Michigan	Michigan	Michigan
RMPA	WECC Rockies	Colorado and Wyoming	Colorado
NWPP	WECC Northwest	Washington, Oregon, Montana, Idaho, Utah, and Nevada	Washington
AZNM	WECC Southwest	Arizona and New Mexico	Arizona
CAMX	WECC California	California	California
FRCC	FRCC all	Florida	Florida
SRSO	SERC South	Georgia and Alabama	Georgia

Marginal emissions Factors Data

Marginal emissions factors (MEFs) used in this work have been calculated using 2014 EPA emissions data using the same framework as Siler-Evans et al. [59] found at: https://cedm.shinyapps.io/MarginalFactors/. This study chose to focus on 2014 carbon dioxide marginal emissions factors which are in units of kilogram of CO_2 per megawatt-hour [59]. Siler-Evans et al. regressed the CEMs information into hourly rates for three different seasons (summer, winter, and intermediate) for 22 eGRID sub-regions[81]. The EPA's Continuous Emissions Monitoring System (CEMS) provides hourly data for raw emissions of SO_2, NO_x, and CO_2 for every fossil fuel power plant with a capacity of 25 MW or larger within the United States. Using EPA data from 2014, Siler-Evans et al. divided hourly plant pollution and electricity generation into respective eGRID sub-regions. Then for each eGRID sub-region, the difference of electricity generation and the difference of total pollution was found for each hour. This information was then graphed on a scatter plot with one axis labeled generation difference and the other axis labeled pollution difference. A linear regression was performed to identify the slope of the curve or in other words the pollution per one megawatt hour of electricity of that given eGRID sub-region. Siler-Evans et al. expressed marginal emissions factors as emission rates, such as, kilograms of a pollutant per megawatt-hour. This study chose to focus only on carbon dioxide marginal emissions factors which are in units of kilogram of CO_2 per megawatt-hour. MEFs from power plant storage operations have been used in previous studies [9], [59], [65]. MEFs were the second set of inputs used in the mathematical optimization and they were also used to estimate the annual emissions results if a hypothetical bulk energy storage device had been integrated into each eGRID sub-region.

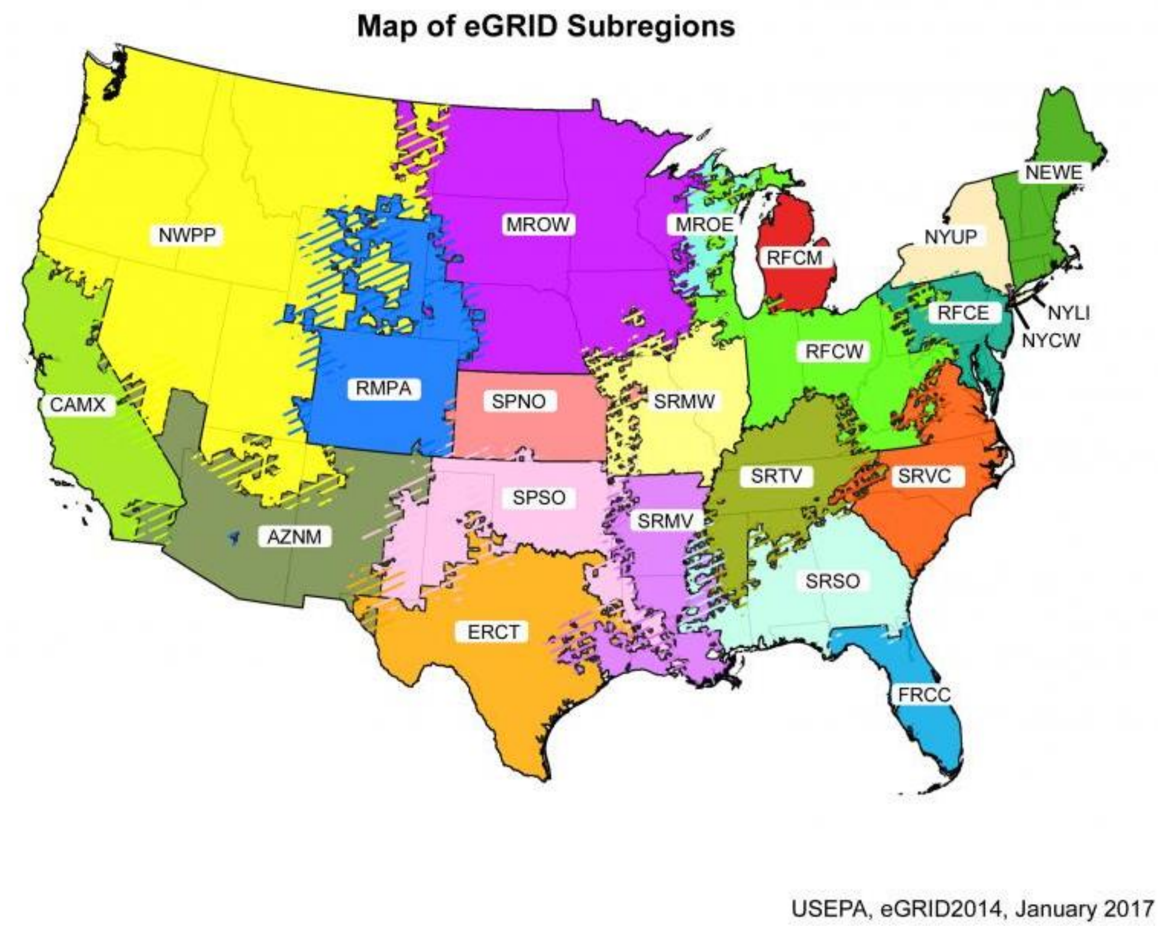

Figure 6. Twenty-two EPA eGRID sub-regions evaluated using 25 MW of Bulk Energy Storage. All 2017 eGRID continental regions were evaluated. Alaska and Hawaii eGRID sub-regions were omitted from this study.

Storage Operation

The mathematical formulation treated the storage unit as a bulk energy, time-shifting device. The storage mimicked a private company intending to maximize annual revenue while avoiding increasing storage-induced emissions. A Pareto optimization was used to maximize the revenue (1st objective), but considering emissions as cost penalties (2nd objective). Both objectives are linear objective functions with a scalarization performed on the second objective using a term referenced as a "carbon value". Different values for carbon values were used to identify a threshold that will prevent the storage system from excessively increasing pollution. The higher the carbon value was, the less likely the bulk energy storage will increase pollution, but also, the less revenue it will generate. The storage in this study was large enough to reduce the peak energy need, but small enough not to interfere with the market prices or marginal emissions systems. The shifting of the demand loads was all that the storage can alter, and everything else in the energy system, such as prices, energy sources, and marginal emissions factors stayed constant while the technology shifted energy from one hour of the day to another. The bulk energy storage could cycle as much as the specific ramping on and off rates allowed it to, without any degradation to the assumed initial performance.

For each eGRID sub-region, MATLAB was used to solve the multi-objective optimization using scalarization, or iterations of optimal solutions using a weight. Since the two functions are linear, the outputs are considered multi-objective trade-offs Pareto optimal solutions. The main objective function (Eq. 1) is to maximize two linear functions revenue (Eq.2) and reduction of CO_2 emissions(Eq.3). The decision variable,

E_t, is positive if the unit is discharging or selling electricity, and negative if the unit is charging or buying electricity. The system could not charge and discharge at the same time; it does one or the other. The revenue function (Eq.2) uses P_t, electricity prices, and Et, the displaced energy from bulk energy storage, to find the maximum income. The emissions reduction function (Eq.3) uses $MEFS_t$, marginal emissions factors in units of kilograms of CO_2 per megawatt-hour, V_i, a unique carbon value in units of USD per tonnes of CO_2, and E_t, the displaced energy from bulk energy storage, to find the minimum storage induced-emissions.

$$\boldsymbol{max} \sum_{0}^{t} [\mathbf{F_1}(\mathbf{E}_t), \mathbf{F_2}(\mathbf{E}_t)]$$

Main Objective Function (Equation.1)

$$\mathbf{F_1} = \boldsymbol{max} \sum_{0}^{t} [\mathbf{P}_t \times \mathbf{E}_t]$$

Revenue Function (Equation.2)

$$\mathbf{F_2} = \boldsymbol{min}\ \mathbf{V}_i \sum_{0}^{t} [\mathbf{MEF}_t \times \mathbf{E}_t]$$

$$\mathbf{V}_i \in \mathbf{0}, \mathbf{1}, \mathbf{2}, \mathbf{5}, \mathbf{10}, \mathbf{20}, \mathbf{36}, \mathbf{50}, \mathbf{100}, \mathbf{200}, \mathbf{500}, \mathbf{1000}, \mathbf{2000}, \mathbf{5000}, \mathbf{10000}, \mathbf{20000}, \mathbf{50000}, \mathbf{100000}, \mathbf{200000}, \mathbf{500000}, \mathbf{1000000}.$$

Emissions Reduction Function (Equation.3)

V_i is the weight vector

For every eGRID sub-region, various solutions are formed using a weighted vector, a carbon value; each V_i produces a solution that is equally as good. Each linear programming formulation was solved using the single dual simplex method integrated into MATLAB. The limitations of the storage unit serve as constraints in the linear optimization problem, as seen below. The initial energy (Eq. 4) of the storage unit is assumed to be zero.

$$\boldsymbol{s_1 = 0}$$

Start Energy Constraint (Equation.4)

The charging efficiency of a single charge or discharge (Eqs. 5 and 6) are found using the square root of the round-trip efficiency, η_{rt}. The base-case round-trip efficiency used was 75%, as seen in Table 5.

$$\boldsymbol{s_t = s_{t-1} - \left(E_t \div \left(\sqrt{\eta_{rt}}\right)\right) \; if \; E_{t-1} \geq 0}$$

Charging Inefficiency Constraint (Equation.5)

$$\boldsymbol{s_t = s_{t-1} - \left(\left(\sqrt{\eta_{rt}}\right) \times E_{t-1}\right) \; if \; E_{t-1} < 0}$$

Discharging Inefficiency Constraint (Equation.6)

The capacity of the storage device is restricted to be greater than zero (Eq. 7) but less than the maximum capacity of the device (Eq. 8). The base-case maximum capacity used was 100 MWh, as seen in Table 5.

$$\boldsymbol{S_t \geq 0}$$

Charging Capacity Constraint (Equation.7)

$$\boldsymbol{s_t \leq s_{max}}$$

Discharging Capacity Constraint (Equation.8)

Lastly, the charging rates of the storage unit are set within the feasible rates of the device (Eqs. 9 and 10). Maximum allowable charge rates for the main operation are 25 MW as found in Table 5.

$$\mathbf{E_t \leq R_{max}}$$

Charging Rate Constraint (Equation.9)

$$\mathbf{E_t \geq -R_{max}}$$

Discharging Rate Constraint (Equation.10)

In total, 462 schedule configurations were found, not including the sensitivity analysis; e.g. 21 carbon values for each of the 22 eGRID sub-regions. Each one of these configurations yielded different optimum charging and discharging schedules and resulted in unique annual revenue and changes in grid emissions. Additional summations using the $\boldsymbol{E_t}$, the displaced energy, were needed to get the annual results for each optimization. Annual revenue (Eq. 11) was calculated as the summation of purchased electricity minus sold electricity of the displaced energy.

$$\sum_{\mathbf{0}}^{\mathbf{t}} [\mathbf{E_t} \times \mathbf{P_t}]$$

Annual Revenue (Equation.11)

Annual CO_2 emissions (Eq. 12) were calculated using the MEFs of CO_2 for the given hour and the displaced energy. The summation of the emissions from the charged energy minus the emissions from the discharged energy resulted in the total additional storage emissions for the year.

$$\sum_{0}^{t}[-\mathbf{E_t}\times\mathbf{MEF_t}]$$

Annual Emissions (Equation.12)

A negative change in emissions indicates that storage charged with low emitting electricity and discharged to replace electricity that would have been high emitting, therefore, preventing grid emissions. Each one of these summations is found for every optimal Pareto operating solution. The results aid to compare the annual trade-offs of each schedule.

To get a better understanding of how the system selects when to charge or discharge, Figure 7 displays four energy storage operating solutions for the eGRID sub-region, SPNO (Kansas) from late February to early March. The figure demonstrates the optimal storage schedules for carbon values of $0, $36, $100, and $1M USD per tonnes of CO_2. As the carbon value is increased, the formulation prefers to give solutions with lower emissions, instead of only focusing to generate revenue from electricity prices. In Figure 7, for example, the observed spike of prices on March 5th becomes less influential in the operation as carbon value is altered. Another example of the system choosing a performance which emits less is when the emissions were over 500 kg of CO_2 (February 26-28), the storage finds increasing pollution too expensive and decides not to shift dirty fuel. The storage device can simultaneously operate with the objective to maximize revenue and reduce grid emissions, but when the carbon values are very high, the system can achieve solutions in which grid emissions are prevented. Overall, these results show the operating opportunities that bulk energy storage has, if different severities of pollution are considered.

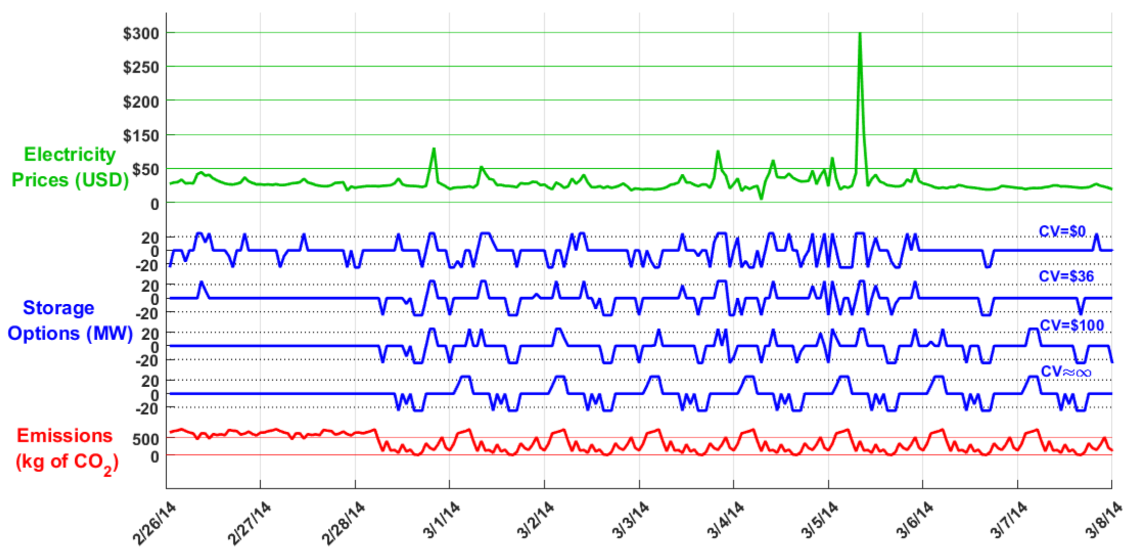

Figure 7. Four optimal charging and discharging schedules for bulk energy storage for SPNO (Kansas) during late February and early March in 2014. As pollution becomes more expensive, carbon value increase, storage behavior is more influenced by emissions rather than by revenue.

The main objective of this thesis was to identify the trade-off relationship between the change in emissions and revenue of bulk energy storage, for each specific eGRID sub-region. For each eGRID sub-region, various Pareto solutions were identified using the nearest available hourly electricity price minus the nearest marginal emissions factor times the respective carbon value, as seen in the flow chart of Figure 4. All solutions are nonnominal and satisfy the objective preferences, but a human decision maker is needed to identify the best point on the Pareto curve. In the case of bulk energy storage, the decision maker would identify the trade-off between revenue and induced-storage emissions given a series of optimal operating schedules. The optimization simply clarifies the various opportunities that exist, by simply altering the operation, to modify the effects of bulk energy storage onto the grid. In conclusion, the outputs comprise of all the opportunities that exist in the operation of bulk energy storage.

CHAPTER VII

RESULTS

Figure 8 presents the annual results of each optimization with different carbon values for three different eGRID sub-regions CAMX (California), NYUP (Upstate New York), and ERCT (Texas). Each point in the figure represents the annual revenue and annual CO_2 emissions from a possible operating schedule of storage in 2014, using a unique carbon value. In particular, carbon values \$0, \$36, and \$100 have been outlined to demonstrate the incremental progression of the Pareto front that exist for each eGRID sub-region. The solid lines connecting consecutive data points represent the Pareto curve, or the representative set of Pareto efficient solutions. As the carbon value is incremented to represent a higher cost of increasing grid pollution, the optimization process prefers schedules that reduce emissions by changing the charging operation; but there is a trade-off because these schedules reduce the possible revenue. For each region, using a carbon value of \$36 USD per tonnes of CO_2 seems to decrease the revenue in a small proportion, but it results in a large reduction of emissions. On the other hand, when carbon values above \$100 USD per tonnes of CO_2 are used, the decrease in emissions is less marked, but there is a significant decrease in revenue. It is important to note that the last emissions are the most expensive to reduce, as is the case with most technologies. For all three regions, a low to moderate carbon value has a significant, positive effect on the environment.

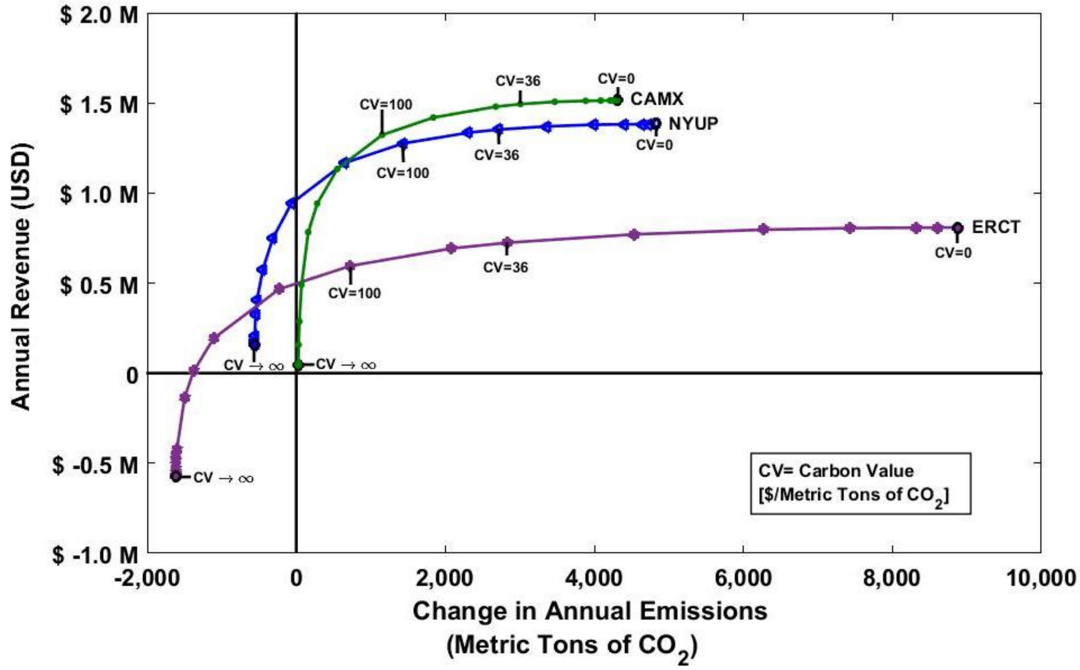

Figure 8. Bulk energy storage optimal operational results from 2014 for three eGRID sub-regions, CAMX (California), NYUP (Upstate New York), and ERCT (Texas). The solid lines represent all the possible Pareto efficient solutions if a 25 MW storage device had been integrated in each eGRID sub-region. By rearranging charging schedules, bulk energy storage can trade-off excessive emissions for a slight cost.

Annual economic and environmental results of a hypothetical storage technology vary greatly from California to New York to Texas. In NYUP (Upstate New York), bulk energy storage has the potential to earn a maximum of about $1.38 million dollars annually, but at the expense of increasing CO_2 pollution by about 4,800 tonnes. If the bulk energy storage is mandated to behave more environmentally conservative (EPA advised social carbon cost of $36 per tonnes of CO_2 [75]), then NYUP (Upstate New York) would make $1.35 million dollars annually and increase CO_2 pollution by about 2,700 tonnes. That is a 56% reduction in new NYUP eGRID emissions for $30,000 dollars. The same suggested carbon value, would have a 70% reduction from new CAMX eGRID emissions for $20,000 and a 30% reduction from new ERCT eGRID emissions for $85,000. For eGRID sub-regions NYUP (Upstate NY) and CAMX (California), where the modeled storage device is expected to make over a million dollars annually, this is a very small percent (<3%) of the annual revenue for a large fraction (56-70%) of reduced storage emissions. For ERCT (Texas), it is equivalent to 11% of the annual revenue. However, due to the large range of daily fluctuations in MEFs, more than 2,500 tonnes of CO_2 emissions could be prevented. These percentages are based off the maximum allowable emissions by the bulk energy storage device, which depends on how dirty the sources of the electricity in the eGRID sub-region are. Since eGRID sub-regions have different power system characteristics, altering the behavior of the bulk energy storage will have different effects. However, given the opportunity, storage companies will operate to seek the highest revenue and act without the existence of a carbon value (CV=0). Therefore, any kind of emissions prevention from bulk energy storage operation is better than none.

Bulk energy storage Pareto solution curves for all 22 eGRID sub-regions (each one has 21 different carbon values) are plotted in Figure 9. As expected, states with similar electricity prices and energy resources tend to have similar results. For example, NYUP (Upstate New York), NYCW (New York City), NYLI (New York Long Island), NEWE (Massachusetts, New Hampshire, Vermont, Maine, Connecticut, and Rhode Island) and RFCE (Pennsylvania, New Jersey, Maryland, and Delaware) all make about $1.4 million USD and, approximately, emit six million tonnes of CO_2 a year. Likewise, SPSO

(Oklahoma), SPNO (Kansas), SRVC (North Carolina, South Carolina, and Virginia), as well as SRTV (Tennessee and Kentucky), all make less than $500,000 USD and emit about seven thousand tonnes of CO_2 a year. Plots with higher resolution of eGRID sub-region results can be found in the Appendix. Although demographics plays a huge role on the allowable revenue and resulting emissions, most eGRID sub-regions follow a similar trend. For all eGRID sub-regions, Pareto solutions with lower carbon values tend to retain high revenue while preventing high amounts of annual emissions.

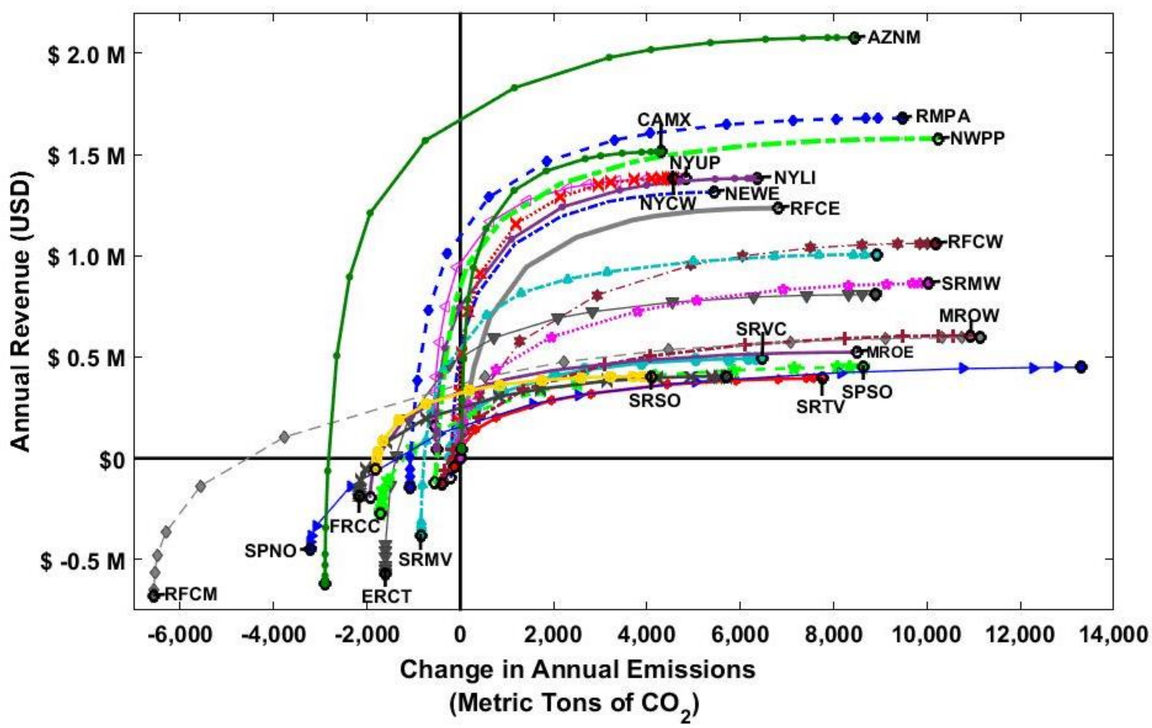

Figure 9. Bulk energy storage annual revenue and emissions results for 2014 from optimal charging and discharging cycles for 22 eGRID sub-regions. Each line represents a set of possible Pareto solutions within an eGRID sub-region, starting with a carbon value equal to zero (most revenue and highest emissions) and ending with a $1M carbon value (lowest emissions and least revenue).

In 2014, the final economic and environmental results of a hypothetical storage technology would have varied greatly. The optimization was unique for every eGRID sub-region and the bulk energy system did not always decide similarly. As the cost of pollution was steepen by the carbon value, bulk energy storage was forced to make critical charging and discharging decisions. In many instances throughout the year, storage was observed not shifting energy. This was caused due to any of the following reasons: the emissions were too high, or the inefficiency loses were too high, or the ramping rate was not fast enough, or the prices were too low. There are several restrictions that change the behavior of storage when increasing the amount of grid CO_2 emissions becomes more expensive.

When forced to make decisions due to environmental costs, storage has two possible responses, to rearrange the scheduling or to shut off operation. For the most part storage tries to rearrange the scheduling to retain high revenue. This convolutes in a steady decrease of emissions with minimal shift in revenue as seen by the initially flat slopes on most curves in Figure 9. When the carbon value becomes too expensive to find a feasible schedule, storage stops working periodically. Initially this occurs partially within a season, but environmental costs could become so high that the bulk energy storage shuts off completely for a whole season. As seen in Figure 9, in eGRID sub-regions like CAMX (California), RFCE (Pennsylvania, New Jersey, Maryland, and Delaware), and SRMW (Missouri and Illinois), the device loses revenue fast and there is a rapid drop or abrupt stop in operation when the weight of carbon values is high. There are some special cases however, where altering the carbon value to an aggressively high cost, results in income from the reduction of grid emissions. In regions where the daily emissions range largely, bulk energy storage remains working even with high carbon values, and instead charges with clean energy to displace dirty pollution. As seen in Figure 9, bulk energy storage can reduce energy grid emissions in certain eGRID sub-regions like AZMN (Arizona), ERCT (Texas), and RFCM (Michigan). Although the idea of cleaning up grid emissions is favorable, bulk energy storage would make zero or negative revenue by charging with cleaner energy and displacing dirty generation. Decisions made by the bulk energy storage device are logical because the pattern between revenue and emissions is evident.

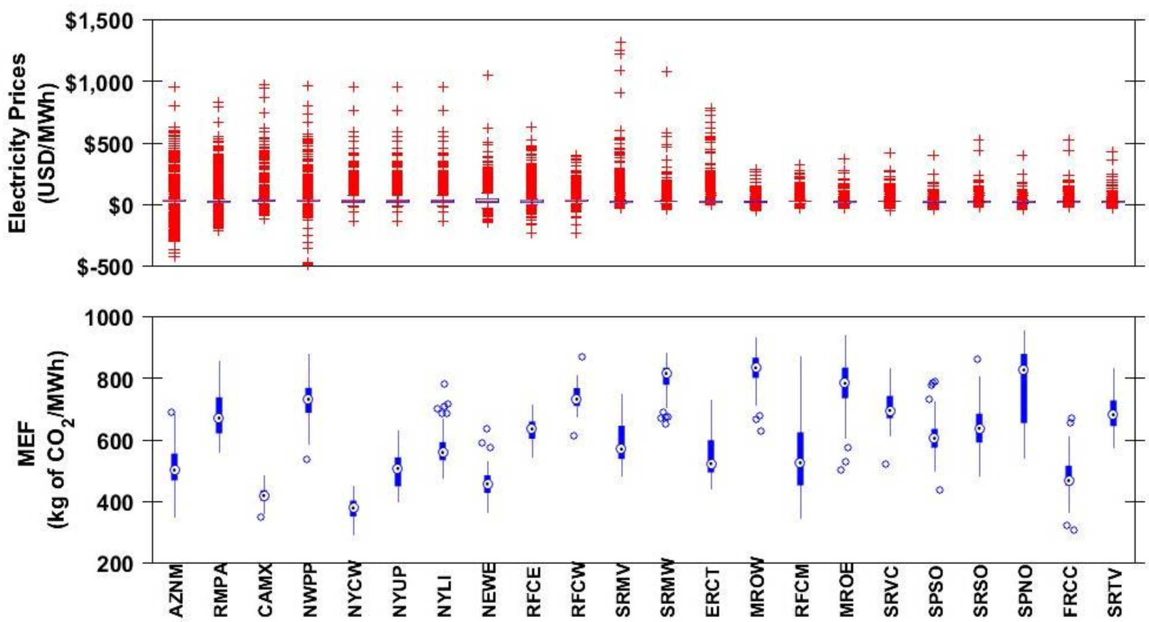

Figure 10. Box and whisker plot for electricity prices and marginal emissions factors. There is not a strong correlation between electricity prices and marginal emissions factors, therefore, bulk energy storage result will tend to vary greatly from region to region.

The storage decision results as seen in Figure 9 originate from two factors: daily electricity price fluctuations and daily opportunities to reduce emissions. Figure 10 displays box and whisker plots for the two simulation inputs, electricity prices and marginal emissions factors. The eGRID sub-regions on the x-axis are listed in ascending order of highest annual revenue (left) to lowest annual revenue (right). The first plot, in Figure 10, shows that eGRID sub-regions with the largest ranges of electricity prices tend to have made more annual revenue. Electricity prices have a high correlation with annual revenue, as expected. The second plot shows that there is little correlation between electricity prices and marginal emissions factors. Instead, marginal emissions factors affect how flexible bulk energy storage is to adapt to a new charging and discharging schedule. The larger the range of the MEFS, the more likely the results will retain revenue (remain flat curves in Figure 9). Regions with large MEFS ranges like RFCM (Michigan) and SPNO (Kansas) retain revenue as carbon values increased for much longer, as seen in Figure 9. On the other hand, regions with short MEFS ranges like RFCE (Pennsylvania, New Jersey, Maryland, and Delaware) and CAMX (California) drop in revenue fast because there are fewer opportunities to shift energy around cleanly. Each eGRID sub-region has a unique set of electricity prices and marginal emissions factors which results in variable optimal solutions during bulk energy storage integration.

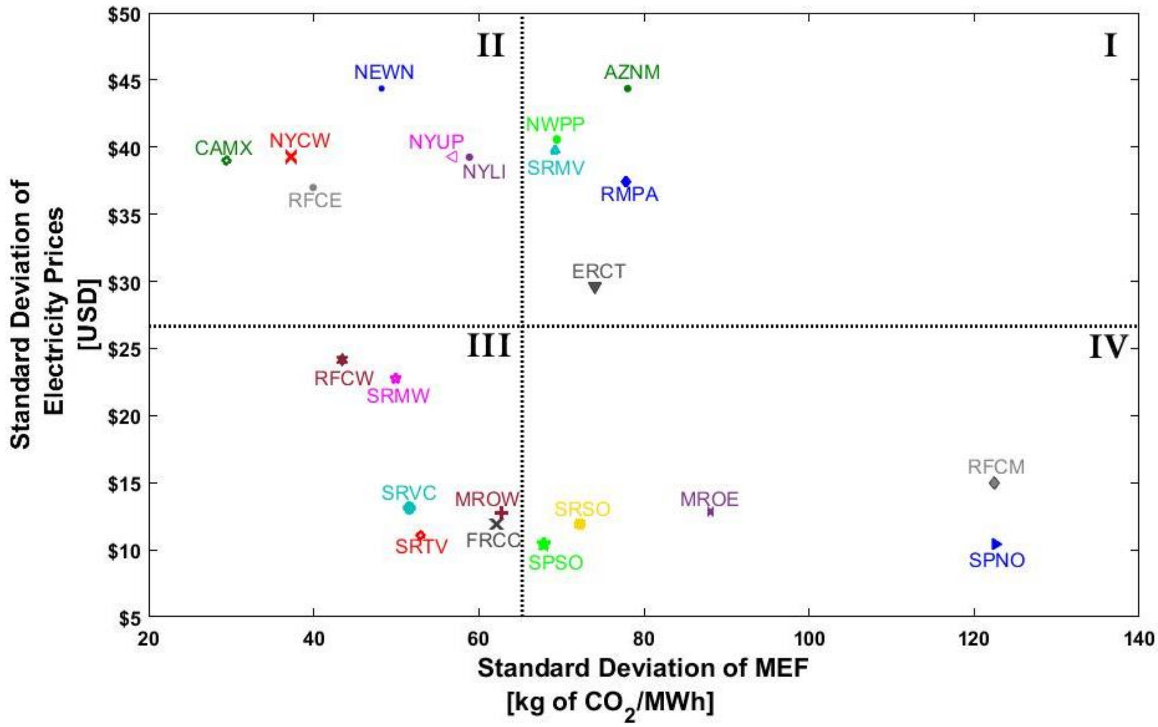

Figure 11. A scatter plot of the standard deviation of the inputs used in the optimization, electricity prices and marginal emissions factors. The quadrants represent the upper and lower halves as depicted by the mean of each set of standard deviations. The greater the standard deviation in either data set, the more play for the storage device to make higher revenue and emit less emissions, respectively.

The more flexibility in electricity prices or in marginal emissions rates, the more options there are for the bulk energy storage to optimize around. Figure 11 shows the standard deviation of electricity prices versus the standard deviation of MEFs. The graph has been broken up into four quadrants using the mean to divide the lower half from the upper half of each data set of the regions presented. Roughly speaking, regions that have more sustainable economic solutions for bulk energy storage are located higher and more towards the right on the graph. Regions in quadrant one, make high annual revenue and can shift emissions around due to the large range of MEFs. Regions in quadrant three, increase emissions the most, because there is not much play in the shifting of emissions.

Regions in quadrants two and four, have a high standard deviation in one data set but not the other. Although the standard deviation does a decent job at explaining the optimal results from bulk energy storage, daily fluctuations in each of the data sets are the true contributors to the behavior of the system. The large range of variability between the data sets of each region result in vast differences in the operational schedules of the bulk energy storage.

The number of charging-discharging cycles that the storage performed varied significantly in each scenario. Although storage performance is not penalized for the number of cycles, it is important to understand the cleanliness or dirtiness the energy that was actually shifted. Figure 12 provides a clearer illustration of the emissions per energy that are being shifted, in units of kilograms of CO_2 per megawatt-hour. Similar to Figure 9, Figure 12 shows a steep decrease in pollution and a moderate revenue decrease using lower carbon values for most regions. However, there are some eGRID sub-regions that experience large decreases in revenue, like NYCW (New York City), RFCE (Pennsylvania, Maryland, New Jersey, and Delaware), and CAMX (California). As previously explained, this large decrease is mainly driven by short ranges in marginal emissions factors. The small fluctuation in emissions causes the bulk energy storage to stop moving energy because these is no cleaner way to charge and discharge. Figure 12 best displays the steady progression of shutting down production for each eGRID sub-region because of pollution expenses. Oppositely, some regions gradually drop and retain revenue a lot longer, for example AZNM (Arizona and New Mexico) and SRSO (Georgia and Alabama). These regions have longer ranges of marginal emissions factors as found in Figure 10. This allows the bulk energy storage to rework the charging and discharging schedule to maintain high revenue. Figure 12 provides a better representation of the total rate of emissions for the energy that is being displaced in the format of pollution mass per energy moved by the bulk energy storage.

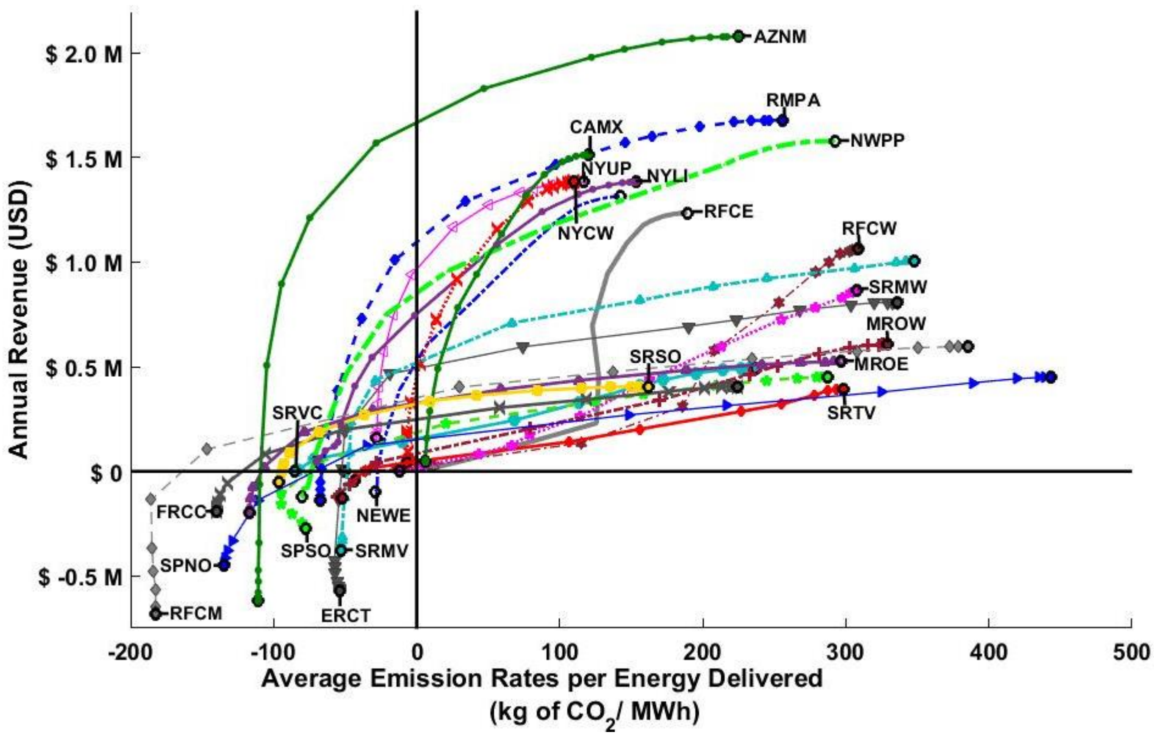

Figure 12. Bulk energy storage options for 22 eGRID sub-regions in terms of increasing pollution from the energy displaced. Energy displaced by storage has varied pollution rates in different regions. As carbon values increase the regions with larger ranges of MEFs drop gradually while regions with very small ranges of MEFs drop rapidly.

Further, Figures 13 and 14 display the same information about emisisons/ rate of emissions per energy delivered in a different manner, using a map of eGRID sub-regions within the United States. Figure 13 displays the information using the same emission units of annual tonness of CO_2, as seen in Figure 9. Figure 14 displays the information using the same emission rate units of tonnes of CO_2 per megawatt-hour, as seen in Figure 12. Both figures include annual revenue in units of USD. Each eGRID sub-region was independently shaded to represent either the emissions/ rate of emissions per energy delivered (left), or the annual revenue (right). Only four sets of the previous optimal results are displaced using maps of the United States. The studied carbon values presented in Figures 13 and 14 are $0, $36, $100, and $1M USD per tonnes of CO_2. Although not all of the solutions are displayed on the US maps, similar trends as seen previously apear through the maps.

The contour of the maps, in Figures 13 and 14, helps to identify which regions will be more influenced if the storage device acts considering a finite carbon value. The maps also show the large variations in revenue and emissions among the eGRID sub-regions. As seen previously, the higher the carbon value, the less revenue the storage technologies can make. However, some eGRID sub-regions, like AZNM (Arizona and New Mexico) and CAMX (California), continue to make a significant revenue while simultaneously decreasing their emissions. Other eGRID sub-regions, like SPNO (Kansas), FRCC (Florida), and SRSO (Georgia and Alabama), are more renounced because of their ability to largely reduce emissions as carbon values are implemented. Storage results are greatly influenced by the grid infrastructure and demand profiles, both of which largely vary per eGRID sub-region. Since eGRID sub-regions have different power system characteristics, it becomes very difficult to select a carbon value that would affect every region in the same manner.

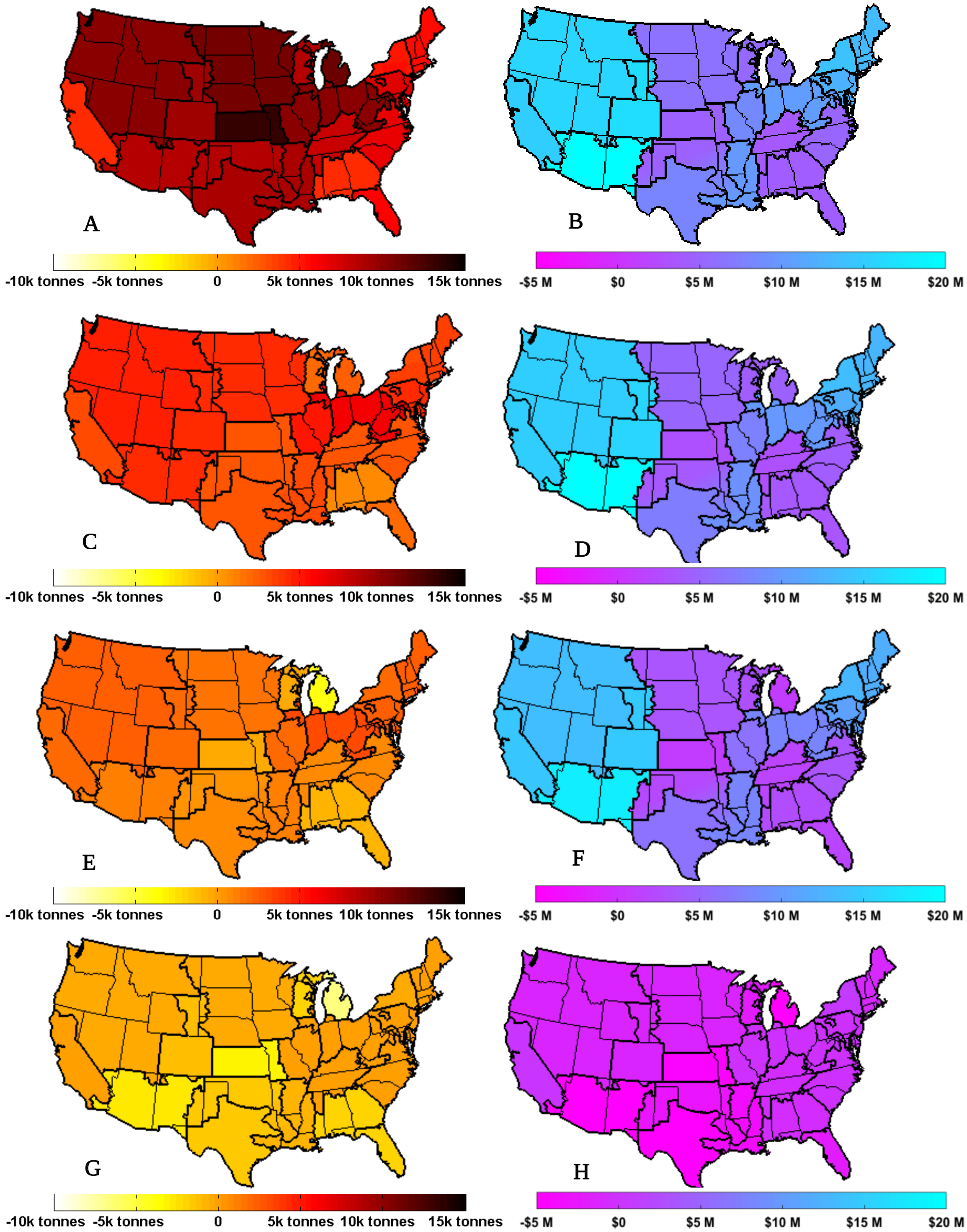

Figure 13. US map of emissions(left) in kilograms of CO_2 and revenue (right) in USD, with increasing carbon values. Maps A & B have a carbon value of $0 per tonnes of CO_2. Maps C & D have a carbon value of $36 per tonnes of CO_2. Maps E & F have a carbon value of $100 per tonnes of CO_2 Maps A & B have a carbon value that $1M per tonnes of CO_2.

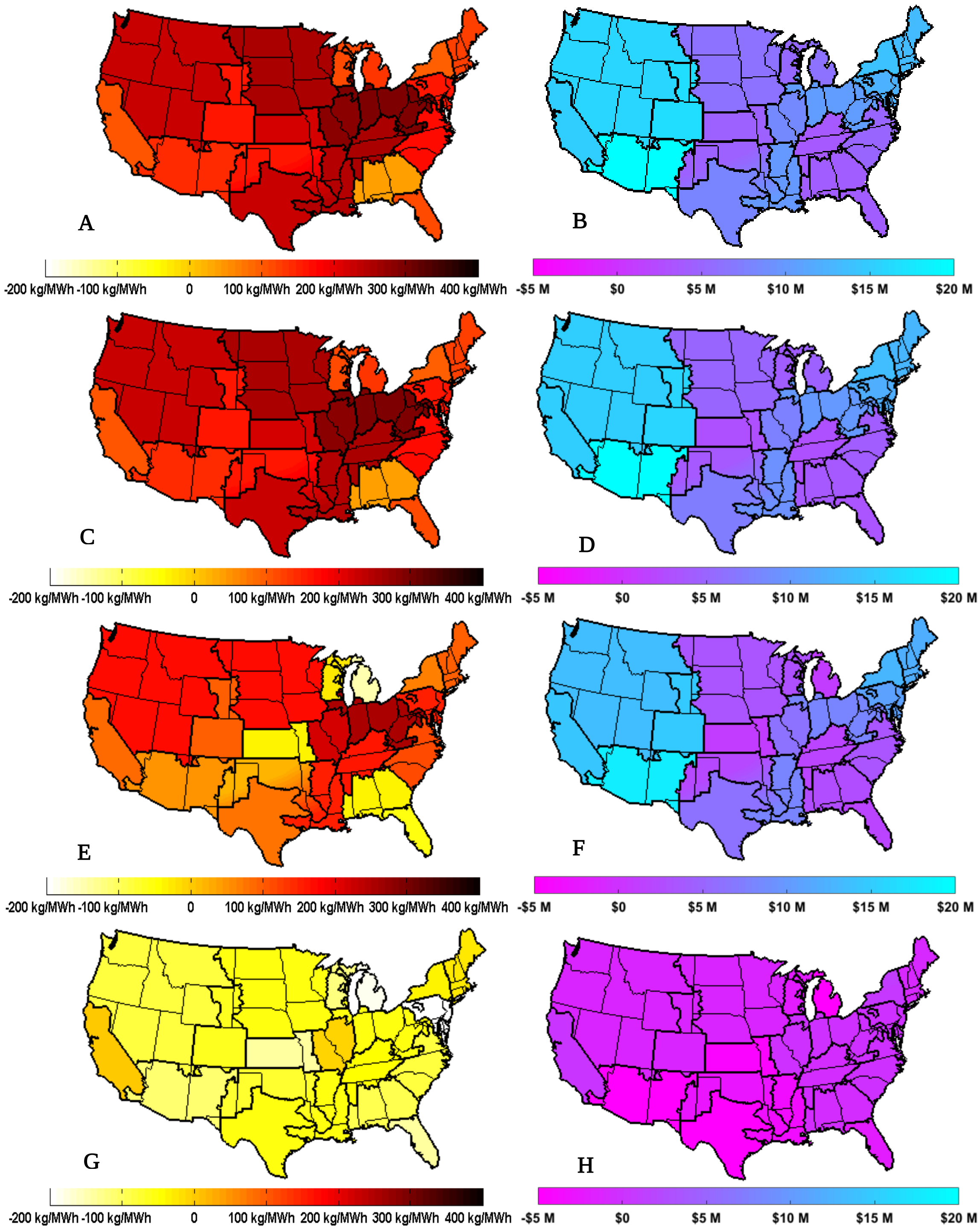

Figure 14. US map of emission rates (left) in kilograms of CO_2 per megawatt-hour and revenue (right) in USD US map of emissions rates and revenue with increasing carbon values. Maps A & B have a carbon value of $0 per tonnes of CO_2. Maps C & D have a carbon value of $36 per tonnes of CO_2. Maps E & F have a carbon value of $100 per tonnes of CO_2. Maps A & B have a carbon value that $1M per tonnes of CO_2.

A different way of looking at the results is to analyze the cost of reducing emissions by a certain percentage. This method penalizes eGRID sub-regions that pollute the least, however, it provides an understanding of the nationwide costs to reduce emissions. Figure 15 shows the cost of reducing CO_2 emissions by cumulative percentage intervals for 22 eGRID sub-regions. All 22 eGRID sub-regions are posted, but many of the regions with lower emission reduction costs, overlap and cannot be easily identified. For the most part, reducing the storage-induced emissions by 25% costs less than $10 per tonne of CO_2 in all regions; the cost of reducing the storage-induced emissions by 50% is less than $30 per tonne of CO_2 in all but one region; the cost of reducing the storage-induced emissions by 75% is less than $30 per tonne of CO_2 for sixteen regions; and the cost of reducing the storage-induced emissions by 100% is less than $60 per tonne of CO_2 for sixteen regions. Therefore, following the EPA-derived social cost of carbon cost of $36 per tonne of CO_2 [34] would justify an operational schedule that removes about 75% of storage-induced emissions. Only six eGRID sub-regions have 75% carbon mitigation costs that exceed the $36 social cost of carbon: CAMX (California), RFCE (Pennsylvania, New Jersey, Maryland, and Delaware), NYCW (New York City), SRMW (Missouri and Illinois), RFCW (Indiana, Ohio, and West Virginia), and NEWE (Massachusetts, New Hampshire, Vermont, Maine, Connecticut, and Rhode Island). Unfortunately, the cost of reducing emissions is higher in cleaner eGRID sub-regions because there is not much that can be done to reduce the already low pollution. Figure 15 shows that it becomes very costly to reduce larger percentages of emissions from bulk energy storage and terribly expensive to reduce the larger percentages from cleaner eGRID sub-regions. In general, however, making reductions in the lower percent of bulk energy storage emissions is not so expensive. In removing lower percentages of emissions, the cost per tonnes does not vary much from region to region. A 50% reduction of bulk energy storage emissions is a practical goal with a reasonable cost because on average the cost to remove those emissions is in quantitative agreement with the EPA social cost of carbon [75]. Overall, Figure 15 shows that the costs of reducing emissions through shifting of storage charge/discharge patterns is quite low, indicating an opportunity for intervention.

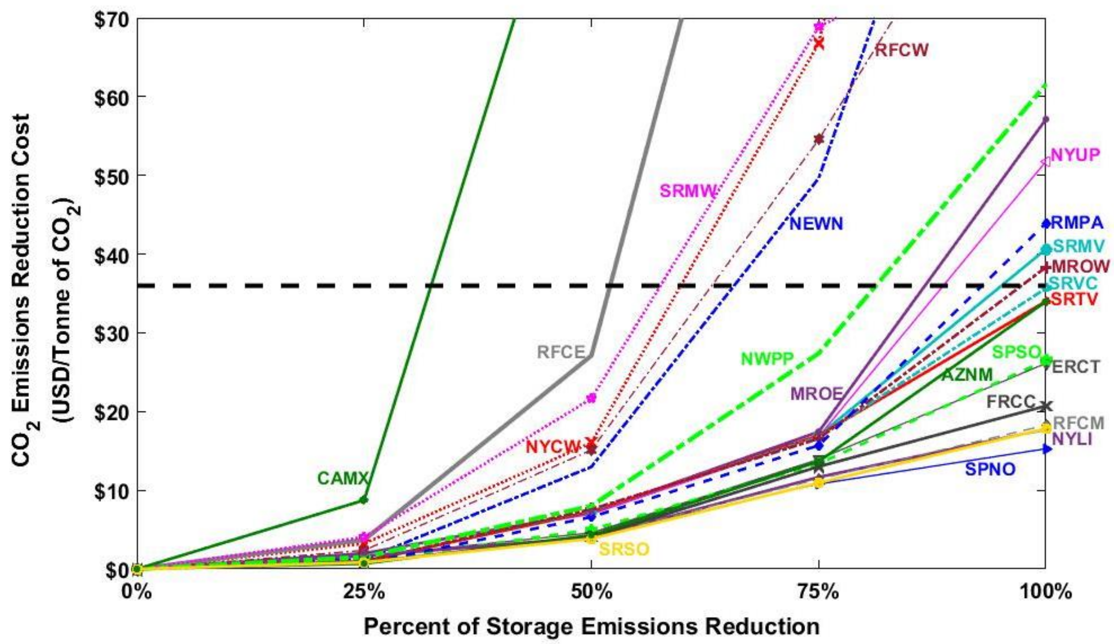

Figure 15. Emissions reduction cost for bulk energy storage. Reducing lower amounts of emissions is not very costly, a 25% emissions reduction can be achieved in most regions by spending $36 dollars per tonnes of CO_2. However, reducing the last bit of emissions by percentage is much more expensive, especially in cleaner regions.

Every eGRID sub-region is vastly unique in electricity sources and costs associated with the delivery of the service. Bulk energy storage grid effects are heavily linked to the distribution of electricity prices and marginal emissions factors. Some eGRID sub-regions have more potential to produce high revenue (wide range of electricity prices), and some others have the potential to be very polluting (short range of MEFs). The manipulation of technology to pursue an environmental-friendly operation is a difficult task for many industries. Bulk energy storage runs into similar difficulties as most of the air polluting technologies do. It is important to note that bulk energy storage technologies working under the same regulation will have higher or lower environmental expenses depending on demographics of the energy grid and the regulation implemented. While many variances may exist between the optimal charging and discharging schedules, simulation results showed that opportunities exist to reduce emissions for a low cost. These opportunities can be achieved by explicitly demanding small changes in the behavior of the bulk energy storage system.

CHAPTER VIII

SENSITIVITY ANALYSIS

All presented results were obtained using the energy storage base-case assumptions, as shown in Table 5. A sensitivity analysis on both the efficiency and the charging rate of the bulk energy storage was performed. Efficiency was analyzed because it has a direct impact on the ability of the system to pollute and earn more money. Similarly, the speed of the charging and discharging will enable the system to act more rapidly or slower during prices and emissions fluctuations. The energy capacity of the system was not analyzed in this study, since a different storage capacity would simply scale the current base-case results. There are multiple technologies that can store energy in various ways. Therefore, it is applicable to change some of the base-case assumptions of the hypothetical storage device and run the simulations again.

First, the round-trip efficiency (i.e., the ratio between the input energy and the output energy) was varied in order to observe the response of the system. The preliminary study presented in this thesis used a round-trip efficiency of 75% for the base-case as seen in Table 5. Figure 16 shows the sensitivity analysis for bulk energy storage with a 75% efficiency, as well as the cases where the efficiency is low (65%) and high (85%). Operating under a low storage efficiency (65%, red dashed lines in Figure 16), reduces the revenue, but it slightly increases emissions, when compared to the base-case. On the other hand, working with a high storage efficiency (85%, blue dotted-dash lines in Figure

16) produces a higher increase in revenue, even higher than the revenue increase when shifting from a 65% to a 75% efficiency. However, operating with an efficiency rate of 85% is most influential in reducing emissions. The reductions in the relative emissions when shifting from 75% to 85% efficiency is more than double than the reductions when switching from 65% to 75% efficiency. Increasing the efficiency of the system positively impacts the obtained revenue but it results in significant emissions reductions. More importantly, with an 85% efficiency, the Pareto curves for many eGRID sub-regions include points that are both profitable and emissions-reducing, as shown by the many blue dotted curves that lie to the left of the y-axis. Increasing the efficiency of the system positively impacts revenue but it results in significant CO_2 emissions reductions across every eGRID sub-region.

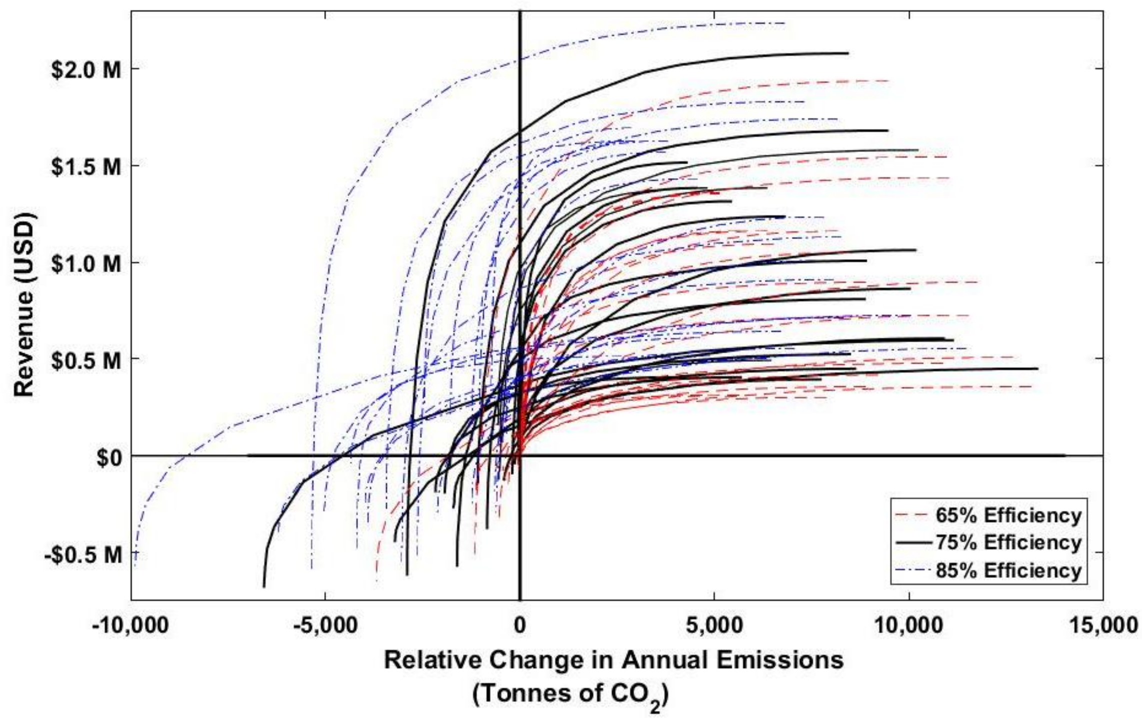

Figure 16. Sensitivity analysis on the efficiency of the bulk energy storage device. The round-trip efficiency used in the main work was 75% (solid black lines), a lower efficiency of 65% (red dashed lines), and a high efficiency of 85% (blue dotted lines) are also displayed for comparison.

Second, the charging rate for the bulk energy storage device (i.e., the amount of time it takes for the whole system to charge) was studied. This thesis used an initial 100 MWh storage device and a four-hour charging rate as the base-case assumption. In other words, the device takes four hours to be fully charged, with 100 MWh of energy. Figure 17 shows the sensitivity analysis for the charging rates of bulk energy storage under the four-hour assumption. Further, Figure 17 shows the cases where the charging rate is slower (eight hours) and faster (two hours). When the device operates with a low charging rate (eight hours, red dashed lines in Figure 17), there is a significant reduction in revenue, and this reduction is accompanied by an unexpected reduction in emissions, when compared to the base-case. The inability of the slow charging rate to move energy fast enough, disables the device from making money decreasing the amount of emissions. A storage device with this slower charging rate and a capacity of 100 MWh would not be able to serve as a daily capacity shifting device. Unexpectedly, Figure 17 also shows a drastic revenue increase when a device with a fast charging rate (two hours) is used. The emissions for this case increase, since it is practically impossible not to have any impact on the environment when increasing storage revenue. However, the escalation of revenue was much higher than the escalation of emissions. This high revenue can be explained considering that the charging speed increases the ability of the storage to work from smaller fluctuations in price. The increase in emissions is not as significant because the faster charging rate results in a bigger solution space (i.e., more charge/discharge schedules are available), and the optimization model selects the less environmentally harmful ones. The sensible explanation is that a higher charge rate allows storage to simply do more movement of energy under the same patterns, amplifying the current trends in both revenue and emissions.

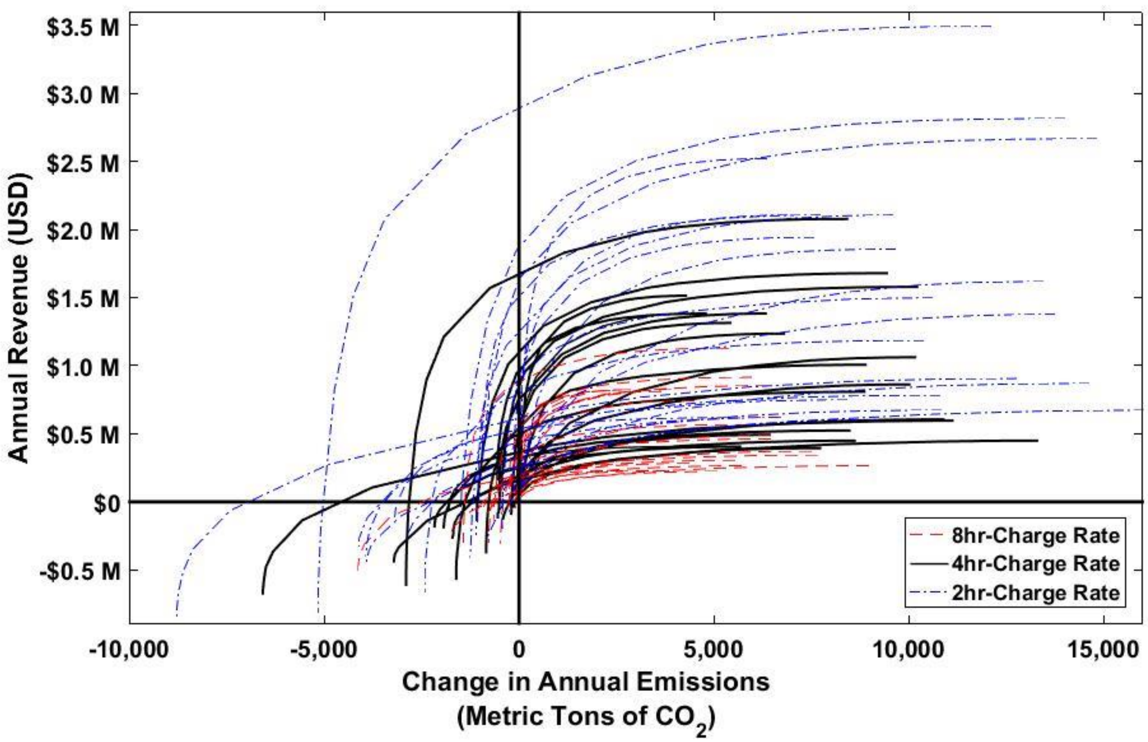

Figure 17. Sensitivity analysis on the charge rate of the bulk energy storage device. The charging and discharging rate used in the main work was four hours (solid black lines), a slower charge rate of eight hours (red dashed lines), and a faster charge rate of two hours (blue dotted lines) are also displayed for comparison.

CHAPTER IX

POLICY IMPLICATIONS

This thesis considered the generation of emissions as a penalization on an otherwise economically-driven objective function. The penalization was weighted using a price value for carbon; this carbon value has no effect on the sources of fuel nor the hourly prices of electricity. Currently, real world storage technologies are not subjected to carbon costs, and they are not held accountable for any emissions they generate or induce. Without an environmental incentive or a policy push, bulk energy storage will continue to act carelessly of the environment. This technology will become one of the many tragedies of common which tries to profit at the expense of society, in this case by adding greenhouse emissions. Countless possible solutions exist which can direct bulk energy storage onto a greener path, like a carbon tax on storage, cleaner energy charging requirements, renewable credits or incentives, and market rules, to name a few.

There are several policies that have the potential to force bulk energy storage devices to act non-profiting, preventing excessive polluting. A carbon tax on just bulk energy storage, or something equivalent, would force systems to get more creative in fulfilling the demand with cleaner approaches. As seen in this thesis, bulk energy storage could be economically competitive if a carbon cost ranging from $10 to $40 USD per tonne of CO_2 is enforced. Unfortunately, any storage pollution tax, would continue to affect bulk energy storages devices in different proportions due to the demographic variability of eGRID sub-regions. Regional discrimination will be present if fossil fuels continue to contribute with energy generation. Even so, the regions that experience lower benefits from environmental regulations have already indulged in externalities by sourcing their energy from dirty cheap fuel. The EPA used this same rationale when they implemented the Clean Power Plan in 2015 [26]. Although it would be difficult to arrange, a storage-only carbon tax may help bulk energy storage and behave with environmental manners, complying with international promises like the Paris Agreement [21]. The effects of a system wide carbon tax on the entire electricity grid, are outside the boundaries of this study because a federal carbon tax would shift the energy generation and pricing around for each eGRID sub-region. Yet, it is speculated that bulk energy storage would still try to work of the flexibility of the marginal emissions factors to reduce the amount of pollution, as reported in this study.

Any policy that tries to incentivize an overall cleaner electricity grid will help reduce the emissions from bulk energy storage. Reducing any amount of electricity emissions will give storage devices cleaner fuels to charge from. However, reducing the dirtier fuels will be even more beneficial. Having vast amounts of renewable power on the grid is most beneficial because storage could charge from completely green energy sources that would otherwise be wasted [17]. Although a clean grid will constraint bulk energy storage, storage may still find ways of acting environmentally harmful due to arbitrage. Tax cuts or green credits could promote bulk energy storage to behave less environmentally harmful, but a regulation that forces storage to charge with marginal renewable fuel would be most effective in reducing the baseload emissions. This may seem very restricting, but the original motivation for a bulk energy storage market was to help integrate renewables onto the grid and to reduce curtail from renewable resources. Incentivizing bulk energy storage policy with renewable or clean energy programs would progress the goal of a cleaner energy grid. Any regulation or incentive that promotes the collaboration of the renewable industry with the bulk energy storage industry will consolidate the two entities into working together to diminish air pollution more effectively [69].

The development of a market rule is another policy formulation that could guide bulk energy storage to behave cleaner. Market rules regulate technical specifications to adjust the performance of publicly/privately purchased technology. The corporate average fuel economy (CAFE) standards [82] for vehicles are a perfect example of strict market rules that help moderate emissions in a multimillion dollar industry. In the same manner, market rules within the bulk energy storage industry could demand minimum efficiencies or minimum charging/discharging rates to prevent unnecessary pollution. The sensitivity analysis performed in this investigation found that higher efficiencies would greatly reduce emissions in every region. However, higher efficiencies did not yield in significantly higher revenues. In conclusion, companies would hesitate to purchase more efficient, greener technology unless required to do so. Although market rules tend to be less effective in solving the entire gravity of the problem, they are more easily accepted by the free market. Enterprises prefer market rules because it is easier for companies to express venture limits and have an impact on the establishment. Market rules could act as a compromise between bulk energy companies and environmental protections government agencies.

The featured policy implications gives a general idea about the effectiveness but there are difficulties with each type of legislature. A carbon tax on storage only, would be very effective in reducing bulk energy storage emissions, but it would be very complex to administer and difficult to get approval to pass this federal law onto the entire electricity system. It might also hinder the technology from flourishing and entering the energy grid mix. Pairing bulk energy storage incentives/regulation with renewable incentives/regulation would be ideal, but it is difficult to estimate the matureness of each of these industries and whether they are ready to collaborate. Market rules could be strategically developed using the cooperation of industry. However, industry is notorious for manipulating the market and alleviating strict standards. Finally, given that each policy has a weakness, a combination of policies using the described strategies, or others, could be convoluted to tighten restrictions on emissions pollution on bulk energy storage from more than one direction without limiting the start of the market.

The issue presented in this thesis is extremely relevant because of the current wave of programs, mandates, and incentives that several states have passed to promote bulk energy storage markets. This movement adheres to a very valuable goal of transiting into cleaner fuels to power the electricity grid, but more environmental precautions need to be taken into consideration, because these laws might have the opposite effect. Policies need to consider how bulk energy storage will act during the transition, and what will be the purpose of the storage in future energy grids. Through a linear programming model, this thesis has proven that Pareto efficient solutions exist where bulk energy storage can earn a profit and simultaneously greatly decrease their emissions for the year 2014. A similar process can be used to model near future optimal storage schedules that are both economic and environmentally less harmful. Using data to estimate revenue and grid emissions outcomes form bulk energy storage enables the drafting environmentally sound polices. However, as advancements in the clean energy field develop and new regulation are formulated, bulk energy storage results will likely vary from the result found in this thesis.

Bulk energy storage in future energy grids will not pollute as much because the overall emissions from charging the device will be much lower from a cleaner grid. The policy implications described here are suitable for the current energy mix of coal, natural gas, nuclear power, and some renewables. As technological advancements occur, renewables are expected to become self-sufficient, and batteries will become more effective, resulting in bulk energy storage that is less harmful for the environment. Additionally, if any policy that promotes a cleaner grid or penalizes carbon is passed, then not only will storage evolve to be more sustainable, but it will be forced to act cleaner. Even though bulk energy storage will likely progress into a green technology, the current infrastructure allows storage to pollute unnecessarily, when more environmental and economic options are available. The transition from a fossil fuel grid to a renewable grid, combined with bulk energy storage, needs more environmental attention so that the full potential of minimizing pollution is reached.

CHAPTER X

CONCLUSION

Previous studies have elaborated on the fact that bulk energy storage will increase emissions if the storage technology solitarily serviced arbitrage. This contribution aimed to find optimal charging and discharging decisions in which a storage device could make to operate in a cleaner manner, while trying to make as much revenue as possible. The optimization procedure was based on real-world data, electricity prices and marginal emissions factors, obtained from 2014 [78], [81]. Originally from an economic perspective, demanding bulk energy storage devices to reduce their pollution, could be thought as having serious negative consequences. However, the presented results showed otherwise. Using a sustainable objective function, where both annual revenue and emissions were considered, resulted in scheduling solutions that were simultaneously high in revenue and environmentally conscious. Similar to most environmental concerns, reducing the first percentiles of emissions is economically feasible, but reducing the last percentiles of emissions becomes detrimental to the annual revenue.

The purpose of this thesis was to find solutions where bulk energy storage can be considered a sustainable technology, using a linear programming formulation. This will provide valuable information for politicians and lawmakers to understand that there are sustainable practical solutions to bulk energy storage that are also economically attractive. As computational methods for marginal emissions factors develop and become more readily accessible, new research will start to highlight some of the environmental disadvantages of bulk energy storage. The presented theme of greatly decreasing emissions for a small percentage of the revenue, is one that is universally applicable to various types of storage technologies, including pumped-hydro, compressed air, flywheel, capacitors, and batteries. The research in this thesis found feasible solutions where bulk energy storage can be used in an environmentally friendly manner with plenty of economic opportunities for the new storage market to thrive. Sustainable opportunities are plentiful and inexpensive; however, it is unlikely that storage companies will submerge to these practices because they are not unequivocally free.

Making the transition from a fossil fuel energy grid to a renewable energy mostly grid coupled with bulk energy storage is a challenging task. The inefficacies of storage technologies are a main limitation, as well as the marginal emissions factors from the combination of generators within the electricity grid. Moreover, the life cycle assessments of batteries predict harmful emissions from the mining of rare-earth materials and from the intensive manufacturing processes [50]. These additional emissions should be considered when assessing the "greenness" of storage technologies. Future work could consist of a cost-benefit analysis to compare the life cycle assessments of specific bulk energy storage technologies in individual eGRID sub-regions using the optimization model proposed in this study. Each technology would have a different return on investment but revenues like the ones presented here could be used in the analysis. In addition, life degradation of the technology and external pollution factors, could also be taken into consideration. Such research would better predict the best suitable storage technology for a green and economic transition into cleaner eGRID sub-regions.

Robust, sustainable assessments are needed to evaluate the environmental consequences of energy storage systems, as well as their deployment, and the operation scenarios in which they will be used. It is true that bulk energy storage could help mitigate the integration of renewable energy onto the electricity grid, but any misuse of this technology could mean that policy makers are investing to increase emissions during the transitional period. Bulk energy storage provides the leverage that will resolve many of future energy crises, however, it is important that methods in which the technology is incorporated are sustainable to achieve these goals. The transformation phase of adding storage into the national electricity grid will be lengthy and iterative. During this path, sustainability needs to include both, environmental and economic growth so that the technology will be better suited to meeting and surpassing the originally intended goal. As of 2015, there are more sustainable ways to transform the electricity grid, which include modifying current policies to alter the behavior of the funded bulk energy storage. Polices makers need to be well informed of the environmental consequences of pursing new technologies and of the innovative sustainable solutions that arise, which could provide a better alternative. Any decision to fund a pollution emitting technology must be prepared to defend the environmental consequences, now more than ever.

CHAPTER XI

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CHAPTER XII

APPENDIX

The entire simulation of bulk energy storage integrated into all continental eGRID sub-regions generated 22 Pareto curves, as seen in Figure A1 (same as Figure 9 in the main text). Figures A2 through A5 provide the same information as seen in Figure A1, but the plots contain fewer results per figure for clarity.

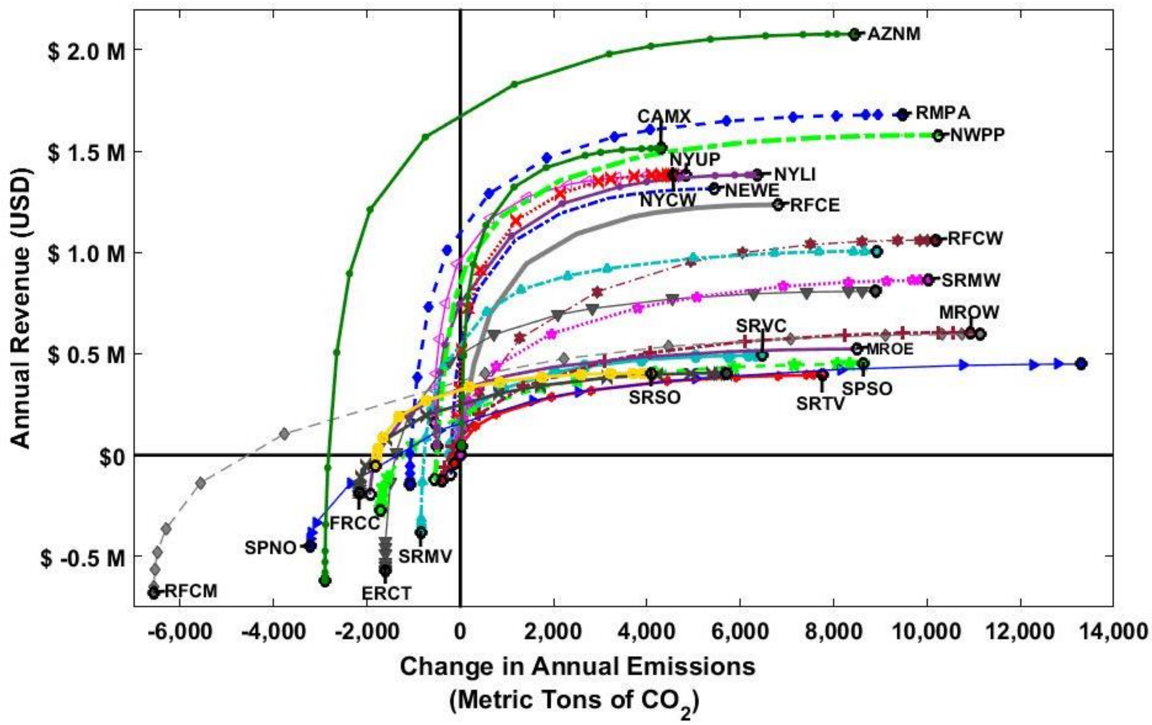

Figure A1. Bulk energy storage annual revenue and emissions results for 2014 from optimal charging and discharging cycles for 22 eGRID sub-regions. Each line represents a set of possible outcomes within an eGRID sub-region, starting with a carbon value equal to zero (most revenue and highest emissions) and ending with infinite carbon value (lowest emissions and least revenue). By rearranging charging schedules, bulk energy storage can reduce excessive emissions for a slight cost.

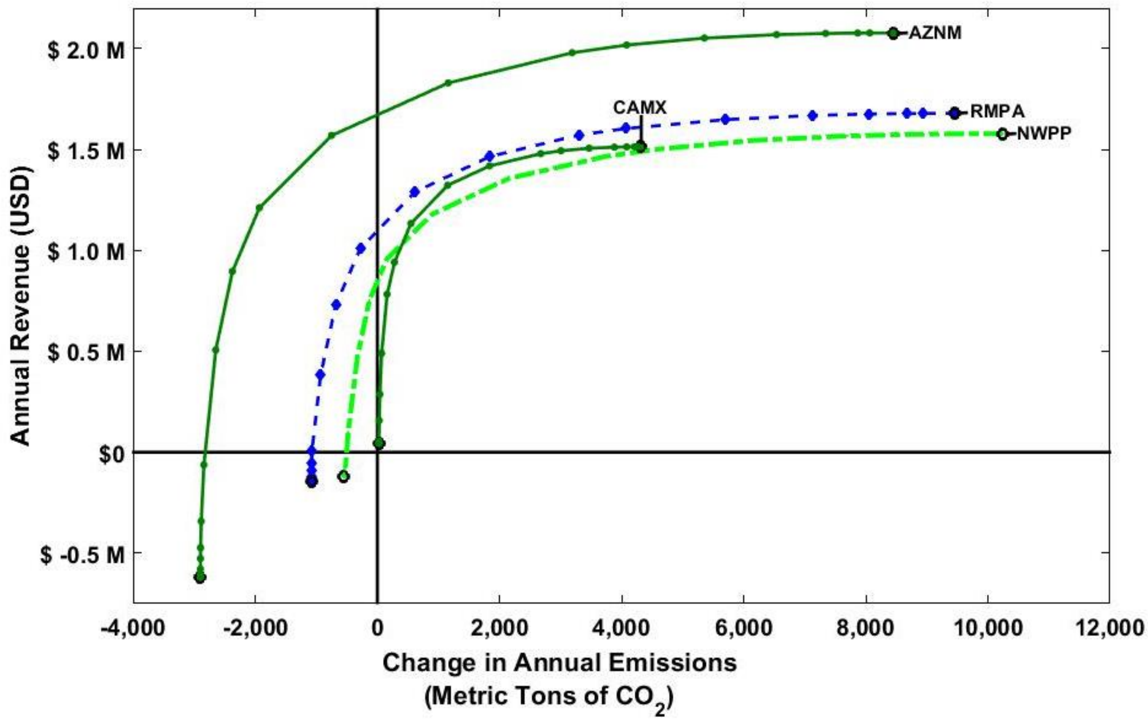

Figure A2. Bulk energy storage operational opportunities from 2014 for four eGRID sub-regions, CAMX (California), AZNM (Arizona and New Mexico), RMPA (Colorado and Wyoming), and NWPP (Washington, Oregon, Montana, Idaho, Utah, and Nevada). The solid lines represent all the possible optimal solutions if a 25 MW storage device had been integrated in each eGRID sub-region.

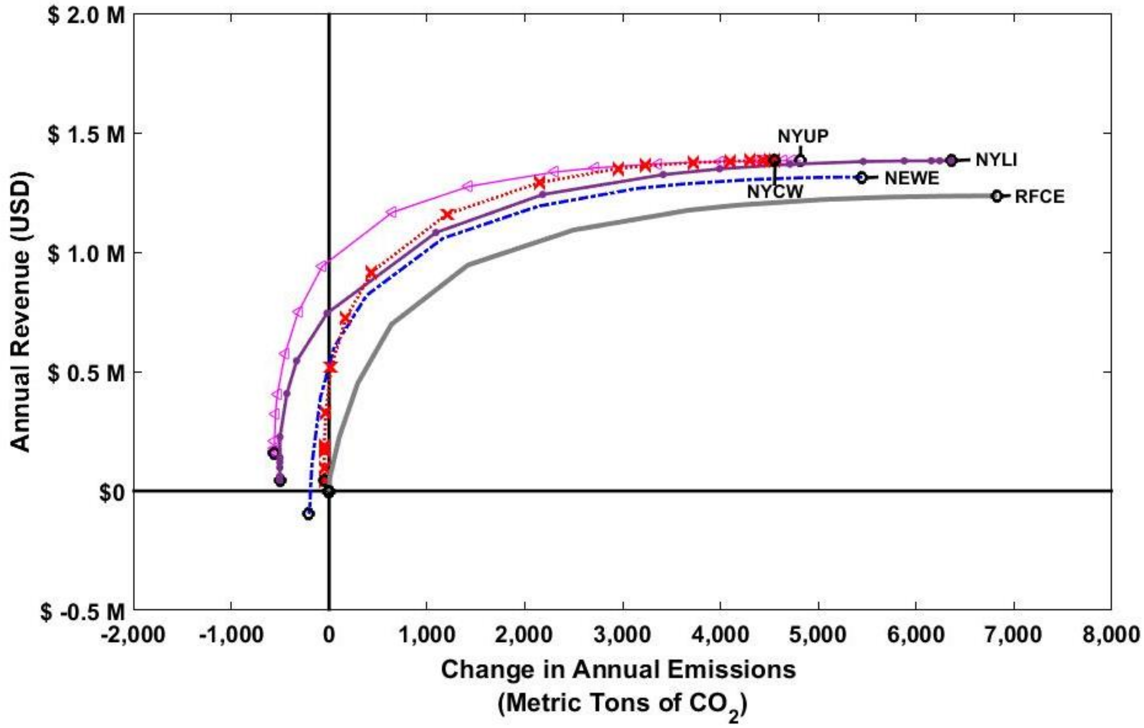

Figure A3. Bulk energy storage operational opportunities from 2014 for five eGRID sub-regions, NYCW (New York City), NYUP (Upstate New York), NYLI (New York Long Island), NEWE (Massachusetts, New Hampshire, Vermont, Maine, Connecticut, and Rhode Island), and RFCE (Pennsylvania, New Jersey, Maryland, and Delaware). The solid lines represent all the possible optimal solutions if a 25 MW storage device had been integrated in each eGRID sub-region.

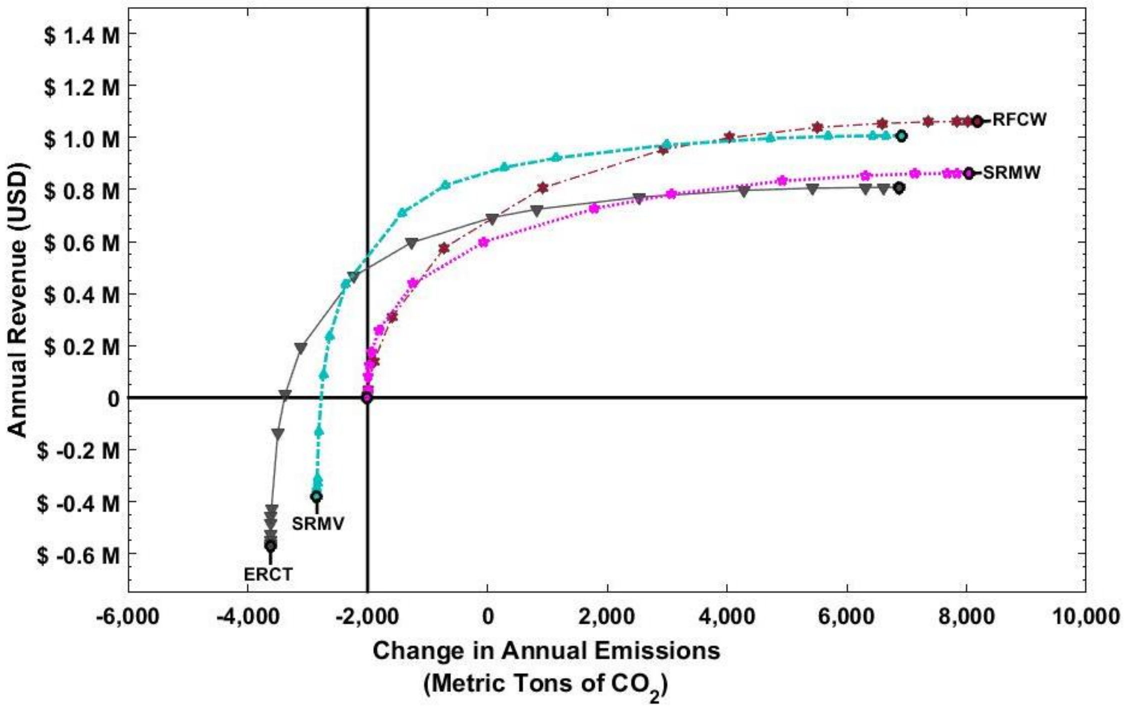

Figure A4. Bulk energy storage operational opportunities from 2014 for four eGRID sub-regions, ERCT (Texas), SRMV (Louisiana, Mississippi, and Arkansas), SRMW (Missouri and Illinois), and RFCW (Indiana, Ohio, and West Virginia). The solid lines represent all the possible optimal solutions if a 25 MW storage device had been integrated in each eGRID sub-region. By rearranging charging schedules, bulk energy storage can reduce excessive emissions for a slight cost.

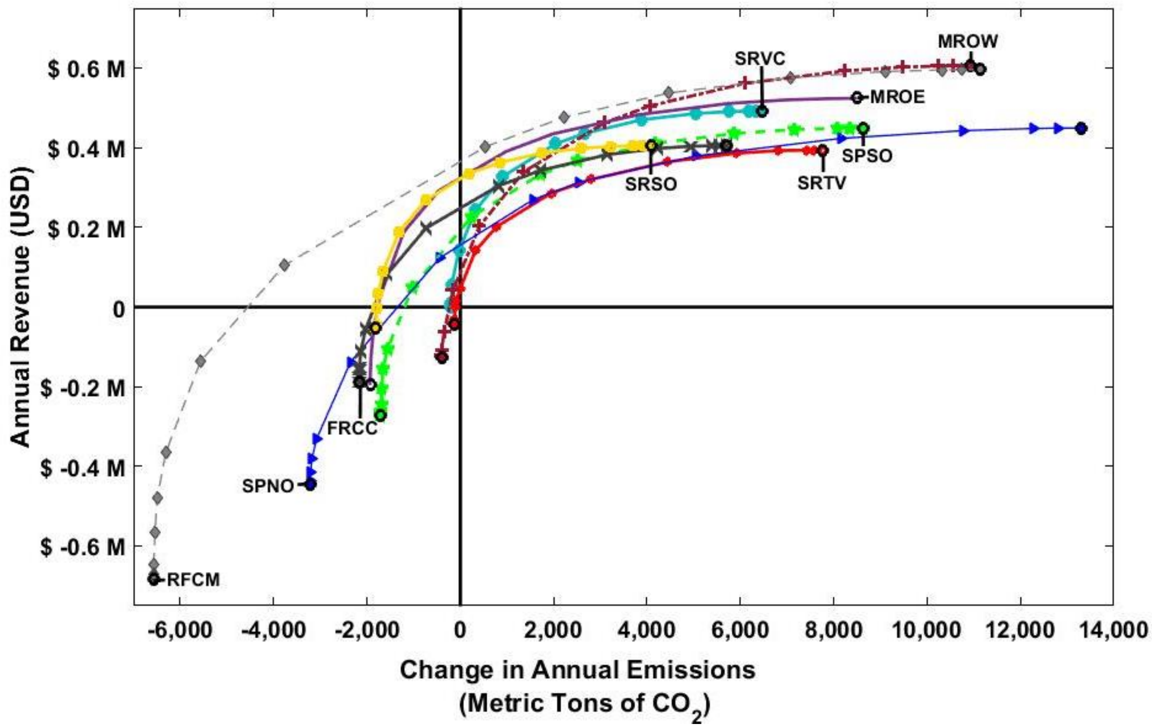

Figure A5. Bulk energy storage operational opportunities from 2014 for nine eGRID sub-regions, RFCM (Michigan), SPNO (Kansas), FRCC (Florida), SRSO (Georgia and Alabama), SRVC (North Carolina, South Carolina, and Virginia), SRTV (Tennessee and Kentucky), SPSO (Oklahoma), MROE (Wisconsin), and MROW (North Dakota, South Dakota, Minnesota, Nebraska, and Iowa). The solid lines represent all the possible optimal solutions if a 25 MW storage device had been integrated in each eGRID sub-region.