The Value of Electricity Storage under Large-Scale Penetration of Renewable Energy: a Hybrid Modeling Approach

by

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In memory of my father

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Abstract

Due to the physics of electricity, and the current high costs of storage technologies, electricity generation and demand need to be instantaneously balanced at all times. The large-scale deployment of intermittent renewables requires increased operational flexibility to accommodate fluctuating and unpredictable power supply while maintaining this balance. This dissertation investigates the value of electricity storage for the economy. Specifically, what is the value of storage under large-scale penetration of renewable energy in the context of climate policy? To answer this question, I develop a new hybrid modeling approach that couples an electricity sector model to the MIT EPPA model, a general equilibrium model for climate change policy analysis. The electricity sector model includes the main constraints for reliable and secure operation; electricity demand; wind, solar and hydro resources on the hourly time-scale; and utility-scale storage technologies. The hybrid modeling approach reconciles the very short-term dynamics required for renewables and storage technologies assessment, and the long-term time-scale required for the analysis of economic and environmental outcomes under climate policy.

Using Mexico as a case study, this dissertation analyses policies currently under discussion in the country. The experimental design explores increasing shares of renewables with varying levels of storage capacity. Under scenarios with increasing shares of renewables in the power grid, the value of storage increases sharply. By 2050, with 50% renewables penetration, the present value of storage capacity per MW installed in Mexico is estimated at \$1500/MW and \$200/MWh. Energy management services resulted in the highest value component (58%), followed by operational reserves provision (22%) and capacity payments (18%). Storage capacity in the system changes both investments and operational decisions, allowing larger penetration of wind technologies and displacing gas technologies. Storage capacity in the system reduces price volatility and the occurrence of negative prices that would otherwise result as renewables scale up.

The general equilibrium analysis shows that the availability of competitive storage technologies under an economy-wide climate policy reduces the overall policy costs. Simulating a 50% emissions reduction by 2050, the model demonstrated that storage could decrease total welfare losses by 0.7% when compared to the case without storage.

Despite the sharp increase in the value of storage driven by renewables penetration, the findings suggest that the current cost of most storage technologies will still have to drastically be reduced for them to be economical.

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Mario Molina, who discovered the mechanisms by which chlorofluorocarbons decomposition produce ozone depletion in the stratosphere. His discovery of the linkages between chemistry, the environment and human behavior, triggered international action that has successfully eliminated much of the pollution that was causing the ozone hole. For his scientific contribution, he has been awarded with the highest academic awards. I feel so fortunate to have worked with him in the Center he founded in Mexico, and grateful for his continuous support and encouragement for my studies at MIT. He is a true inspiration to me, and I must say, for my generation in Mexico. A leader in Mexico's climate and energy policy, it is to him that we owe much of the advancement of Mexico's climate efforts. For this, I think, many more generations will remember him, along with the lead scientists that leave the labs to raise awareness of the climate problem.

John Reilly, who once told me that I needed to narrow down my research question, that I will have a lifetime of research to keep asking questions. He said: "Look Claudia, in my PhD I was proposing to do a model that would track all of the global emissions of

GHGs, and I am still working on that..." and he is, and he is still passionate about it. He guides his students through difficult technology questions and their intersection with economics. I am always so impressed by how he travels from agriculture, to water, to energy, and to climate policies. What I've learnt from John, is that, despite the imperfection of economics science, there are simple economic principles that can guide our inquiries if we are able to make our way through the layers of complexity and find the questions that are worth pursuing. So I want to thank him for helping me narrow down my research question. I want to thank John also for welcoming me to the Joint Program (JP), for his talks on the introduction to the "EPPA cult" in those wonderful workshops in Sunday River, for the lobster parties at his place, with a good fire, good drinks, and good conversation. He's such a terrific leader. In my first EPPA workshop, he said: "Sunday, we'll do an easy hike, all should join." I was sore for a week after the easy hike, but I'm glad I joined and followed John, it was so much fun! In a way, that hike and the PhD have quite a lot of similarities.

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Let me share too something else about Ignacio. He did his PhD at MIT under Fred Scheweppe's supervision, and I think that also, like his own advisor, he is ahead of his time. I suspect that it is this vision, this passion to effect change, that underlines his immense commitment, the reason he works tirelessly to transmit to his students, to regulators, to his colleagues around the world, the need to transform the electric power sector. He works now non-stop on renewables, energy access, climate change and the regulatory challenges of the utility of the future. I would need 10 Claudias to do what Ignacio does. I am sure Scheweppe would be proud to see him; no one else would have taken the power systems research agenda at MIT with so much passion and dedication as his own student has done.

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Chapter 1

Introduction

While critical to decarbonize the power sector, large-scale deployment of intermittent renewables such as wind and solar requires a real transformation of current power systems to accommodate fluctuating and unpredictable power supply. The great need to find low-carbon energy solutions that could deliver at the scale needed to face the climate challenge has spurred research on the costs of deploying large amounts of renewable electricity. Current literature on the integration of renewable energy to the power grid has identified the need for increased operational flexibility [140, 107]. Briefly defined, operational flexibility is the capacity of a power system to respond on real time to balance supply and demand, maintaining grid stability and system reliability. Sources of flexibility include greater transmission capacity, dispatchable hydro generation, thermal generation in different degrees depending on the technology, energy storage in different modes of which pumping hydro storage is overwhelmingly dominant today, and demand response.

Energy storage has for decades been considered as a possibility to avoid expensive standing capacity to meet peak demand.[1] Yet, worldwide capacity for electricity

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[1] In this dissertation I refer to electrical energy storage or energy storage as the process of converting electrical energy into a form that can be stored (mechanical, chemical, etc.) for converting back to electrical energy, i.e., electricity is not stored as electrical energy but as mechanical potential energy of stored water, or mechanical energy of compressed air, etc. Note that a normal hydro reservoir can also store energy, and could provide similar services as electrical energy storage technology with the exemption of using excess energy from the grid. I will discuss the role of hydropower in Chapter 6.

storage is currently only 127 GW, 99 percent of which is pumped hydro storage (PHS); the rest is a mix of compressed air energy storage (CAES) and batteries [63]. With the deployment of renewables, however, the services that storage could provide to power systems had acquired a new dimension. The recognition that storage could be a game changer to facilitate renewables integration, by decoupling supply and demand during critical hours of the system operation and by providing a bi-directional service both injecting and absorbing energy to and from the grid, has reopened the question of the value of these technologies with the advent of intermittent generation. Stakeholders, including regulators, system operators, investors and the scientific community, are all revisiting the value of storage and the state of these technologies under the lenses of stringent climate policy and renewables integration.

Electricity storage could provide valuable services in power systems. Storage could help to actively reduce peak load by storing energy in low-load hours and releasing it during peak hours (thus artificially shifting load by filling-in "valley" hours and reducing the need for standing capacity to meet peak demand). Also, storage can assist the integration of intermittent resources by firming its power supply. By storing energy, curtailment of renewables could be reduced or avoided, allowing for a more efficient use of wind and solar infrastructure. In addition, storage could allow the operation of other technologies by reducing to some extent the cycling of thermal units derived from the increased variability in a system with intermittent renewables. As mentioned by Black et al., thermal units operate less efficiently when part-loaded, with an efficiency loss between 10 and 20% [16]. Even some capacity of storage could help alleviate critical operational conditions, by injecting or absorbing energy at times when need is greatest. Due to faster response rates of some storage technologies than current thermal generators, storage could provide frequency regulation, voltage control support, and load-following services in some moments when the system experiences fast and/or pronounced fluctuations of renewable energy and demand.

The International Energy Agency estimates that, under a climate stabilization scenario, about 310 GW of grid-connected electricity storage capacity would be needed to accompany their estimated levels of renewable electricity deployment. This estimate considers only the US, Europe, China and India, with an approximate investment of 380 billion dollars [94]. In Europe, where renewable energy deployment at scale is already taking place, storage has come to the policy debate with a variety of policies promoting investment. For example, Germany is subsidizing 30 percent of the cost of storage installations following its policies for residential solar with a program of 260 million dollars [8]. In Asia, Japan is rapidly developing its hydro and solar power industry after the Fukushima accident, installing 48 GW of hydro in 2011, half of it in PHS, and 13 GW of solar photovoltaic (PV). To help residential PV, Japan has assigned a 98 million dollar program for subsidies of up to two-thirds of the cost of storage for homeowners and businesses [43, 53].

In the US, markets are preparing for the adoption of greater storage capacity. The US Federal Energy Regulatory Commission (FERC) issued Orders 755 (2011) and 784 (2013) on energy storage deployment, instructing system operators to compensate for specific ancillary services and to open some of these markets to non-utility providers [69, 68]. As a result, California, New York, and the PJM systems have prepared specific rules to compensate for some of these services. In addition to market regulations, systems that have ambitious goals for renewables deployment are complementing these policies with economic incentives and even targets for storage deployment, such as California's goal of 1.3 GW of storage deployment by 2020 [130]. As a result, industry experts are projecting a growing market. IHS industry report expects a global demand of more than 40 GW of grid-connected energy storage by 2022, resulting from the growing portfolio of renewable energy investment worldwide. According to this report, storing electricity could pass from being a business of 200 million dollars in 2012, to a 19-billion-dollar industry in 2017 [95].

Despite the belief in policy circles and among industry advocates that storage could facilitate ambitious policy goals for renewables, the current state of research presents mixed results regarding the value of storage. As I will discuss in the literature review, many studies suggest that the value proposition does not justify storage capacity in most systems today, given current technology costs.

Sandia National Laboratory, NREL and EPRI coincide in that storage solutions have yet to experience sharp cost reductions to be economical [3, 67, 63, 37]. Sandia and EPRI state-of-science report on storage identified four barriers for storage technologies: cost-competitiveness, reliability and safety, current regulatory environments and industry acceptance [67]. Also, storage will have to compete with other sources of flexibility, such as transmission expansion and demand response. For instance, NREL Renewable Electricity Futures Study estimates a need for 153 GW of storage capacity for a scenario of 80 per cent renewables penetration in the US by 2050 [76]. In this high renewable deployment scenario, storage is required, but is constrained by the current specifications and costs of the technologies used by NREL in its analysis, and competes with transmission expansion as a source of flexibility.

Under these circumstances, it is important to provide estimates of the value of storage that consider new changes brought about by renewables and the social value of these technologies under climate policy. In the next sections, I describe the challenges that incorporating renewables pose for the power sector, the potential role of storage under increased renewables penetration, and the modeling approach adopted in this dissertation to estimate the value of storage.

1.1 Problem Statement

Due to the physics of electricity, and the lack of economic storage devices, electricity generation and demand need to be instantaneously balanced at all time. Power systems have always dealt with variable demand and with its uncertainty, thus modern power systems have some flexibility already built-in for load following purposes and to maintain system stability and reliability. However, the challenges brought about by variability in supply, and the unpredictable nature of wind and solar resources, make the operation of power systems more complex. Figure 1-1 shows a week in an electricity system with and without variable electricity generation.

As shown in the picture, the shape of net load - demand minus the generation of variable renewables- dramatically changes from the initial load profile, becoming

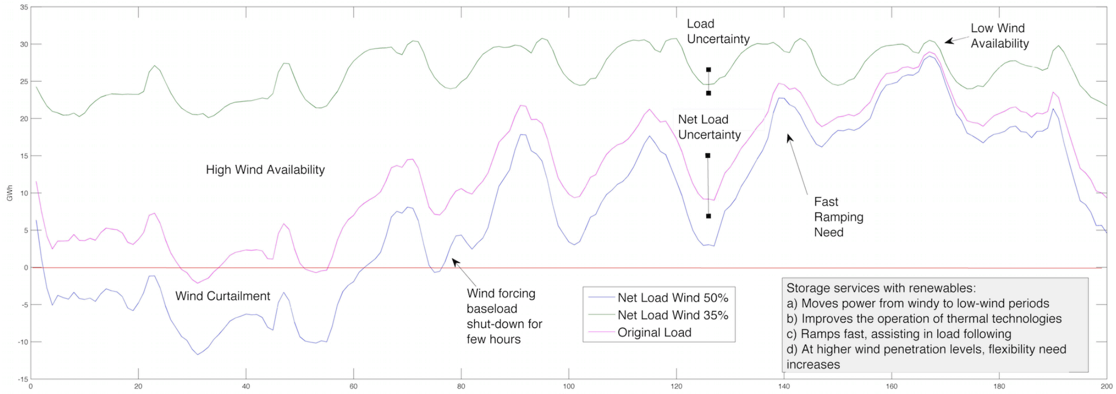

Figure 1-1: The Challenge of Intermittency and New Requirements for Flexibility
Source: Author with sample demand data from Mexico's system operator (CENACE) based on[88]

more variable. This added variability in the system disrupts the traditional operation of units. First, as renewable penetration increases, the operation of thermal units needs to change to follow the new profile of net load, resulting in increased cycling of thermal generation (start-ups and shut-downs of units). This cycling is expensive, as it requires both fuel consumption and increased operational and maintenance cost. Second, as renewables participation in electricity generation increases, inflexible units that cannot cycle either put hard limits for renewables integration, need to operate under operationally difficult conditions (to the minimum stable thermal limit) and/or decide to bid zero or even negative prices in certain hours of the day in order to avoid expensive shut-downs of units. This behavior has implications in electricity markets. For example, nuclear power plants must comply with certain thermal minima to operate in a safe fashion and have long starting-up times, therefore could be in situations when it would be more economical to pay in order to continue operations than to shut-down and restart.

Opportunities for new storage technologies as the penetration of renewable energy increases are illustrated in Figure 1-1, which shows the hourly profile of demand and net loads resulting from a penetration of wind energy of 35 and 50 percent. In a traditional system with no penetration of renewables, there is some room for storage devices to assist load following, but as shown by the pattern of the original load (green line) the demand for this service can be fairly small. Although demand fluctuates, the pattern of the load is fairly predictable and the spread of minimum and maximum loads is not too large in this sample of hours. In contrast, the patterns of net load with wind penetrations are very different from the original profile. With a medium penetration of renewable energy of 35 percent (magenta line), storage could assist in load following and providing operating reserves (and for regulation and frequency responses not shown in the picture). In this medium term scenario, negative net load hours are few. At large scale penetration, not only the uncertainty in the system increases but also situations where net demand could be very low, negative, or have spikes (blue line). In these situations, economically available storage could assist the system to actively manage bulk power, by actively reducing or increasing demand and supply, and could also provide reserves and other needed ancillary services. As shown in the picture, in the high penetration scenario storage could avoid wind curtailment for many hours when the system experiences negative net load [93].

At very high penetration levels of renewables, the traditional concept of base load units does not hold anymore, since all units will have to accommodate to fluctuations in net demand. This fluctuating nature of power will determine the economics not only of renewable energy, but of the system as a whole. Third, at high penetrations of renewable energy the net load can become negative- this is a situation in which total electricity generation from renewable energy exceeds total demand at a particular time. In this situation, without electricity storage, or other sources of operational flexibility such as the possibility of transmission to other areas or demand response, renewables most be curtailed [88].

Intermittency includes both resource variability and resource uncertainty [107]. In addition to the operational changes described above to accommodate increased variability, the uncertainty in supply – because wind and solar resources are only partially predictable – adds to the complexity of system operation. Traditional power systems have dealt with the problem of uncertainty by planning and operating the system with some excess capacity to account for needed reserves – both at the operational level and for long-term security of supply. However, with increased levels of intermittent generation power systems planning needs to also consider the problem of ensuring bulk power reliability. The traditional calculation of reserves as a percent margin over rated capacity, considering potential outages and maintenance of units will not suffice, particularly at high levels of renewables penetration. A careful calculation of what is the capacity contribution of wind is required. The study of the impacts of uncertainty in power supply that come with intermittent renewables, and their repercussions in system planning and in ancillary services markets (the markets for regulation and frequency response, energy imbalances, and operating reserve services) is an active area of research in the power systems literature [140, 125, 121].

1.2 Thesis Contribution

This dissertation investigates the value of storage from a particular unexplored angle. While the analysis of specific storage technologies in power systems is important, a critical component to understand the value of storage that has not been studied is the overall effect that its economic availability will have in the economy and vice versa, the feedbacks of the rest of the economy response to the power system. This dissertation investigates the economy-wide implications of the availability of storage for long-term climate policy. The critical short-term dynamics that determine the economics of different technologies interacting in power systems, particularly the value of storage technologies, is fully internalized into a general equilibrium macroeconomic analysis.

Instead of focusing on a specific storage technology specification, I adopt a reverse engineering approach to elicit the value of storage. I ask the question of what is the value of storage in power systems with large-scale penetration of intermittent renewables. Our ultimate goal is to uncover the value of storage from a social welfare perspective by accounting for the economy-wide interactions triggered by storage technologies in a system with very large penetrations of renewable energy and climate change policy. For example, I investigate the impacts on the price of electricity, driven by more renewables and storage, which has economic repercussions for consumers and industries. Also, renewable integration alters the demands of different fuels by the power sector, having indirect effects on fuels markets.

I focus on the case of Mexico as an example of a power system in the developing world that has committed to deploy high levels of clean generation, including fast deployment of renewables. As described in Chapter 2, Mexico has committed to provide 35% of its power supply with clean energy sources by 2025, and to pursue stringent mitigation goals for the overall economy, with a goal of 50% GHG emissions reduction from its business as usual scenario by 2050.[2] Mexico's power system is currently experiencing important regulatory changes. From 2015-2018 the Mexican electricity market will be launched, and several mechanisms to ensure adequate levels of investment in the system are under design – including a mechanisms to increase the role of renewable energy in the mix. With this research I can provide specific insights for Mexico on the demand for storage technologies, and renewable energy investment, which could inform the new regulatory framework. The analysis of this country may have broader implications for similar countries with fast growing demand looking into the deployment of renewables at scale, as a potential mitigation option, which drives the demand for storage.

An economy-wide model analysis can account for the interactions and indirect effects throughout the economy and estimate economy-wide policy costs and emissions outcomes. However, in order to be able to evaluate the value of storage for an efficient integration of renewables, the general equilibrium approach needs to be improved. Due to the coarse time-scale typically used in these models and other modeling specifications, the critical short-term dynamics that determine the economics of renewable energy, storage technologies, and the overall electricity mix under the presence of high levels of intermittent generation are not properly captured in general equilibrium models, as I have discussed in previous work [101]. My approach is to simultaneously solve the economy-wide model with a detailed electricity sector model. This approach allows me to characterize the interactions of the electricity sector with the rest of the economy. A hybrid modeling approach is needed to account for macroeconomic interactions and renewables characteristics.

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[2] Mexico's goal is subject to international cooperation to canalize international investment flows for mitigation in the country.

1.3 A hybrid modeling approach

Traditional modeling approaches, both in the domains of economics and engineering, have investigated possible electricity mixes in a carbon constrained world. In the realm of economics, computational general equilibrium (CGE) models are widely used analytical tools to investigate the impacts of energy and climate policy in terms of technological pathways, environmental impacts (i.e., greenhouse gas emissions reduction potentials) and their social costs and benefits. While the strength of these models is to include energy supply and demand decisions within an internally consistent macro-economic framework, they typically lack the technological, spatial, and temporal resolution needed to adequately represent the electricity generation in systems with high levels of intermittent renewables.

Engineering models of the power sector, on the other hand, typically feature a highly resolved and technology-rich representation of electricity technologies, but fail to include interactions with the broader economic system due to their partial equilibrium nature. Importantly, engineering models are hence not capable of incorporating macro-economic determinants of energy demand and supply and they cannot assess policies in terms of their social cost (e.g., GDP or consumption impacts).

Although these models are routinely used to derive policy recommendations, often under the underlying assumption of a potential large presence of renewable energy policies, the present generation of models do not fully capture the important dynamics brought about by renewables. Implementations of the CGE approach lack the required detail and model features to adequately represent intermittent renewable energy sources [101]. Investigating the value of specific infrastructure supporting renewable integration, such as storage or transmission networks, under the current structure of general equilibrium models is not possible. On the other hand, detailed engineering models of the power sector disregard important interactions with other sectors of the economy and indirect effects of policies to decarbonize power supply, failing to capture the true value of infrastructure supporting renewable energy integration from the climate change mitigation perspective. Thus, both approaches need to be improved to capture impacts of large-scale changes in the electricity system.

Recognizing the limitations of these traditional modeling approaches, the analysis of climate change mitigation has used so-called hybrid modeling approaches [83]. Hybrid models use techniques to translate engineering data into macroeconomic models or vice versa, economic responses into partial equilibrium models [115, 11]. Traditional models have proven to generate adequate and reliable approximations of electricity systems characterized predominantly by fossil-based energy sources and technologies when some engineering information is used to help the parameterization of top-down models. Partly, the reason for this good approximation of traditional power systems is that the behavior and interactions of technologies within the power system were well understood, and the economics of different technologies remained fairly constant over years, with changes in electricity technologies driven primarily by changes in fuel prices. However, with renewable electricity many of the assumptions currently adopted in models do not hold. Renewables are new disruptive technologies that drastically change the operation of the system. Currently, both CGE and electricity modeling tools need to adapt to properly capture the changes brought about by renewables.

A great amount of research has evaluated operational changes needed from the power systems perspective [93, 126, 140], however hybrid models that account for energy-economy interactions have yet to incorporate new advances of the power systems literature in understanding the impact of renewables in the power mix. This thesis is largely about introducing new capability into one class of economic models – CGE models – to represent better the transformation of power systems with large-scale penetration of renewable energy, and more specifically, the role of specific technologies supporting renewables penetration: storage technologies.

While CGE models have attempted to incorporate renewable energy, often the assumptions taken are not consistent with the actual operation of power systems with renewables. For example, parameterizing a total back-up or storage requirement is problematic, since these costs are very system specific and dependent on the penetration level of renewables. Compounding this problem, the modeling of renewables in this framework is highly sensitive to the modeler's choice of critical parameters that intend to represent the costs of renewables and reliability concerns [101]. Some of the problems in the current structure of CGE models that impede a through analysis of renewables and storage devices include:

First, CGE approaches typically do not explicitly model the electricity dispatch or the system capacity expansion, but rather use historical data to benchmark the initial conditions of the economy and stylized production functions to assess changes in generation driven by price variations in fuels and other production inputs.

Second, CGE models rely on Constant Elasticity of Substitution (CES) production functions to depict production activities. Key modeling assumptions within a CGE context related to electricity generation then entail specifying whether or not electricity is a homogeneous good (i.e., electricity supplies generated from different technologies are perfect or imperfect substitutes) and picking a nested substitution structure between conventional fossil fuel-based generation, nuclear, hydro and new advanced technologies. Also, modelers specify the substitution structure between inputs to production within each of the different technologies. The unique attributes of the non- extant low-carbon technologies need to be captured through the parameters of the CES function.

Third, as substitution and complementarity patterns of non-dispatchable technologies are not known a priori, multiple ad-hoc assumptions are needed in CGE models to approximate the costs of maintaining system reliability in power systems, for example through the representation of backup generation; other sources of operational flexibility such as transmission networks, storage devices, short-term demand response and hydro power are fully ignored or highly aggregated in some of the parameters used to represent the production processes.

Fourth, while some engineering information is sometimes used in CGE models to introduce new electricity technologies, the aggregate information commonly used might not be enough in systems with renewables. For example, the use of the levelized cost of electricity to compare traditional and renewable energy technologies is inappropriate given that renewables are not dispatchable technologies [99]. Also, with high penetration of renewables the capacity factors normally assumed for thermal generation will change. As mentioned, the traditional concepts of base, shoulder and peak generation change in a system with renewables changes, both due to price changes but also due to new operational conditions.

If not properly upgraded, traditional simulation tools run the risk of misrepresenting the implications of future policies in a context of high penetration of intermittent renewables. In particular, the role and implications of specific technologies, such as storage, could be completely missed in these models.

1.4 Purpose of this dissertation

In sum, the purpose of this dissertation is to investigate the value of storage under large-scale penetration of renewable energy, considering critical short-term dynamics in the power sector and economy-wide interactions under climate policy. For this, a new modeling framework that enhances the capability of CGE models to incorporate renewables and storage devices is proposed. In the literature of power systems, and in particular on studies on integration of renewable energy, a few have evaluated the role of storage in some detail [37]. However, these studies cannot address economy-wide and social welfare implications. On the general equilibrium literature, researchers have incorporated intermittent renewables, but given the above mentioned characteristics of these models, eliciting the value of electricity storage has not been possible. This dissertation provides a new framework that models both the general equilibrium effects and the dynamics determining investment in electricity generation technologies and infrastructure supporting new technologies, such as storage devices. It does so by merging two methodologies: power systems modeling and general equilibrium modeling. The joint modeling tool allows obtaining new insights on the social value of storage under large-scale penetration of renewables. It also allows to understand the overall emissions reductions once renewables are integrated into the power sector, after accounting for price interactions and demand adjustments in the economy.

The economy-wide component of our integrated model is based on the MIT

Emissions Prediction and Policy Analysis Model (EPPA) model, a global recursive-dynamic, multi-sector, multi-region numerical general equilibrium model designed to analyze climate and energy policy [136]. To assess the value of storage, an electricity generation capacity expansion model with renewable resources at the hourly time-scale and constraints to ensure system reliability and security – the new Renewables Integration and Storage Assessment (RISA) model – is coupled to the MIT EPPA model. With the new modeling capability in hand, it is possible to compare several policies and policy combinations in terms of their effects on the value of storage for the economy, and costs of renewable energy policies with and without this source of operational flexibility. Also, with the general equilibrium framework, it is possible to discuss economy-wide costs and emissions outcomes. This information can provide new insights regarding policies to promote both renewables and storage technologies, and the implications of deploying renewables without enough built-in system flexibility. The modeling framework demonstrates that CGE models can be combined with more detailed electricity planning tools and facilitates further analysis of policies affecting the power sector in a fully consistent general equilibrium approach.

1.5 Dissertation structure

This dissertation is structured as follows. Chapter 2 describes the specific power system I study to elicit the value of storage: the Mexican electricity sector. I provide a background on climate and energy policy in the country, and describe renewable energy potential and current regulatory framework.

Chapter 3 presents the literature review. First, I survey the literature on the value of storage. Second, I describe the current state of modeling tools to analyze climate change policy and their treatment of renewables and storage technologies. Third, I summarize the current state and perspectives on electricity storage technologies to provide a landscape of current technological developments, costs, and potential developments. Finally, I discuss the thesis contribution to the literature.

Chapter 4 describes the modeling and analysis framework. First, I describe the hybrid modeling approach of the dissertation. Second, I describe the CGE model used in this analysis, in particular focusing on the interactions of the electric sector with the rest of the economy. Third, I present the new electricity capacity expansion model – the RISA model– including its mathematical formulation. Fourth, I describe the coupling methodology by which I link the CGE model and the electricity model, including the benchmarking of the models, the iterative algorithm, the disaggregation of demand, and the dynamics of the modeling.

Chapter 5 five discusses results on the value of storage. First, I describe the experimental design by which I evaluate the value of storage. Second, I present results on the value of storage for supporting intermittent renewables, and discuss the resulting the value of storage against current technology costs. Third, I describe the mechanisms that determine the value of storage in a system with increased renewables penetration. I conclude this chapter with the general equilibrium effects of the availability of competitive storage technologies.

Chapter 6 presents critical sensitivities that will impact the value of storage. First, I discuss the influence of different storage characteristics, such as efficiency and power. Second, I explore the sensitivity to the availability of hydropower, considering both a potential expansion of this technology, and a decrease in water inflows due to climate change. Finally, I present the sensitivity to the price of natural gas. The price of natural gas is important for the value of storage, since it is often the marginal technology setting energy prices in the system. Also, natural gas technologies often provide many of the ancillary services that storage could provide, and therefore are in direct competition with storage.

Chapter 7 concludes on the value of storage, and implications for large-scale renewables deployment. I also draw conclusions on policy implications for Mexico, both on climate and electricity policies. Finally, I present some future areas of research.

Chapter 2

Mexico's power system

In this chapter, I discuss the main issues regarding the specific system I use to evaluate the value of storage: Mexico's power system. As one of the most proactive countries in the climate policy arena, Mexico's case provides a good example of the challenges that middle-income countries face in crafting climate policy, and importantly, the economic costs that these countries could incur to reach stringent mitigation objectives, and specifically in deploying renewable energy. First, I present an overview of the regulatory landscape shaping the development of the power sector in Mexico. Secondly, I describe current infrastructure in terms of generation and transmission capacity in the system. Third, I examine renewable energy potential for wind, solar, geothermal and hydro resources in the country. Fourth, I discuss short-term and medium-term investment plans, specifically the Renewable Energy Special Program. I conclude this chapter with some remarks regarding the future development of Mexico's power system in light of policies promoting an energy transition towards low-carbon electricity, and the potential case for storage technologies.

2.1 Climate change and energy policy

I briefly discuss first Mexico's current climate legislation, identifying targets for the power sector, and then I describe energy policy and its interaction with climate policy.

2.1.1 Climate change policy in Mexico

Although Mexico's emissions contribute roughly only 2% of global GHG emissions, the country has set ambitious mitigation targets. For 2020, Mexico's emissions reduction goal is to cut down 30% from its baseline emissions; for 2050, the country has pledged a potential 50% reduction from 2010 levels, provided international investment flows for clean energy and adaptation action. In 2012, Mexico enacted its *General Law for Climate Change* that sets the legal foundation to advance climate policy [48]. First, the law establishes an institutional framework and mandates a multi-sector approach, including responsibilities for several Ministries of the Federal Government, as well as the requirement for a national consultation process involving local governments, and the private and social sectors. Mexico's *National Strategy for Climate Change: Vision 10-20-40* (NSCC) results from this process, and provides the vision of the country's mitigation and adaptation policy for the next 40 years [159]. By assessing the short, medium, and long-term mitigation potential in the next 10, 20 and 40 years, respectively, Mexico has started a process of mainstreaming climate change concerns in development planning[1]. The Strategy identifies key principles or so-called "bulwarks" for policy design: a) energy transition, b) energy efficiency, c) sustainable cities (transportation, waste and buildings), d) best agricultural and forestry practices to increase natural carbon sinks, and e) reduced emissions of short-lived pollutants with local co-benefits. In particular, the NSCC has targeted emissions from power generation, with the goal of 35% generation of electricity from clean energy (non-fossil) sources by 2020, 40% by 2040 and 50% by 2050.

The NSCC, designed by the Ministry of Environment and Natural Resources and approved by the National Commission for Climate Change[2], will be implemented through concrete policies described in the Programs and Special Programs[3] of each of

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[1] All federal programs derived from the NSCC need to align with the *National Development Plan.*

[2] The National Commission for Climate Change has representation from 13 Ministries in charge of specific actions for climate mitigation and adaptation, including the Ministries of Energy, Agriculture, Social Development, Foreign Affairs, and the Council for Science and Technology, among others. The Commission also has representation from the academic community, which advises on the science of climate change and potential impacts to Mexico.

[3] Budgetary allocations are done based on actions described in the Programs of each Ministry and/or on Special Programs that coordinate cross-sectoral policies

the Ministries of the Executive Branch. A *Special Program on Climate Change 2013-2018* (SPCC) is in place targeting reductions in the short-term (during the current administration) with the overall goal of reducing 83.2 $\mathrm{Mt/CO_2}e$ per year. In addition to the economy-wide reduction goal, the SPCC specifies a target to reduce carbon intensity for the electricity sector (from 0.456 to 0.350 $\mathrm{tCO_2/MWh}$). Currently, most of the committed mitigation of the SPCC will take place through actions from the federal government, particularly by reducing emissions in the energy sector through mitigation in the state-owned companies for oil production and electricity generation, PEMEX and CFE[4], respectively, and by improving current practices of urban and agricultural waste management. In addition to the SPCC actions, Mexico has implemented other policies with the goal of shifting energy consumption patterns. For example, Mexico introduced a carbon tax of $5 USD/tonne of CO_2 on some fossil fuels (excludes natural gas), and is gradually reducing gasoline subsidies. Although these measures are not currently quantified in the SPCC reduction goals, it is expected that in the future the use of economic instruments will allow Mexico to move forward with more mitigation that does not directly depends on budgetary allocations. Mexico's ambitious long-term climate strategy will require a major transformation of the energy sector. Following, I describe main interactions between climate and energy policy in the country.

2.1.2 Energy policy and new regulatory landscape

A profound transformation of the energy sector in Mexico is on its way. In December 2013, constitutional amendments were passed by Congress to enact an Energy Reform [45]. In a nutshell, the Reform aims to modernize the oil and electricity sectors through market-based mechanisms. As a fundamental part of Mexico's *National Energy Strategy* [168], the reform's objective is to channel investment in new technologies to ensure adequate energy supply in the country.[5] The new regulatory

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[4] Petróleos Mexicanos (PEMEX) is the oil company and Comisión Federal de Electricidad (CFE, Federal Commission of Electricity) is the electric utility

[5] The underlining reason for the reform as stated in its preamble is the need for new investments outside the federal budget, particularly given budgetary constraints and new technological challenges

environment will open the oil and electricity markets to private investment; markets formerly reserved (for the most part) for the state-owned companies PEMEX (oil) and CFE (electricity). In the case of electricity, a major modification of the Electric Energy Law was enacted in 2014 and new regulations are under development to create a wholesale electricity market [47, 171, 173]. The official market overview and expected development for the electricity sector is presented each year by SENER and CFE to disclose short and medium-term planning of the government, facilitating also the investment analysis of independent power producers (IPPs) and providing information to the public in general. These overviews include the perspectives for the electricity market [167], the renewable energy market [165] and natural gas [166].

In addition to an adequate investment level, energy policy in the country aims to prepare Mexico for the so-called Energy Transition. By issuing the *Law for Renewable Energy Use and Financing of the Energy Transition* (LREFET) [46] and the *Law for Sustainable Use of Energy* [44], Mexico has established specific mandates and guidance for the deployment of clean technologies, including renewable energy and energy efficiency. Importantly, based on LREFET, specific targets for renewable energy are established and progress on meeting these goals is made public each year. Derived from these laws, Mexico has a *Special Program for Renewable Energy*, a *Special Program for Energy Efficiency*, and the Energy Funds for Sustainability and for Energy Security, which support the financing of clean technology development and deployment in early stages [163, 170].

A particular link between new regulations in the power sector and climate change policy is the mechanism to ensure compliance with the national goal for clean electricity. The Executive Initiative for the Electric Industry Law (EIL), which includes the details of the organization of the wholesale electricity market and the new operation of the power sector, proposes a “clean certificates mechanism” in order to distribute the goal for clean energy among generators, both public and private. Mexico’s next steps to maintain its ambitions mitigation goals and set adequate legal frameworks and incentives for clean technology deployment are still under development. Additional

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to tap off-shore oil resources and develop renewable energy resources.

provisions in the EIL, describing the future operation of the wholesale electricity market and for renewable energy deployment, include:

- Planning for the energy sector will still be a state prerogative. The government should consider public and private investment projects in the planning of the sector, as well as on the network expansion.

- The National Center for Energy Control (CENACE) will be in charge of the management of the power grid, and rules should be designed for adequate and open access to the grid, without favoring any provider.

- CENACE will operate the wholesale electricity market, and compute prices based on generators bids and regional demands. Generators will submit daily bids, and load-serving entities (LSE) will report their electricity demand.

- Rules for the private sector participation in transmission and distribution networks expansion should be established.

- Barriers to the interconnection of solar and wind projects should be eliminated.

- CFE remains the main provider for residential and small industrial and commercial users, both of which will continue under a tariff scheme established by the government ("basic service" scheme).

- CFE will buy electricity for the "basic service" through contracts in the wholesale market. This will allow CFE to compete for lowest-cost energy in the market. CFE will retain the right for preferential energy coming from its own plants, and will keep the long-term contracts that it already has with independent power producers (IPPs).

- New users above the consumption level established for large industry, and users under the current modalities of self-consumption, cogeneration, and importation, will be able to directly participate in the wholesale market.

- LSE will compete for users in the market, including the current self-supply users which might shift to the new scheme (CFE could recover some of those users under the new modalities)[6].
- Generators can engage in long-term contracts with qualified users, with other generators, LSE and with "energy brokers"; this is expected to reduce the total amount of energy sold in the spot market (whose price is more volatile).

It is interesting to note that storage technologies are not specifically mentioned in the current text of the EIL. This is not surprising, since currently storage technologies are not present in the power system in the country, and have just recently come to the attention of regulators in several countries, particularly driven by the deployment of renewable energy resources (as discussed in Chapter 1). As will be discussed in Chapter 7, introducing appropriate regulatory frameworks for storage, and in general for other sources of flexibility in the power grid in view of the expected penetration of renewable, is an important regulatory issue that needs to be considered as part of a comprehensive policy design. The establishment of markets for ancillary services should also be addressed in the up-coming regulation of the nascent electricity market in Mexico. Considering potential storage participation in the provision of services to the power grid could become important both considering the potential large-scale penetration of renewables and also the need for transmission and distribution expansion in many networks (storage could participate in the markets of ancillary services, and in some cases could allow the deferral/substitute the need of networks expansion). A summary of current legislation, national high-level strategies and perspectives, and specific programs is presented in Table 1.

In sum, Mexico has made remarkable progress in developing its institutional and legal framework for climate change and energy policy, and has taken concrete steps in the mitigation arena, particularly targeting emissions from the power sector. The country is also in the midst of important changes in its energy sector, and specifically in the regulation of its power system. As we look into the future for Mexico's climate

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[6] Due to the previous regulatory environment, many industries decided to generate electricity for its own uses because CFE was the only provider and its tariffs for industrial use were high.

Table 2.1: Current regulatory framework

Regulation / Programs	**Reference**
Laws & Regulations	
General Law of Climate Change	[48]
Law for Renewable Energy Use and Financing of the Energy Transition	[46]
Energy Reform	[45]
Electric Industry Law	[47]
Electric Industry Regulations	[171]
Principles of the Electricity Market (draft)	[173]
High-level Strategies for Medium and Long-Term Planning	
National Strategy for Climate Change: Vision 10-20-40	[159]
National Energy Strategy 2014-2028	[168]
National Strategy for the Energy Transition and Sustainable Energy Use 2013	[162]
Energy Perspectives by Sector	
Perspective for the Electric Sector 2013-2027	[167]
Perspective for Renewable Energy 2013-2027	[165]
Perspective for Natural Gas and L.P. Gas 2013-2027	[166]
Programs	
Program for the Energy Sector 2013-2018	[164]
Program for the Environment and Natural Resources Sector 2013-2018	[160]
Special Program for Climate Change 2014-2018	[161]
Special Program for the Renewable Energy Use 2013-2018)	[163]
Special Program for Sustainable Energy Use 2014-2018	[170]

policy, however, key challenges remain to be tackled. Removing barriers for policy implementation, better aligning climate and energy policy particularly under the new energy regulatory framework, directing adequate levels of investment, monitoring and verifying emissions reductions, and scaling-up clean energy technologies will require a substantial effort from key stakeholders.

Finally, it is worth mentioning that underlining the ambitious mitigation targets of the country is Mexico's goal to set an example for other countries and achieve a binding climate agreement. Mexico has for long recognized its special vulnerability to climate risk, and has participated in the international negotiation process as a Party of both the UNFCCC and the Kyoto Protocol. A key challenge for Mexico's climate policy is to effectively design measures to counteract potential negative effects from national mitigation, such as loss of competitiveness (resulting for example from increases in energy prices). Moving forward to more aggressive emissions reduction will be costly for the country, thus a through discussion of how Mexico could finance technological change will be certainly needed.

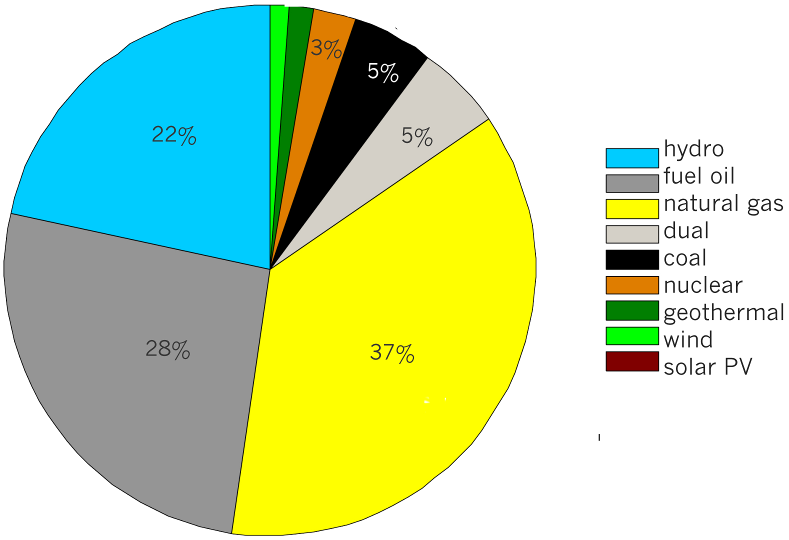
2.2 Current infrastructure

As of December 2013, Mexico's electricity sector had a total installed effective capacity of 53.5 GW, 76% of which was owned by CFE, the state-run electric utility, and the remainder by independent power producers (IPPs) [172]. Currently, natural gas technologies account for 37% of total capacity, while conventional thermal powered by fuel-oil and hydroelectric plants comprise 26% and 22%, respectively, followed by coal and dual coal/fuel-oil at 5% each, nuclear at 3%, geothermal at 2%, wind at 1%, and one small solar PV installation (6 MW) with 0.005% (See Figure 2-1a).

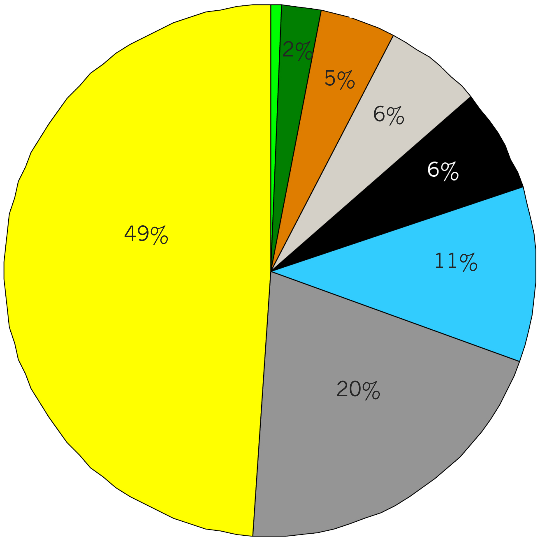
In 2013, electricity generation was 258 TWh, 67% of which was generated by CFE and the remainder by the private sector. Natural gas accounted for 49% of generation, followed by conventional thermal (mainly fuel-oil) with 20%, hydro with 11%, coal and dual plants with 6% each; nuclear with 5%, geothermal with 2%, and finally wind developments contributed with 0.7% of total generation (See Figure 2-1b). Altogether, non-fossil fuel technologies produced 18% of electricity, including mainly hydro and nuclear generation [172].

Mexico's power system is divided into 5 electric regions: Northeast, North, Northwest, Central, and South-Southwest (see Figure 2-2). The regions are diverse in terms of technology mix, resources, and demand characteristics. As shown in Figure 2-3 most of the installed capacity in the country is in the South, where the big hydropower reservoirs are located. The southern region is also the more varied in terms of its technological mix, with an important participation of hydro, nuclear, coal, fuel-oil, dual plants and combined cycle technologies. In contrast, the northern part of the country is much more fossil-fuel dominated, with the majority of capacity provided by natural gas combined cycle technologies, followed by coal and fuel oil.

In terms of its operation, the interconnected system has 50 subregions, grouped in 9 balancing areas: Central, East, West, Northeast, North, Northwest, North Baja



(a) Total Installed Capacity in 2013 (53.5 GW)



(b) Total Generation in 2013 (258 TWh)

Figure 2-1: Mexico's Electric Capacity and Generation in 2013

Figure 2-2: Main Regions in Mexico's Power System
Source: Ministry of Energy of Mexico [167]

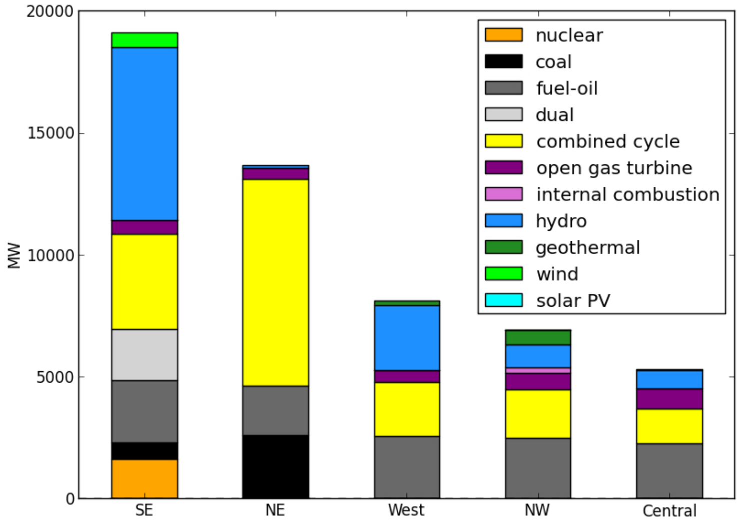


Figure 2-3: Installed Capacity per Region (MW)
Source: Author with data from SENER [167]

California, South Baja California, and Peninsular (see Figure 2-4). In addition, there are small systems that are not connected to the grid, with 0.01% of the capacity, which serve remote areas. The transmission and distribution network comprises 853.5 thousand km of lines; 6% are high voltage 230-400 kV that allow for high-range transmission, and 5.7% are 69-161 kV which support the interconnection within regions. The remainder are lower voltage lines, 48% with voltage between 69 and 161 kV, and the rest with voltage less than 34.5 kV, serving the distribution networks.

Figure 2-4: Mexico's Transmission Network
Source: Federal Commission of Electricity of Mexico [167]

The Northeast region has the highest demand, with 25% of electricity sales, followed by the Central and West regions with 24 and 23%. The South and Northwest areas have lower demand, with 15 and 14% of total sales serving those areas. Regarding peak load levels, coincident peak demand for the system was 38 GW in 2012 [167]. Central and West regions present the highest peak demand with 8.8 and 8.9 GW, followed by Northwest and East regions (See Figure 2-5). Peak demand is lower in the North and Northeast part of the country, and in the peninsular areas of Baja California and Yucatan. While Central and West regions have the lowest capacity, they have been historically high-demand areas given that the two largest metropolitan areas in the country, Mexico City (in Central) and Guadalajara (in West), and some of the main industrial corridors, are located in these regions. Therefore, most of the transmi ıgh power.

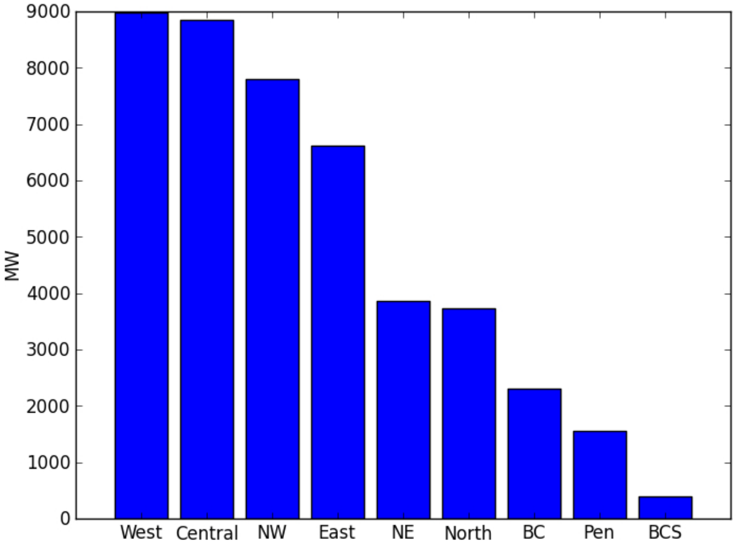


Figure 2-5: Mexico's Regional Peak Demand 2012
Source: Author with data from SENER [167]

In terms of the composition of demand, 60% of electricity demand comes from the industrial sector, 25% from residential, 11% for commercial and services and 5% from agriculture. There are differentiated tariff schemes for the sectors, with residential and agriculture electricity prices having highly subsidized tariffs, while industrial tariffs are higher than those in the US and similar to other OECD countries[7] [106, 89].

Many of the power plants in the system are more than 30 years old, with some facilities older than 50 years. CFE estimates that 11.8 GW of capacity will be retired between 2012-2027 [28]. Most of these aging infrastructures are conventional thermal generators powered by fuel-oil. The reason the system has an important amount of fuel-oil capacity follows the way the Mexican energy sector was at one time planned. Since PEMEX and CFE both belong to the government, in order to decrease transportation costs and facilitate the management of the residuals for PEMEX, many of the big power plants were co-located with the oil refineries[8]. Because

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[7] Electricity prices for households were 90.20 USD per MWh the lowest of all OECD figures for 2012, and 114 USD per MWh for industry similar to most OECD countries but higher than the 67 USD per MWh in the US.

[8] This later created an air-quality problem because fuel-oil resulting from the refining of Mexican

of their economic-life coming to an end, and also for other economic, environmental and operating factors, such as the increase in the price of fuel-oil compared to that of natural gas, these plants might be retired in the near future. In the next section, I briefly discuss some of the current planning regarding system expansion.

2.3 System expansion: Short and medium-term perspectives

The Mexican system is centrally planned, with SENER and CFE directing investments for future expansion. By law, SENER publishes a 15-year Plan for the power sector each year, outlining the government's programs for electricity infrastructure investment which are coordinated with CFE Investment Program [167, 28]. According to the 2013 Plan, demand for electricity over the next decade is expected to increase by 4.6% per year, reaching a level between 425.9 to 465 TWh by 2026[9]. Meeting this demand will require 47.5 GW in expanded system capacity (between new capacity and retirements, new capacity additions compare to the size of the current system). It is expected that 85% of the new installed capacity will be connected to the grid, while around 15% could be under the modality of self-supply and cogeneration. To meet growing demand, and replace old power plants, Mexico's investments plan for the coming two decades accrues to $109.7 billion US dollars [28]. Of this amount, 52% is for new generation facilities, 20% for the distribution network, 14%t for transmission, 13% for maintenance, and 1% for other public investment. As a result of this Plan, Mexico will speed its transition away from fuel-oil generation and invest heavily in natural-gas-fired power.

The investment categories will change with the new energy reform, but since planning will remain a State prerogative, the expected mix could still (in principle) align in the short and medium term as follows. The private sector is expected to take the

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heavy oil had very high-sulfur content and heavy metals. Hot spots were created due to the emissions of the refineries and the power plants planned without emissions control equipment

[9] SENER expects that energy efficiency programs could curve demand to 425.9 TWh from a baseline of 465 TWh

lead mainly with more investment in natural gas combined cycle technologies, and the government directing investment to transmission, distribution and the maintenance of the current infrastructure. Currently, Mexico has three main modes of capacity investment: public works, financed public works, and IPPs. Of the total investment needs for 2012-19, 70% will come from the scheme for financed public works, 25% from IPPs, and 5% from the federal budget for public works (Table 1). Public works will account for 67% of new investment in transmission and 88% of investment in distribution. The government expects that 74% of IPP investments will be in natural gas combined cycle (CC) plants and the rest in wind farms. Investment in financed public works will be allocated to natural gas CC plants (42%), new hydro plants (23%), new wind farms (19%), and 16% to other technologies yet to be defined. Two-thirds of budgetary expenses will be allocated to maintenance and one-third to hydro upgrades.

In terms of total fossil fuel use, the current Plan will require Mexico's energy sector to expand natural gas use by 3.7 percent per year [166]; pipeline distribution will originate from domestic and U.S. sources, as well as liquefied natural gas (LNG) import terminals[10]. The country has limited coal reserves, located mainly in the north; therefore coal would have to be imported to meet power-plant needs if more coal units are built.

Regarding the planning of investment in renewable energy, in the short-term the Special Program for Renewable Energy specifies a goal of 32.8% participation of renewable energy, including current existing big hydro facilities. Current renewable energy projects are developed mainly under the modality of self-supplier (off-grid mostly) and for the planning period include 2892 MW.

For the medium-term planning, it appears to be a "tension" between the goals established for climate change mitigation in the NSCC and law for energy transition (LREFET) with the current 15-year Plan for the electric sector. The energy sector planning documents identify a "planning" scenario and an "alternative" scenario. The

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[10] Mexico is also heavily investing in expanding its pipeline system, particularly given the availability of low-cost natural gas coming from the US after the shale gas developments

planning scenario, which is the one thoroughly discussed in the 15-year plan and the Investment Plan of CFE, keeps natural gas at the core of the planning system, with hydro and coal additions as presented above. The policy scenario is presented at the end, highlighting the increased costs and capacity requirements. The "alternative" scenario considers additional 16 GW of extra capacity to increase wind participation at the expense of decreasing natural gas and generation from fuel-oil units.

The planning document underscores the need to further investigate the costs of increasing the penetration of renewables, and points out that, currently, the official plan made simple assumptions and has not incorporated renewables in current planning models or in the network analysis [167]. For example, wind farms are assumed to have a 30% capacity factor, 10% firm capacity and it is considered that additional capacity needs to be fully backed-up with additional open gas turbines for reliability reasons. The Plan underscores the need to clarify financing mechanisms for the increased costs of adding more renewables. It also considers the need to develop new methodologies for estimating resource adequacy to ensure system security, as well as methods for rigorously accounting for pollution externalities and energy security issues in order to better justify the need for emissions reduction and fuel diversification.

2.4 Renewable energy resources

Mexico's National Inventory of Renewable Energy (NIRE) provides a first assessment of geothermal, mini-hydro, wind, solar, biomass and tidal resources. The NIRE is the result of a joint effort of several institutions, including the federal government (the Ministry of Energy, the Ministry of Environment and Natural Resources, the CFE, the Commission for Energy Regulation, the National Institute for Statistics and Geography), the scientific community (the National Autonomous University of Mexico, Centro Mario Molina), and the private sector (Vestas, GPG, GEIC). It classifies resource potential in *Possible*, *Probable*, and *Proved* resources, depending on the level of detail in the assessment methods. The total theoretical availability of the resources estimated by modeling techniques, without any economic, technical or environmental limitation, is gradually constrained to consider issues such as accessibility of the resources due to land-use restrictions, and technical and economic considerations. *Possible* are resource estimates supported in models and complemented by secondary research (such as land-use and restricted areas information) to estimate potential installable capacity; *Probable* are estimates that, in addition, have conducted field research to corroborate modeling results; and *Proved* are resource potential estimates that, on top of field research, have been evaluated for economic and technical feasibility. Table 1 summarizes the renewable energy potential in Mexico.

Table 2.2: Renewable Energy Potential, MW

	Geothermal	**Mini-hydro**	**Wind**	**Solar**	**Biomass**
Proved	514	3,498	11,621	1,825	607
Probable	60,286	23,028			391
Possible	52,013	44,180	87,600	6,500,000	11,485

Source: Mexico's National Inventory of Renewable Energy [169]

As shown in Table 1, wind has the highest proved potential, followed by mini-hydro, solar, geothermal and biomass. If Mexico were to use these resources today, 18 TWh of energy could be generated per year with already *Proved* resources, or around 7% of current demand, more than doubling the current participation of geothermal and wind of 3%. While wind has the best *Proved* potential today, the highest *Possible* potential of sun outweighs that of all other renewables. Geothermal and mini-hydro *Probable* resources together could contribute almost the same amount as wind. It is worth mentioning that geothermal energy is basically a dispatchable source, while mini-hydro operates as run-off river and thus is dispatched when available. Further research to assess how much of the *Possible* resources could be tapped is needed, particularly in light of the policies to scale-up clean generation in the country.

Since all of these resources are site constrained, except for biomass[11], next I present

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[11] Biomass resources potential have been identified in various regions of the country; many different sources could be used including waste from urban, forestry, industrial and livestock, as well as from specific biocrops and forestry activities. The Inventory locates these potential in different regions, however, once produced biomass resources could be used everywhere, therefore I do not further described its location

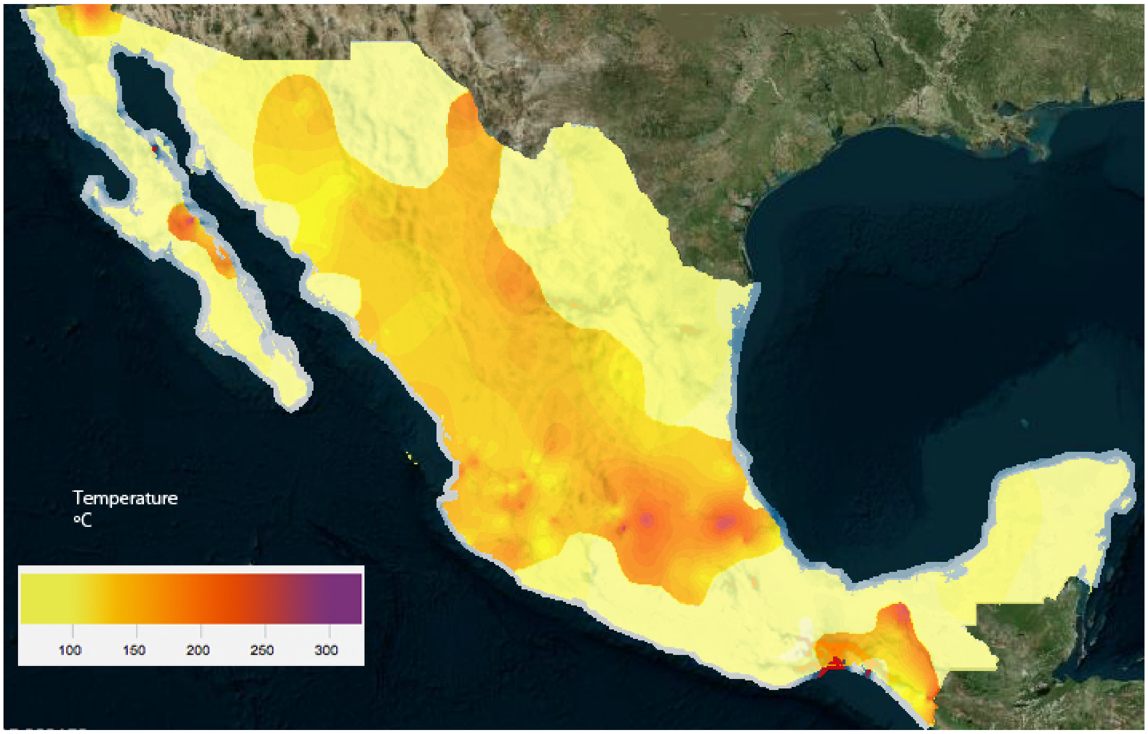

Figure 2-6: Geothermal potential in Mexico (°C)
Source: Mexico's Ministry of Energy Renewable Energy National Inventory[169]

the location of these resources in the country.

2.4.1 Geothermal

Mexico's geography is characterized by volcanic formations and geothermal systems, particularly in the central region of the country known as the Trans Mexican Volcanic Belt. Mexico is the third country in terms of total geothermal generation in the world, with 6 TWh generated in 2013 in four fields with a total installed capacity of 953 MW[12]. The location of resources and potential is presented in Figure 2-6 [145]. Estimations of geothermal potential in Mexico can be found also in [74].

2.4.2 Mini-hydro (less than 30 MW)

In 2013, mini-hydro facilities in the country generated 1.6 TWh. Probable resources could generate 23 TWh per year, of which 3.5 have been proved with technical studies. As shown in the Figure 2-7, potential is wide spread in the country[13], with best sites

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[12] Studies done by Mexico's Autonomous National University and CFE.

[13] Studies done by Mario Molina Center.

Figure 2-7: Mini-hydro potential in Mexico (potential sites)
Source: Mexico's Ministry of Energy Renewable Energy National Inventory[169]

in the central region and southeast [119].

2.4.3 Wind

Wind generation reached 4 TWh in 2013, most of which is located in *The Ventosa* region, in the State of Oaxaca where the best wind resources are sited. *Proved* wind resources in the country could potentially generate 11 TWh, with resources in the States of Oaxaca, Tamaulipas and Baja California. Potential resources have been estimated in 87 TWh/yr[14]. Traditionally, wind assessment has been presented using wind speed as an indicator of the potential; however, it is important to evaluate the resource potential using wind density as a metric since ultimately it is this metric what matters for power generation. For comparison, I present Mexico's wind maps[15] both in wind speed and wind power density in Figures 2-8 and 2-9 [169].

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[14] Studies done by the Energy Regulatory Commission for *Probable* resources and by National Wind Association and PriceWaterHouseCoopers for *Possible*

[15] Wind maps were developed by Vestas using mesoscale atmospheric numerical models, using 13 years of data at a resolution of 3x3 km.

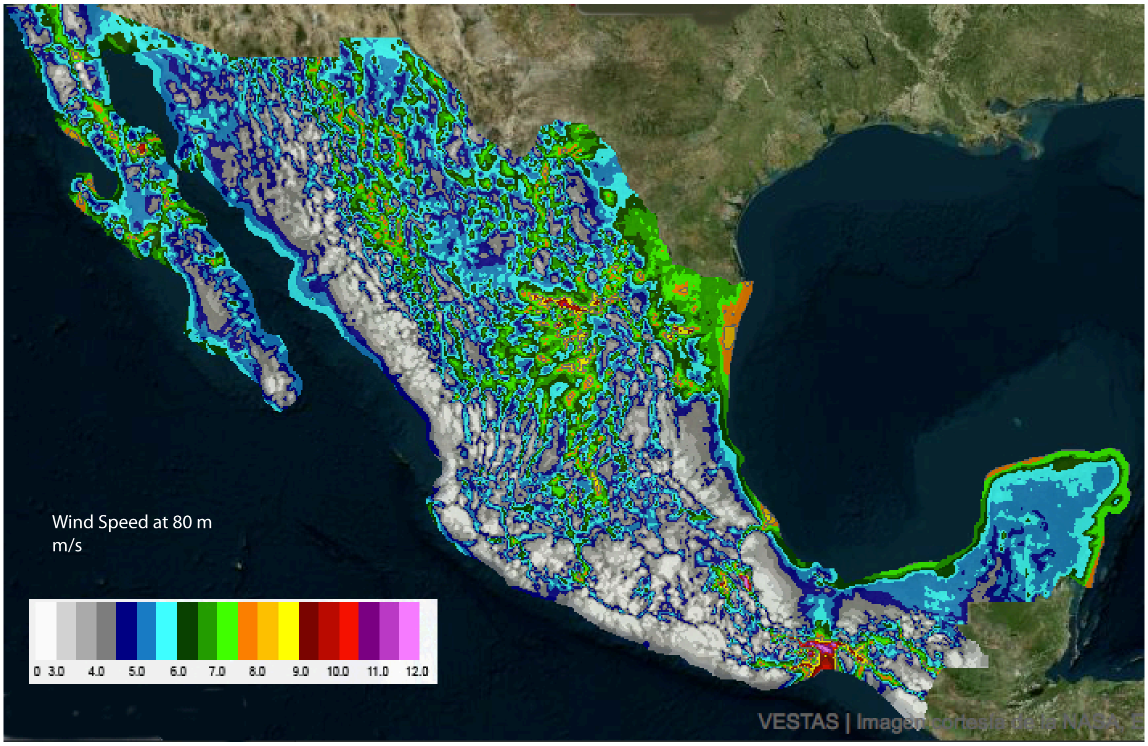

Figure 2-8: Wind potential in Mexico (wind speed m/s)
Source: Mexico's Ministry of Energy Renewable Energy National Inventory[169]

2.4.4 Solar

Part of Mexico is located in the so-called sun-belt (15°N and 35°N), and therefore is endowed with significant solar potential. However, due to costs of solar technologies, solar generation is marginal in the country today contributing only with 19 GWh in 2013. Its potential, however, is the highest among all of renewable energy resources. With a mean solar radiation of 6 kWh/m^2/day Mexico's resources are among the best in the world. Proved resources could generate 1.8 TWh and possible resources could provide 6,500 TWh, considering that 1.5% of land could be devoted to solar installations, and a 10% efficiency[16]. As discussed in Romero et al. [151] and shown in Figure 2-10, the resources are particularly important in the North of the country, also the region with the highest expected growth in electricity demand.

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[16] Study conducted by CFE, Solartronic, NREL and PWC.

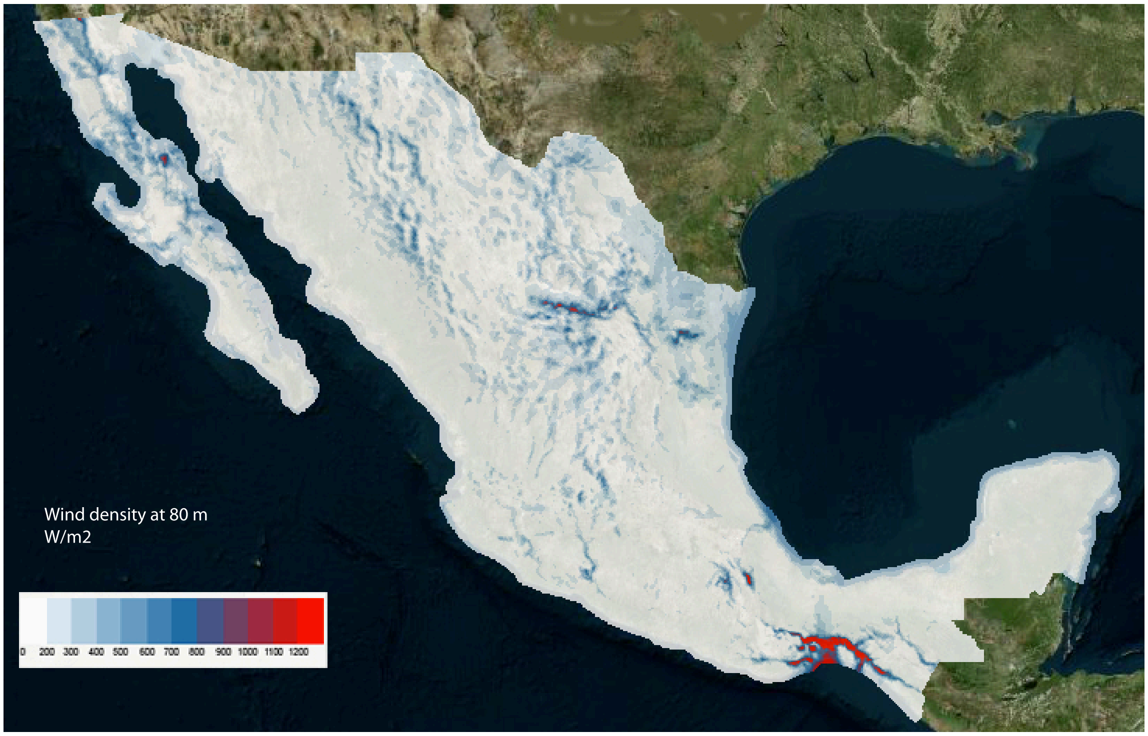

Figure 2-9: Wind potential in Mexico (wind density W/m^2)
Source: Mexico's Ministry of Energy Renewable Energy National Inventory[169]

2.4.5 Tidal

A first assessment of tidal potential included the mapping of resources identifying Oaxaca and Baja California in the Pacific Ocean as the best regions as shown in Figure 2-11, and to a much lesser extent the Atlantic coastal states of Tamaulipas and Veracruz[17]. Studies need to be completed for the estimation of the total potential for generation, particularly given the very early stage of development of technologies to harness these resources.

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[17] The assessment was done using numeric simulation with the model WAVEWATCH III and NOAA/NWS/NCEP data from 1979-2013.

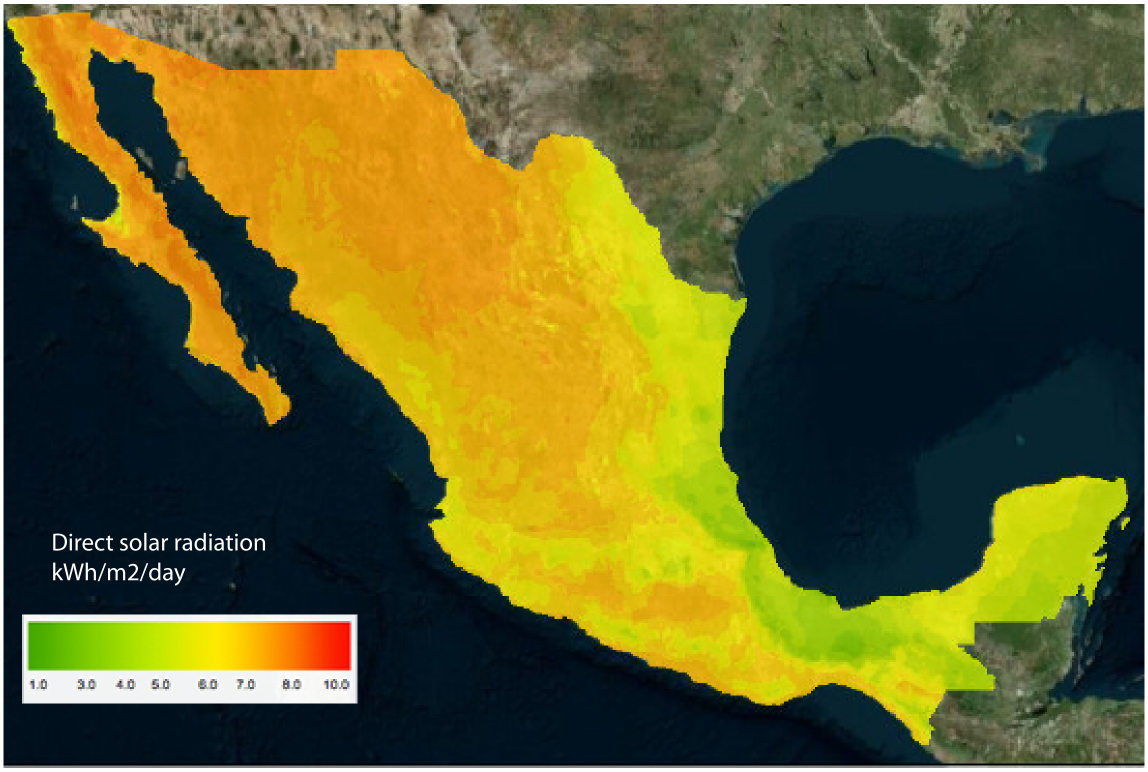

Figure 2-10: Solar potential in Mexico (kWh/m^2/day)
Source: Mexico's Ministry of Energy Renewable Energy National Inventory[169]

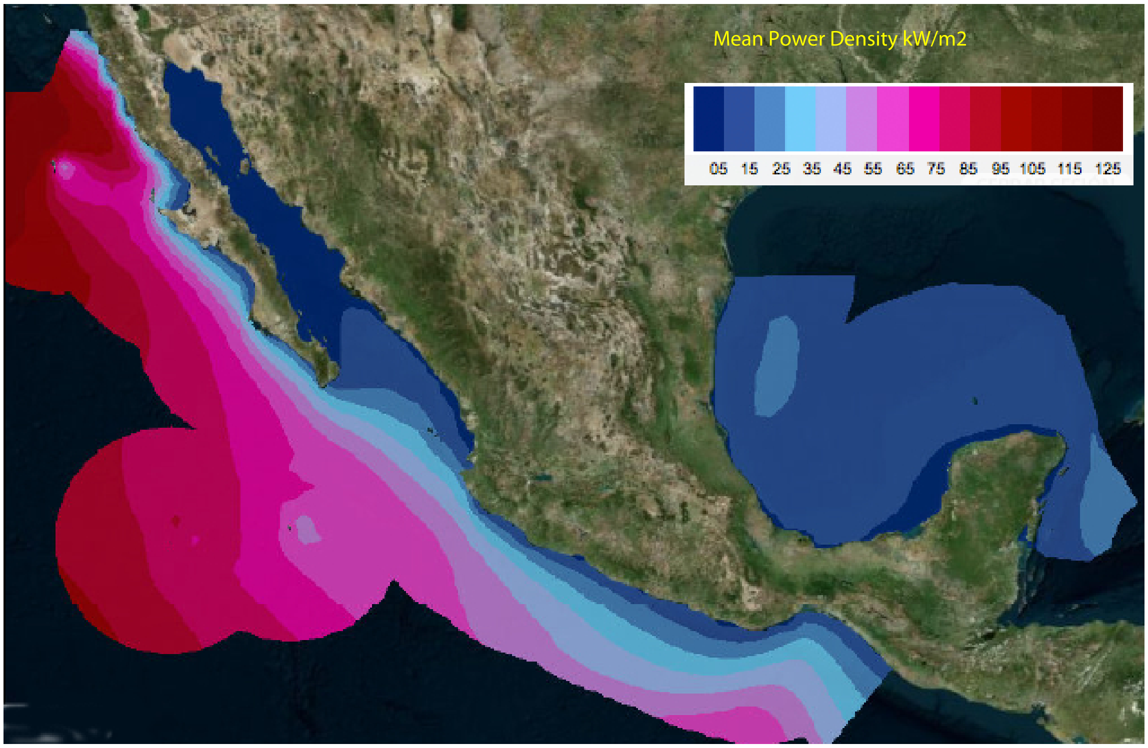

Figure 2-11: Tidal potential in Mexico (kW/m^2)
Source: Mexico's Ministry of Energy Renewable Energy National Inventory[169]

2.5 The future of the power grid in Mexico

Transforming the nation's power sector requires a long-term vision that adequately balances societal needs, with the technological, regulatory and business model solutions to deliver a low-carbon electricity system. Mexico needs not only to design new regulation to gradually rebalance the role of the state-owned utility and new agents in the nascent electricity market, but also at the same time needs to encompass climate change regulation, renewable energy penetration, energy efficiency programs, changing demands including the expansion of distributed generation, and rapidly changing natural gas markets. How to structure utilities and regulation to best serve the interests of society and shareholders is an open question for regulators and the business community in the country.

Liberalizing electricity markets will harness competitive forces to reduce inefficiencies that currently pervade the power system in Mexico [112]. However, as argued by Jamasb [73], market forces by themselves will not provide the best technology choices from a social perspective, in the absence of carbon taxes or policies that reflect the global social cost of carbon and other short lived pollutants or energy security concerns. Because of the nature of the electric industry, the regulatory challenge ahead is of great dimension, and there is no-single path forward as shown by the international experience on market design and deregulation of the electric industry [100]. Transitioning from a vertically integrated system, centrally planned by the government, to a modern market-driven low-carbon power system, will require innovative regulations to reconcile the need for markets with the new institutional frameworks for regulatory oversight and directed environmental and energy planning.

As discussed by Pérez-Arriaga in *Challenges of Power Systems Regulation* [141], the liberalization of electricity markets initialized in the 1990's with the case of Chile and that spread out in the US and Europe during the last decade has proved to be harder than initially thought. As he points out, after two decades of regulatory design supporting the development of wholesale electricity markets, and in some cases complementing those with capacity and ancillary services markets, important regulatory issues remain. Approaches to correctly price electricity transmission, promote efficient distribution networks investment, and efficiently unbundle retail are still discussed intensely around the world. In the midst of the challenges to correctly design these regulations in Mexico, the quest for sustainability adds another full level of complexity. The opportunity ahead of us is also the hope that if we consider comprehensively all the technologies that need to accompany the transition to more sustainable power systems, the costs can be better managed, and sustainable systems can be fostered as we move forward with the next generation of regulation for power markets that will deliver the solutions needed to address the climate risk.

Manifold technological solutions are likely to characterize the future of power systems. As of today none of the available technological options provide a comprehensive solution that delivers low-carbon electricity at the scale and cost that society needs. Therefore, dealing with deep uncertainties about technological change is also part of the state-of-the-world in which utilities and regulators need to operate. While renewable energy is a promising choice, the issues of intermittency, capital cost reductions and site-specificity, require a rigorous analysis to assess the feasibility of tapping these resources in Mexico. In addition, the role of transmission and distribution networks, as well as other technologies and behavioral changes, such as power electronics and information technologies, storage and demand response, needs to be fully integrated in the analysis. Among the technologies that can shift the current electricity paradigm are energy storage technologies; in this research I focus on the study of their potential role for climate change mitigation considering plausible scenarios for the evolution of Mexico's economy.

As I ponder the future development of Mexico's power system, I can identify common challenges that utilities around the world face confronted with the risks of climate change, evolving regulatory environments and new technologies. Impending change have raised awareness in many countries of the need of rethinking the entire business-model of utilities and transform them into what many have called the "utility of the future" [142, 174, 124, 51]. As put by van Nispen: "what's at stake is the creative destruction of longstanding interests and an upending of status quo business models in favor of new physical energy delivery architectures" [187]. Creating the future power system that will fulfill Mexico's goal of low-carbon development requires that key stakeholders, including CFE and new utilities, regulators, customers and innovators, to truly embrace the need of change, adapt to and shape the new system architecture needed to deliver clean power in the country.

Chapter 3

Literature Review

The renewed interest in storage as a technological option to assist the integration of renewables has spurred research in the area in the past years in many regions of the world. In the case of the US, the Department of Energy (DOE) has funded several studies, through its DOE Energy Storage Systems Program, to evaluate the market for storage technologies. A series of studies have been conducted by the Electric Power Research Institute (EPRI) [3, 63, 62, 61, 64], Sandia National Laboratories (SNL) [67, 22, 66], the National Renewable Energy Laboratory (NREL) [37, 36] and the Pacific Northwest National Laboratory [103]. In response to the many different developments around the world, with the goals of following the technological developments and creating a collaborative framework, DOE has also funded a Global Energy Storage Database that provides information on storage projects as well as policy developments not only in the US but around the world.[1]

Numerous studies on the value of storage have been conducted in Europe also, where many countries' renewables penetration is reaching very large-scale. In an effort to inform policy-making and investors in the sector, the European Union funded a study through its Joint Research Centre Institute for Energy and Transport (JRC), in collaboration with *Electricité de France* (EDF), which reviewed over 200 papers [202]. The study, which I will discuss later in this chapter, mainly focused on cases and research conducted to evaluate the value of storage in European systems, and

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[1] For more information about the dataset visit http://www.energystorageexchange.org/

included 3 of the main studies conducted in the US. Also, the EU has funded research on regulatory mechanisms and policy frameworks that could assist the deployment of these technologies [188].

Research on the value of storage in other areas of the world is also emerging. Among these cases are island states and regions, including Japan [65, 128], Australia [81], New Zeland [183], Barbados [7], and Portugal Azores islands [33]. Isolated systems where generation depends on imports of fossil fuels, and/or do not have well-meshed grids, could provide cases where the economics of renewables and storage are justified. Other large-systems studies include assessments for China [118], Canada [13], and one study assessing potential for energy storage in combination with renewable energy in Latin America and the Caribbean [7]. In this last study, 3 market types were evaluated: a small off-grid town in Colombia, a small island country, Barbados, and a large interconnected market, Mexico [7]. I discuss results of this study in detail, since it is the only study available focusing on Mexico.

I build on these institutional reports and specific country assessments to frame the discussion of the value of storage provided by available studies and the current-state-of-the-art of methods to assess it. Other relevant issues that surround the question of the value of storage, such as the cost of the technologies (and current state in the research and development area) and the topic of market mechanisms, business models, and regulatory frameworks that could allow the technologies to adequately be remunerated and participate in the electricity market, were also addressed in some of these reports, and are currently also focus of much research. In this section, however, I focus only on the available research regarding the estimations and methods of the value of storage in order to identify current gaps in the literature, and to position the methodology that I am proposing to estimate the value of storage within the body of literature.

Nonetheless, it is important to mention that there is a fine line between the methods used to compute the value of storage, and the assumptions used within these studies that relate to the market structure where storage technologies operate, which eventually determine the value of storage. Therefore, the research related to regulatory frameworks is strongly intertwined with the underlying services used for estimating the value of storage, as I will discuss below. On this issue, I refer to an international overview of regulatory frameworks for grid level electricity storage conducted by Oghenetejiri et al. [4].

I restrict this literature review to studies evaluating the value of storage for technologies serving the electric grid for bulk power management. I do not discuss the value of storage in distributed systems, which is a rapidly growing area of research, particularly driven by the potential large-scale deployment of residential solar technologies[2].

Finally, the value of storage can be estimated without restricting the assessment to any given technology, as far as it concerns the costs. However, it is still necessary to make assumptions about important parameters that govern the performance of storage technologies, for example regarding duration, rated power, and efficiencies. For this reason, in section 3 of this chapter I present a brief overview of storage technologies commonly discussed in the literature, with the goal to provide context on the technology options and explain the critical specifications that play a role in determining its value. For a detailed overview of storage technologies, I refer to the International Energy Agency storage technology roadmap *Technology Roadmap for Energy Storage* [94], and to EPRI's white paper on storage technology options [63].

I conclude this chapter with a summary of the contribution of this dissertation to the literature.

3.1 The value of storage in literature

The question of the value of storage has been pursued with varied levels of complexity in the analysis. There is no generalized framework to categorize the available methodologies currently used to estimate the value of storage. Zucker et al. broadly classify the approaches as "engineering models" and "system models", the former referring

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[2] The review includes only 2 studies that reported storage values for generation and distribution, but I did not survey the whole literature on distributed generation

mainly to models that use a “bottom-up” approach to estimate the value of storage from the perspective of the storage investor, simplifying the operation of other components in the analysis, and the latter reffering to those studies using power systems or energy systems models [202]. Alternatively, Denholm et al. describe the approaches as “price-takers” and those that use production costs modeling, in the domain of the power systems literature [36].

Drawing terminology from both Zucker and Denholm, I will refer to “price-taking” methods, “system-level” modeling, and other methods. I find the term engineering models confusing, since power systems models are engineering models and production costs modeling is a narrow term referring to a specific kind of models, that do not need to comprise all of the possible approaches to value storage other than the price-taking methods. By referring to systems methods more broadly, we can expand the boundaries of the system to investigate potential impacts of storage availability in and outside the electric sector. In the category of other methods I position all other studies that do not use the price-taking approach nor apply system’s level analysis, which are few studies focusing on net energy analysis and screening methodologies. Another clarification of terminology is that of “bottom-up” models. In this dissertation, I use the term “bottom-up” to refer to models that study the operation and technical constraints of storage in electric systems (either price-taker models or power systems models) as opposed to “top-down models” – a term I reserve for economy-wide models.

3.1.1 Price-taking studies

In a nutshell, the “price-taking” method assumes that storage in a power system will be too small to affect the price of the provided service, and thus the prices will be determined exogenously. These studies then use historic information of electricity and ancillary services prices to simulate how a storage provider would operate given prices. The majority of studies available in the US and Europe use the price-taker approach. Many reasons explain the dominance of this method, including: a) current systems were designed without storage, and it was assumed that only a marginal capacity of storage would fit (potentially) these systems, making the price-taking assumption tenable, at least in terms of price arbitrage services, b) in many deregulated markets time-series are available for market prices for electricity and ancillary services, c) from an investor's point of view who has no ability to influence the capacity of other technologies in the system a price-taker approach would be a first order approximation, d) building power systems models and calibrating them to specific conditions is complex and many times the needed information on specific systems is simply not available.

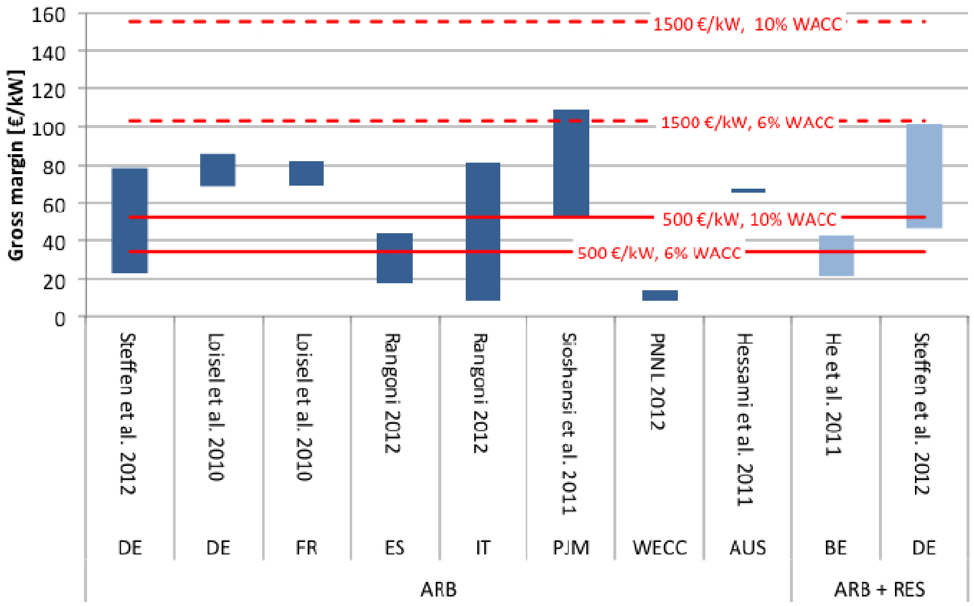
A recent study conducted by the National Renewable Energy Laboratory of the US, *The Value of Energy Storage for Grid Application*, provides a good overview of the literature in the US [37] using the price-taking approach. Thus computed, storage values in US restructured electricity markets, as compiled by Denholm et al. [37], vary for the case of energy arbitrage between \$60 and \$115 /kWh for PJM system using prices from 2002-2007 [175], between \$87-\$240 in NYC using prices from 2001-2005 [194], from \$25 to \$49 for California using prices from 2003-2011 [66, 22, 20], and from \$37-\$45 for 3 US interconnects (NE, CAISO and PJM) considering prices from 1997-2001 [70]. In terms of the remuneration of storage for regulation and contingency reserves, values are higher in the case of regulation: between \$236 and \$429 for the PJM, NY, ERCOT and NE, using prices between 2003-2006, and in the case of contingency reserves, between \$66 and \$149 [38] . The value of storage estimated through the price-taker method for combined services is in the range of \$38 to \$180 for the period of 2002-2010 considering CAISO, PJM, NYISO and MISO according to one study [49]. As shown by these studies, there is a wide range of values estimated in different markets and regions in the US, and the values are very dependent on the time window assessed.

Regarding studies in the European Union, many have evaluated the value of storage in specific countries, particularly in anticipation of higher penetration of renewable energy. A good overview is provided by [202]. The value of storage, as compiled by Zucker et al., is estimated in Germany, for price arbitrage between €20-80 /kW using prices between 2002-2010 [177] , for Spain between €20-41 /kW using prices between 2008-2011 [146], for Italy between €10-80 using prices between 2008-2011 [146]. One study in Europe, projected prices for the period of 2010-2030 and assumed the installation of wind facilities with storage, estimating a value between €70-81/kW for France and between €67-81/kW for Germany [108]. All of these studies evaluated storage considering PHS technology. Given the recent interest in CAES, some studies focus on the value of storage with the characteristics of this other technology, finding lower values in Germany and France between €35-45 and €25-30 [102], respectively, and for Denmark similar values were found [109]. The only study that reported higher values for CAES storage was done for the system of Turkey, finding values between €20-87 [201]. See Figure 3-1 for cross country-comparison.

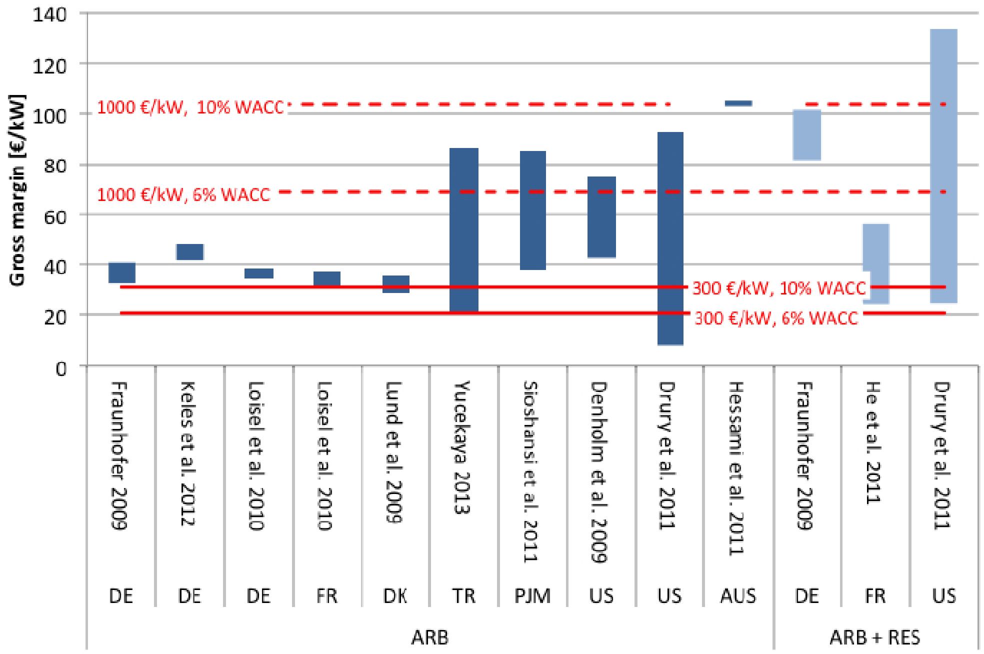
The limitations of these studies are many. By considering prices are not affected by the availability of storage, the analyses provide no information about how the system dispatch will change as a result of storage availability, limiting the understanding of the real potential market size of the technology, and failing to capture important dynamics such as the effect that more storage could have on the reserves markets and on lowering average electricity prices, as pointed out by Denholm et al. [37]. In particular, the price of reserves could drastically decrease as the availability of storage increases. Some authors have tried to improve the price-taking method by using "feedback" functions to incorporate the impact that greater availability of storage could have on prices. For example, Sioshansi et al. use linear supply curves to assess the impacts of large-scale storage on arbitrage value [175]. The problem with using this linear approximation is that in systems with large-scale penetration of renewables price-load relationships are complex, and simple feedback functions will not suffice to estimate prices and dispatch effects induced by renewables and storage.

Another important limitation of the price-taker approach is that the time-series of the prices used in these studies reflect historic conditions of systems, which are influenced by many circumstances, such as the presence of grid bottlenecks, market imperfections such as market power issues, as well as the price of fuels in particular years. Specially, the price arbitrage value is very sensitive to the price of natural gas in many systems where technologies operating with this fuel at the margin set the market price.

An additional drawback of the price-taking method is that it assumes perfect



(a) Pumped Hydro Storage Value



(b) Compressed Air Electric Storage Value

Figure 3-1: Value of Storage – Price-taker method
Source: Assesing Storage Value in Electricity Markets, Zucker et al. [202]

foresight of prices [202]. This means that the studies take a time-series of prices in a given period (one year or two for example) and optimize the operation of a storage device of specific characteristics assuming that the storage operator knows all of the prices to come in the period. This assumption has been contested, since in reality, operators make decisions without perfect foresight of prices. Some authors have applied back-casting techniques and reducing the perfect-foresight window to perform sensitivity analysis of this assumption, finding that in general the perfect-foresight analysis leads to an overestimation of the value of storage. Sioshansi et al.'s analysis suggest that this overestimation is around 15%, concluding that as long as the "load patterns over a variety of different time-frames are to a large extent predictable" the perfect foresight assumption will provide a "reasonable" estimate of the value of storage [175]. Drury et al. followed Sioshansi's method of back-casting and found a range between 65% and 85% of the value is captured with the perfect foresight assumption [49]. Although these studies found, that under some circumstances, the perfect-foresight assumption could approximate the value of storage, it is important to highlight that with large-scale penetration of renewables the load patterns – the net load patterns to be more precise – will not be as predictable and the simplifying assumptions of the back-cast method will most likely not approximate the value of storage.

In order to describe the price-taker approach in more detail, I selected one study that evaluated two different storage types under increasing renewable penetration with a long-term perspective. Loisel et al. [108] investigate the value of storage examining 3 snapshots: 2010, 2020 and 2030, using the price-taker approach for PHS and CAES potential installations in Germany and France. Price arbitrage, secondary, and tertiary reserves provision were assessed using a long-run simulation model of the European power market. In addition to assuming a price-taking behavior, other important variables were parameterized, for example storage capacity is exogenously given and an upper limit of 20% of the storage capacity is sold in the secondary and tertiary reserve markets. The installations receive capacity payments for this percent regardless of whether the units are called to increase or decrease energy output (if they are called, they assumed they will also receive an energy payment). With these assumptions, they simulate the operations of storage applications at an hourly time-scale for a full year using a single unit dispatch deterministic model, which maximizes the annual value of storage. To compute the values for 2010, 2020 and 2030 the authors use linear interpolation considering growing demand, and expected fleets in each of the countries with Germany moving towards renewables and France remaining a nuclear dominated system. Once the value of the technologies was estimated, technologies were compared calculating their net present values (NPV) with a 20-year period using a 10% weighted average cost of capital.

Negative NPV were found for all of the baseline cases explored in each of the countries: wind farms in two options (on-shore and offshore[3]) combined with two storage cases, CAES or PHS. The authors analyze the sensitivity of their results to higher carbon prices, reserves remuneration, storage feed-in tariffs and combined scenario where all of these incentives are simultaneously present. With higher carbon prices storage NPV was still negative for all cases except for offshore-CAES case in Germany. Higher reserve remuneration reports positive NPV only for CAES technology, similar to the effect expected from in-feed tariffs. The combination of all incentives result in positive NPV for CAES in all cases, particularly for off-shore wind farms in Germany and small positive value for PHS by 2030 in France.

3.1.2 System-level studies

A second type of studies to evaluate the value of storage use optimization and simulation methods to model the performance of the technology within a power system. In contrast to the price-taking method, this type of analysis models the full operation of a specific system, and computes the cost difference between a reference case without storage and the case with storage availability. Within the system-level studies, many levels of analysis could be undertaken.[4] There is a growing literature of systems

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[3] Off-shore wind was only explored in Germany.

[4] As discussed by Zucker et al. [202] there are many different types of systems models, which they classify as energy systems models, market models, network models and others. I use the term system studies, but define the model classess differently to provide some details of what features are

studies that analyze the operational and investment decisions under the presence of storage technologies using detailed power systems models. In addition, some recent studies have expanded the analysis to understand the role of storage more broadly in energy systems.

Within power systems approaches, different types of models can address the question of storage with varied levels of complexity, depending on the decision variables and time-horizon that the models include. For example, the models can focus on: the economic dispatch problem, the unit-commitment decisions, the networks analysis, the investment capacity expansion planning, or the market interaction of agents bidding in the electricity market. As pointed out by Ventosa et al. [190], and by Foley et al. [71], the advent of large-scale penetration of renewable energy poses new challenges for power systems modeling, which adds to the complexity already introduced by the liberalization of electricity markets. In particular, as posed by Palmintier [131] and Haller [75], there is a need to incorporate some of the operational details that affect long-term investment decisions under high levels of penetrations of renewables.[5] Adding these details is computationally demanding and requires new methods to properly evaluate renewables and storage technologies in scenarios of large-scale deployment, since the value of these technologies depends on the fluctuations of net-load at fine time-scales and are uncertain.

The first approach to assess the value of storage with power systems models is to conduct production cost analysis. In power systems literature, "production cost analysis is concerned with the costs which vary with the level of unit or system generation (i.e. the variable and operating and maintenance costs)" [87]. Production cost analysis is therefore focused on the operation of the system in the short to medium-term time-scale, where the operating fleet is fixed, and is used for determining the economic loading order useful for examining the changes in utility system costs

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included in power systems model types, which are quite relevant to understand the capacity of these models to evaluate storage value.

[5] For example, the investment decision was normally separated from the operational decisions of short-term nature; however given the large impact that short-term fluctuations of net-load could have in the operation of different technologies, affecting their economics, there is a need to add some of the operational detail into investment analysis.

associated with fuel substitutions and unit outages. In contrast, “revenue requirement analysis” looks into both the fixed costs and variable costs. Production cost analysis is therefore mostly done with economic dispatch models, unit-commitment models and with network models simulating power flow in transmission and distribution networks [41, 184]. Revenue requirement analysis is done with capacity expansion models, and with other financial analysis tools, either for generation, or for generation and transmission expansion.

Market models in electricity evaluate the decision-making of generators in a market setting, as opposed to the centrally-planned system. They are used to understand market interactions, such as bidding behavior and market power issues. In the literature of storage, market models are also used to understand different impacts of the regulatory environment on the value of storage [77].

Evaluating the role of storage with production cost models, is a logical first step beyond the price-taking approach. Instead of assuming prices as given, the models compute the optimal dispatch and unit commitment given the availability of storage. These models can be very complex, representing in detail the different units in a given system, and can also incorporate the stochastic nature of some processes – such as the unpredictability of intermittent renewables. There is a trade-off between the level of detail that the models can incorporate on the number of units and operational decisions constraints and the time-frame that can be computed. Researchers need to make assumptions to solve these models, for example by reducing the number of units modeled on the system [131], the time-scale or the time horizon (for example by selecting only a few representative weeks) [35], the treatment of uncertainty [41], and/or applying new methods to reduce the dimensions in the model [198]. Some of these approximations will be less appropriate for examining the value of storage, for instance, losing the chronology of load by aggregating time blocks will generally make the evaluation of storage problematic. Since the value of storage depends highly on events that might be particularly challenging for the system operation, aggregation of time and averaging of conditions could be detrimental to uncovering the value of storage.

A drawback of studying the role of storage with production cost models, is that the investment decisions are not included. In order to understand the value of storage, particularly at increasing penetrations of renewable energy, understanding its impact on investment in different technologies is critical. Therefore, a few studies have started to use capacity expansion models, including potential changes in the fleet [180, 2].

As a result of the different types of models, storage studies report values that include reduced variable costs or reduced variable costs and investment expenditures. Models looking only at production costs will not be able to provide figures for the investment costs. However, it is worth mentioning that some models with fine detail on the operation of the system in the second to minute time-scale, might reproduce better the very short-term dynamics, or the stochasticity of some processes, needed to capture some of the specific services of storage, such as regulation and voltage support services. Therefore, the choice of model highly depends on the type of storage service under investigation.

To discuss specific studies I use the compilation of Zucker et al.[202]. I also complement this compilation by discussing some studies published during the last year.[6] As shown in Figure 3-6, 12 studies were found that quantified the value of storage[7], half of which studied Germany's power grid[8] [82, 2, 1, 181, 189], two studies for the UK [180, 16] and the rest for Ireland [32] and France [199] systems in Europe and WECC [37] and PJM [175] markets in the US. Because the value of storage in these studies was assessed with varied methodologies and including different storage services, the results are presented decomposing the value in generation, transmission and distribution. Within generation, 3 studies included the investment decision which is shown in Figure 3-6 as generation total, or when disaggregated in the original studies, by showing the split between capital expenditures (CAPEX) and variable costs.

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[6] Zucker et al. included studies until May 2013.

[7] Only studies that quantified the value in $ per kW were included.

[8] Due to large-scale deployment of renewables in Germany, there has been increased interest in storage technologies in the country to alleviate some areas from potential transmission bottlenecks. In particular, the German Energy Agency commissioned several studies on this issue to assess storage value for the grid.

The majority of studies looked at reduced costs of generation in terms of variable costs (GEN VAR in the graph); as shown in 3-6 there is a wide range of results. The largest values were found for the UK system, by Strbac et al., who reported values between €180-520 /kW. This study reports significantly higher values compared to all other studies. Black et al. found values between €20-180 /kW for the same system. Connolly et al. report a value between €5-190 /kW for Ireland. Denholm et al. analysis of a part of the WECC interconnect in the US, finds a value between €40-90 /kW. Values of less than €50 /kW were found for all the other systems, including Germany.

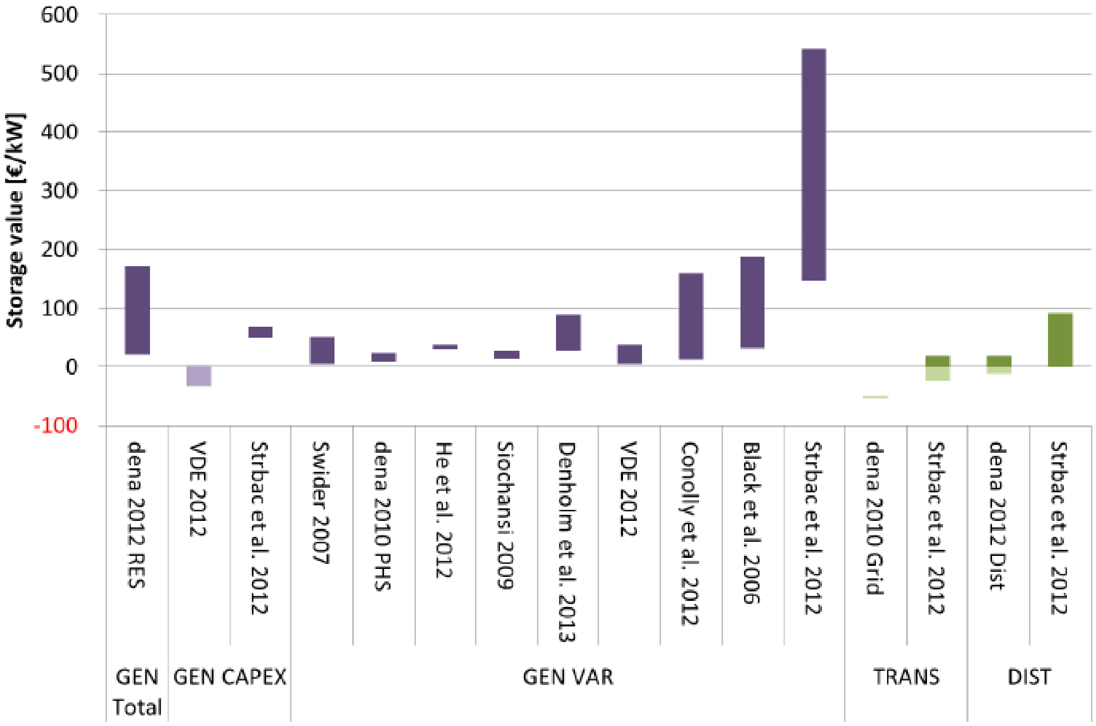

Figure 3-2: Value of Storage – System studies
Source: Assesing Storage Value in Electricity Markets, Zucker et al. [202]

Only 3 studies computed the value of storage derived from capital expenses, two of them studying the German system and one the UK's. In the case of the German system, the studies differ on the value of storage derived from capital expenses. One study found values between €10-180 /kW (Gen Total in the graph) [2]; while the other study found additional costs on capital expenditures instead of savings [189]. The first study, conducted by the German Energy Agency (DENA), explored a potential deployment of 89% of renewables, while the second study conducted by a consulting firm VDE analyzed a range between 40 and 80%; the studies also differ in the models used.[9] In the case of the UK study, a €62 on average could be attributed to savings in capital expenses, that result from reduced investment in open cycle and combined cycle gas turbines, since storage replaced capacity to provide reserves in that system.

The value derived from reduced costs in the transmission and distribution networks was found to be small for the two studies that reported this service (less than €5 /kW), and it was negative in one study, which found increased costs for transmission to reach a PHS site in southern Germany. The benefits for transmission and distribution services were the highest in Strbac et al., reaching up to €95 /kW. The low values found by the European studies for transmission and distribution contrast with potentially high values in the US reported by an EPRI study that used price-taking approaches. According to EPRI, the highest value of storage could come from deferrals in transmission investments [62].[10]

Comparing the price-taker approach and the system-level approach we can see that most values for the first one are below €100/kW and were mostly derived from studies focused on arbitrage services. Results were higher when reserves value was added; however, they were all below €140. An interesting observation is that most production cost models also found values below €100, when assessing low-levels of renewables; in general confirming low values of storage under low levels of renewables penetration. Studies that considered the investment decision found higher values, as well as studies expanding the system boundaries to consider other energy demands in the system [32]. One study that considered the whole chain of generation, transmission and

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[9] The first study's main focus was to explore large-scale penetration of renewables and within this objective performed a sensitivity on storage availability, reporting values for this technology. The second study used a plant and storage dispatch model coupled with a power flow model. The details of the specification of models are in German, and therefore I will not discuss further details on the differences between the modeling approaches.

[10] It should be noted, as discussed by Zucker et al., that the regulatory framework in the US and Europe is quite different and could impact the value of this service. For example, in Europe there is no nodal pricing which is necessary for capturing this service value, and deferrals in the transmission network expansion are not likely to be allowed by regulators according to Zucker et al. [202].

distribution, and very large-scale penetration of renewables found the highest values [180].

When evaluating the value of storage across studies, several factors should be considered. First, countries have different composition of the generation fleet and different network topologies, which directly impact the value of storage. For example, systems that have more built-in flexibility due to the availability of more hydro or fast-ramping natural gas units, would be able to cope with intermittency issues better than systems that have large amounts of inflexible generation, such as the ones dominated by nuclear units. In the same fashion, systems with well-meshed networks or that have long-range interconnections will be more flexible, and probably benefit less from storage unlike systems with transmission constraints where storage could help alleviate intermittency and interconnection issues.

Secondly, assumptions made about the penetration of renewable energy in the different studies vary widely, with studies assuming between 16%(US-WECC, [37]) and 89% (Germany, [2]) of intermittent renewables in the grid. For example, by comparing Black et al. and Strbac et al. values for the same service in the same region we see very different values, but the first study analyzed a 20% penetration while the second analyzed very large-scale penetration of wind with scenarios over 80% [16, 180]. Models also differ in the level of detail represented regarding the stochastic nature of renewables.

Thirdly, the studies explored different services with different models – some techniques to estimate the value of storage for generation, transmission and distribution might privilege more one service over the other. Thus, the boundaries set by the analysis, for example looking only at generation, or including transmission and distribution matters.

I next describe in more detail 3 examples of applications to evaluate the value of storage with different model types: a) production cost models, b) capacity expansion models and c) energy system models. My goal in this description of specific studies is to explain some of the modeling decisions that impact the value of storage. I selected a production cost study conducted by NREL, because it focused on eliciting storage value and tested for the addition of different services and market structure, two capacity expansion models that studied the expansion of the UK and the US systems considering a high-level of renewables deployment, and two system level studies focusing on Ireland and the UK that used a planning tool including other energy demands and not only electricity, thus assessing the value of storage expanding the system boundaries.

a) Production cost model

Denholm et al. [37] provide an example of a production cost simulation. In this case, the authors estimate the potential storage demand in Colorado using a commercially available tool (PLEXOS- a unit commitment and dispatch model[11]). They simulate a future deployment of wind and solar in 2020, assuming a total penetration of 16%. In addition to the remuneration of storage for energy, they include 3 ancillary services: contingency, regulation and so-called "flexibility" reserves to consider services as discussed in Ela et al. to allow for flexible capacity [58]. From the thermal capacity available, only a subset of plants was allowed to provide regulating reserves (based on expert criteria and discussion with the system operator regarding current units ramping capacity). A penalty cost was imposed for cycling into the regulation reserves to account for machine degradation.

With this setting, storage is modeled in 3 main classes: only energy provider, only reserves provider, and one that provides both. The first one simulates an existing PHS. The reserves-only case considers a more flexible device (without ramping constraints and no restriction for charging and discharging) that incurs net energy losses when the storage device is providing regulation. The third device is modeled similarly to the second device, except that it does not incur in energy losses while providing regulation.[12] With this method and assumptions, the authors found, in the energy only application, a value of \$10.5 million for 300 MW (\$35/kW/year), half of

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[11] For more information about PLEXOS see: http://energyexemplar.com/software/plexos-desktop-edition/

[12] The assumption is that a storage device providing real energy can provide regulation without additional charging as long as the regulation capacity provided is equal to or less than its current output.

which comes from the difference in fuel costs, and the other half comes from avoided cycling costs. Comparing the production simulation approach and price-taker approach (using model output to estimate prices), the authors report that the value of storage would have been 25% lower than the price-taker approach. In the case of the regulation-only device the savings in the operational costs are higher reporting a total saving of 11 million for a device of 100 MW ($110/kW/year). In the last case, with a device providing both energy and regulation[13], the authors find an annual value of ($145/kW/year). In all cases, additional storage quickly reduces the market value.

In sum, the recent NREL study confirms previous low-value estimates for load-leveling, but greater value for reserves provision. One limitation of this study is that while it conducted sensitivity analysis to the total availability of storage capacity, it held constant other critical parameters such as the total penetration of renewables and the price of natural gas. The renewable energy penetration evaluated was also fairly small, and thus the study does not provide more insights regarding the value of storage at high-penetration of renewables. Also, the model used is a production cost model, and therefore does not consider the impact of storage (or renewables) in investment planning.

b) Capacity expansion model

Strabac et al.'s study for the UK provides a comprehensive analysis of the potential storage need in the UK in order to meet the national goal to reduce 80% of emissions by 2050 [180]. As mentioned in the comparative analysis of studies, this research presented the highest value for storage technologies. It also implemented a broader assessment, considering all activities of the value chain of electricity generation, transmission and distribution with a long-term perspective to evaluate 2050 emissions reductions targets. I describe in more detail the model used in this study, to exemplify the state of the art of modeling techniques on capacity expansion models looking at the storage question.

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[13] An optimal performing device would have the capacity to switch to the service that reports the highest value.

The Dynamic System Investment Model (DSIM), developed by Imperial College of London, was used in this study. The model minimizes total system costs considering investments and operational decisions, deployment of renewables, transmission and distribution networks expansion, and storage. It runs for a full year considering chronological data for demand and renewable generation, and annualized investment costs. Constraints include power balance, operating reserves, generation min/max, annual load factors, demand response, power flows, distribution networks peak-load, security, and emissions constraints. Generators are grouped by technology type and assigned a generic unit size of 500 MW to reduce the dimensionality of the problem. Storage technologies are characterized using key features, but no specific technologies or market structure is assumed in the modeling (it basically assumes the system is centrally planned). The model has 4 regions for the UK, with interconnections to Ireland and Europe. The authors explore large-scale deployment of renewables, accompanied with a fast deployment of electrification for heating and cooling appliances, consistent with what the authors called a "grassroots" storyline, where a fast movement to clean technologies is socially supported. Electrification under this storyline is critical to reach emissions reductions goals and the technologies chosen are renewable energy technologies, mainly wind. In addition, an important constraint imposed on the model is what the authors called "self-secure" requirement, which translates into two important policy objectives for the UK: a) self-sufficient requirement in terms of capacity and b) energy-neutral requirement, meaning that net annual energy import/export ratio is zero.[14]

The conclusions of the study show that at increasing levels of penetration and electrification the value of storage increases, going from £0.12 billion in 2020, to £2 billion in 2030 and over £10 billion in 2050. This increasing value of storage comes as a result of the assumptions of having more renewables penetrate at very large-scale, at the same time that other energy uses increase electricity demand. The total requirement of storage also increased over time, 15 GW were found optimal for 2030,

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[14] They allow the model to import power from and export to Europe and Ireland "as long as the annual net balance is zero" so they can export power in condition of high winds and low demand and import energy from Europe when economically efficient, such as low-wind conditions.

and 25 GW for 2050.[15] It is possible that island condition of the UK under the "self-secure" assumptions also increased the value of storage in this study.

Another state of the art capacity expansion model with the capability of looking at very high penetration of renewables is the Regional Energy Deployment System (ReEDS) model developed by NREL. This model was used in the *Renewable Electricity Futures Study* that examines scenarios of large-scale renewables deployment in the US [76]. While this study does not focus on exploring the value of storage, it does consider the investment decision in storage technologies exploring very high levels of penetration of renewables, providing the first comprehensive study in the US looking at penetrations of renewables up to 90%. In addition to ReEDs, ABB's GridView model was used in this study, which is a security constraint unit-commitment and economic dispatch model.[16] Following, I describe some details of the modeling of ReEDs, the capacity expansion model in this study, with emphasis on storage technologies.

ReEDs is a generation and transmission capacity expansion model, with a very detailed regionalization of the US (365 regions, with 134 balancing areas, and 21 reserve sharing groups) and a detailed statistical analysis of wind and solar resources. It uses linear programming to minimize system costs including constraints for balance within regions, regional resource supply, planning and operating reserve requirements, local and federal policies, and transmission constraints. The ReEDs model includes PHS, CAES, and batteries as storage technologies. On the generation side the model includes a wide array of renewable technologies: wind (onshore, fixed bottom offshore), concentrated solar power (with and without thermal storage), solar photovoltaic (utility-scale and rooftop), biomass (alone and coal co-fired), geothermal, hydropower. It also includes 3 options for fossil generation: pulverized coal,

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[15] Total installed generation capacity in 2050 is roughly 270 GW, with around 150 coming from fossil fuel energy with and without CCS and the rest from renewables.

[16] As noted by NREL in the RE Futures study, ReEDS handled "limited aspects of adequacy by using coarse time scales slices layered with statistical calculations", considering a capacity value, forecast errors and curtailment for renewables. ABB GridView was used to supplement the ReEDs model both in the dispatch at the hourly time-scale and with a DC load flow assessment. Some variables reported important differences after the solution of GridView, for example curtailment levels (ReEDs estimated by 2050 curtailment of 2, 4 and 7% in the 30, 60 and 90% renewable penetration scenarios, respectively while GridView model results find twice as much curtailment).

natural gas combined cycle and open turbines. It does not include nuclear[17], carbon capture and storage technologies, enhanced geothermal systems, ocean, or offshore wind floating platform technologies. While the model does not consider distribution networks, it does account for distributed solar capacity using an external model (SolarDS) which exogenously computes and provides ReEDs with solar PV rooftop deployment. The cost-optimization routine is applied for each 2-year investment period up to 2050. The economic dispatch in the model uses 17 time slices (four time slices for each season representing morning, afternoon, evening and nighttime, with an additional summer-peak time slice). Statistical information is used to estimate capacity value, forecast error reserves, and curtailment (considering correlation of output and demand in different regions) [76].

Technology costs and performance projections from Black & Veatch were used in the model, as well as studies regarding total availability of storage capacity for PHS and CAES. In the case of PHS, maximum potential of 35 GW was considered, based on proposed plants in the US as provided by FERC. A lower cost of \$1500/kW was assigned for the development of the first 10 GW, and a higher cost of \$2000/kW for the rest. A supply curve was constructed with these two points. Studies assessing technical potential of PHS in the US estimate up to 1000 GW of unexploited sites, but NREL limited the study to projects where cost data was available. Engineering estimates to develop other resources, available to NREL, were as high as \$5595/kW, and were not considered. The study highlights the need to better understand costs of new PSH, since only 4% of total potential could be matched to specific costs. In the case of CAES, construction in salt domes was priced at \$900/kW, bedded salt at \$1050/kW and porous rock at \$1200/kW, assuming a total potential of 23 GW in salt domes, 37 GW in bedded salts, and 62 GW in porous rock. No technology driven cost improvements were assumed in the modeling. For both technologies, PHS and CAES, NREL used the specific location where these resources could be available in the US, since both technologies are site constrained.

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[17] By not including nuclear or other non-flexible generation, the value of storage could decrease as compared to the value in a system that does consider existent nuclear facilities or that allows building them.

According to this study, by 2050, storage capacity requirements were 28 GW in the baseline scenario, 31 GW in 30%, 74 GW in the 60% and 142 GW in the 90% scenario[18]. Based on the cost assumptions, new storage installations resulted in CAES plants, with small amounts of new PSH and some utility scale batteries in the very high renewable penetration scenario. Deployment of storage was limited by the cost assumptions imposed as constraints, as well as location limitations and efficiency losses. As highlighted by the authors the study "did not attempt to fully evaluate, nor did it comprehensively compete, different storage technologies" and did not disaggregate various markets for storage technologies, in particular no assessment of frequency regulation was conducted. Distributed systems were also not included in the assessment, and thus storage services for these networks were not included. As a result, "ReEDS will undervalue many opportunities for storage and likely understate its adoption into the marketplace". As clearly stated in NREL's study, the results from the RE Futures regarding storage were limited due to data constraints. The results suggest that CAES will be deployed instead of PHS; however, since PHS is a commercial technology and CAES has some risks for deployment (only two commercial installations currently operate in the world) the opposite could have been expected.[19] Future assessments of PHS and CAES costs would prove useful for a revision of storage technologies in future studies. Since the objective of this study was not to investigate the value of storage, underlining values of storage were not reported.

The reason I selected NREL's study, despite the fact that it was not designed to provide values of storage, is that it presents, to my knowledge, the most comprehensive modeling of renewables at very large-scale in the US. It has the capacity of analyzing both transmission and storage in supporting renewables integration. As explained, the modeling of storage was highly constrained by the cost specifications (and potentials) of PHS, CAES and batteries, which reflect current cost estimates for

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[18] Total system capacity for each of the scenarios ranged from roughly 1000 GW to 1400 GW of generation; wind generation dominates the renewable scenarios with some participation of solar, geothermal and hydro.

[19] It seems that this result is entirely driven by the cost assumptions and potential specified in the model.

these technologies. As the system evolves, and if new policies to deploy renewables take place, new technologies could become available if there is demand for them. As discussed in the last section of this chapter, developments to reduce the costs of technologies and remove site limitations are currently under investigation.

An interesting finding in comparing these two studies is that at very large penetrations of renewables both found a role for storage technologies. While the study done for the UK was not bound on specific technology costs, the value of storage does exhibit decreasing returns to scale and therefore there is a maximum level of storage that results economic in the simulation. For 2050, at high levels of penetration of renewable energy, Strabac et al. found that storage contributes 9.2% of total installed capacity in the system. NREL's study found a similar value of 10.2% storage as percent of total installed capacity, in the scenario with very high level of renewables penetration. This suggests that at very large-scale penetration, even at high technology costs, storage capacity could assist operations in a future world with very large-scale penetration of renewables, specially if demand response is limited.[20]

Finally, these studies do not perform a full reliability or system adequacy assessment. System voltage of real and reactive power was not addressed, nor frequency control. As explained by NREL, "system adequacy will require a detailed simulation to measure the loss of load probability with the correct probability density functions of various power systems variables". Developing these assessments for long-term renewable integration analysis is an area of research in the literature of power system models, and is very challenging given the very short-time scales that would need to be covered.

c) Energy systems model

To elicit the value of storage, two studies applied an energy systems tool: EnergyPLAN, an input-output model for energy systems analysis [32, 52]. In addition to

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[20] NREL's study consider limited demand response options that grow over time from 1-8% in 2010 to 16-24% in 2050. Strabac et al. conducted a sensitivity analysis on the value of storage to demand response availability finding that the value of storage is in fact highly sensitive to the possibility of flexible load.

the demand of electricity, the model includes the demands for cooling, heating, and fuel for industry and transport, encompassing interactions in the energy sector. It also includes detailed data on the hourly profile of energy demands and resources. The model includes four representations of storage: heat storage, hydrogen storage, electricity storage and CAES. Costs of fuels and technologies are inputs to the model; outputs include an energy balance and fuel consumption and emissions based on heuristic "strategies" provided in the model. The outputs are annual energy balances, fuel consumption and CO_2 emissions. The model total computation time is less than 10 seconds, and makes a number of simplifications in order to do so. For example, each sector is an aggregate of all units. Therefore, there is no distinction between technologies in thermal generation (coal, oil and gas technologies are all grouped), but there is a separate sector for renewable electricity. Transmission is simplified to total electricity trade to and from the region in the model, and is modeled as a total surplus or deficit.

The studies analyzed Ireland and the UK systems . For the UK, Edmonds et al. found that 6 GW of storage would be needed to assist UK's emissions reduction goal, much lower than Stract et al.'s estimate for the same system and emissions reduction goal using more detailed models. For Ireland, Connolly et al. found that, even when accounting for a \$50/ton CO_2 price, PHS will not be economical at 6% interest rates, and other alternatives could be used in similar ways such as electric vehicles, electrification of heat, and thermal storage. The two alternatives to PHS investigated in that study were domestic heat pumps and a district heating network with CHP. Heat pumps were found to be more economical than storage, and with less associated risks (since the value of storage resulted in their analysis as highly sensitive to fuel prices, annual wind productions, and interest rates). However, the two alternatives did not allow for more wind integration, as did PHS. Therefore, the authors concluded that it is possible that adding other socio-economic benefits derived from electricity storage could help justify its cost.

While the model used in these studies highly simplifies the interactions within the power system, the studies do provide a valuable insight in that the value of storage, and competing options, could lie outside the electric sector and therefore other socioeconomic benefits could contribute to the analysis.

3.1.3 Other methods

a) Net-energy analysis

Barnhart et al. [10] use net energy analysis and information from total energy used provided by Life-Cycle-Assessment (LCA) to evaluate storage value. Based on comparing the total energy balance used in the production of a specific technology with the total additional energy that the technology allows to use by preventing wind and solar curtailment, the authors derive conclusions on the "socially desirable" technologies. The authors developed a high-level method and apply it to assess five different types of batteries, PHS and CAES used with wind and solar technologies. This method constructs a new metric, Energy Stored on Investment (ESOI), that complements the commonly use metric in net energy analysis of Energy Return on Energy Investment (EROI), which is the ratio of energy delivered to the lifecycle costs of energy production. ESOI is the ratio of electrical energy stored over the lifetime of a storage device to the amount of embodied electrical energy required to build the device. By using a simplified model of one technology dispatch, assuming that storage operates optimally and that the precise storage capacity required is built, they evaluate different levels of curtailment and resulting use of storage technologies for wind and solar. They conclude that, from a net-energy perspective, solar PV could be complemented by all of the storage technologies evaluated whereas avoiding wind curtailment would only justify options such as PHS and CAES. The limitation of this study is that it only focuses on the energy balance, without considering the economics behind the use of storage technologies in systems. In practice, net energy gains (reduced curtailment) is only one of the services that storage can provide, and other important benefits such as the provision of flexibility in the system under difficult operational situations can be more important even when coming at some energy penalty. Nevertheless, the study provides important information regarding the LCA energy penalties and the different relationships with wind and solar applications of these technologies, an issue that no other study incorporated in the analysis.

b) Screening methodologies

Screening methodologies are simplified methods that aim to provide a first order approximation, in a quick and inexpensive fashion, to a problem and "screen" cases where further investigation is necessary. A study by Balza et al. developed by the Interamerican Development Bank looked at the value of storage for specific cases in Latin America, using screening methodologies [7]. Because this is, to my knowledge, the only study available assessing the value of storage in the context of renewable penetration for Mexico, I describe the method in some detail. The authors studied three case studies: the island system of Barbados, an off-grid small system in Colombia, and Mexico's large interconnect.

A first simplification in Balza et al. study is that of data, which is extremely simplified and aggregated. For example, only one day load-profile from Jamaica is used to study different power systems, scaled to match peak demand in different regions. Only data for one day is considered, and it is then multiplied by 365 days times the years of lifetime of a generic storage technology. Generators are highly aggregated in conventional and renewable energy. Emissions are assed only as an average of all other technologies.

The authors evaluate two services: back-up power and energy management services. The screening method consists of 3 main equations that estimate a) benefits of back-up capacity provided by storage, b) the levelized cost of electricity storage, and c) the net benefit per day for storage technology. To estimate the benefits derived to provide back-up capacity, the authors assumed that without storage renewables will be limited to a 15% penetration; the benefit of storage results then from costs savings resulting for renewable energy supply above the 15% percent. Five parameters enter the analysis in this equation: the total amount of renewables on the grid each hour, the level of demand minus 15% of renewables, the long-run marginal cost of renewable energy capacity, the avoided costs of conventional generation displaced by renewable energy which includes average variable and operation and maintenance costs from displaced generation, and finally the life-time of the storage facility. In this way, storage technologies generate benefits for each kWh of renewable energy generated above 15% of demand if the long-run marginal cost of renewable energy capacity is lower than the avoided cost of conventional generation. With these assumptions, the authors derived "breakeven cost curves" for the cost of capital of storage as avoided costs from conventional generation.

To evaluate energy management services, a levelized cost of electricity storage (LCOES) and the net benefit per day is used. The LCOES is estimated only with 3 parameters: the cost of energy stored, adjusted by the roundtrip efficiency, the fixed costs of storage and the balance of storage cost. In this way a break-even cost curve can be estimated for different technologies; storage is considered not economical if its fixed costs are above the cost curve. The net benefit of renewable integration is computed as the sum for the 24 hours of the day of the total supply times the difference between the long-run marginal cost (LRMC) of renewables (LRMC) and avoided costs in each hour. There is an assumption that a capacity credit the size of the LRMC of conventional generation should be given to storage, assuming storage is a reliably dischargeable at any time. The model selects renewable energy capacity to minimize the cost of meeting daily load, computed as the total cost of the system in the business-as-usual case minus the net benefit of renewables each day.

With this screening methodology the authors found that the small isolated system of Colombia and the island State of Barbados, could increase from 6 to 49 percent and from 11 to 50 percent, but in Mexico's system the optimal penetration remains unvaried at 7%. Thus, they conclude that storage could increase the share of renewables in small isolated systems and island states, but not in large-scale systems such as Mexico's. The authors conclude that "for renewable energy with electrical storage to be economically viable in large inter-connected countries, the cost of conventional peak generation would have to rise to about $0.17 US dollars per kWh".

Although the idea of providing screening methods is interesting, the study has severe limitations to assess the value of storage. First, the time-scales used and aggregation of a 24 hour-profile applied to the whole year for 20 years is quite limiting since it is not representative of the operation of a unit. By arbitrarily picking a level of penetration of renewables of 15%, the real optimal level of storage penetration without storage might be misrepresented. Also, subtracting 15% of the load without a time profile for wind and solar, the added variability in the system is completely disregarded, which is one of the main reasons that storage could potentially be more valuable as an additional source of flexibility for systems operations. In practice, the procedure fails to capture the real concerns that are raised with increased renewables. Furthermore, the authors aim to provide an estimate for Latin America by extrapolating the 3 cases with these assumptions, concluding that since storage was not viable in Mexico's interconnect, it was "not likely that combining renewable energy with storage will be economically viable in Latin America and the Caribbean large interconnected grids in the newer future" and therefore did not look to any other large interconnects. The diversity in power systems in the region call for more robust analysis and for more qualified conclusions of results derived from screening methods.

3.1.4 Synthesis of current modeling approaches to estimate the value of storage

As summary of my literature review of current studies, I schematically represent the different methods used to estimate the value of storage in Figure 3-6. The majority of studies available today belong to the price-taker approach, but more studies have started using systems approaches, particularly using production cost methods. Two studies were identified that used capacity expansion models and another two used simplified energy systems analysis. Finally, two approaches that do not use prices nor compute operations of the system were presented. The net-energy analysis evaluates the value of storage in terms of a life-cycle assessment of energy use, focusing on reducing renewable energy curtailment, but is limited to understand the economic value of storage. Screening methods were also discussed in this chapter, along with some of their limitations.

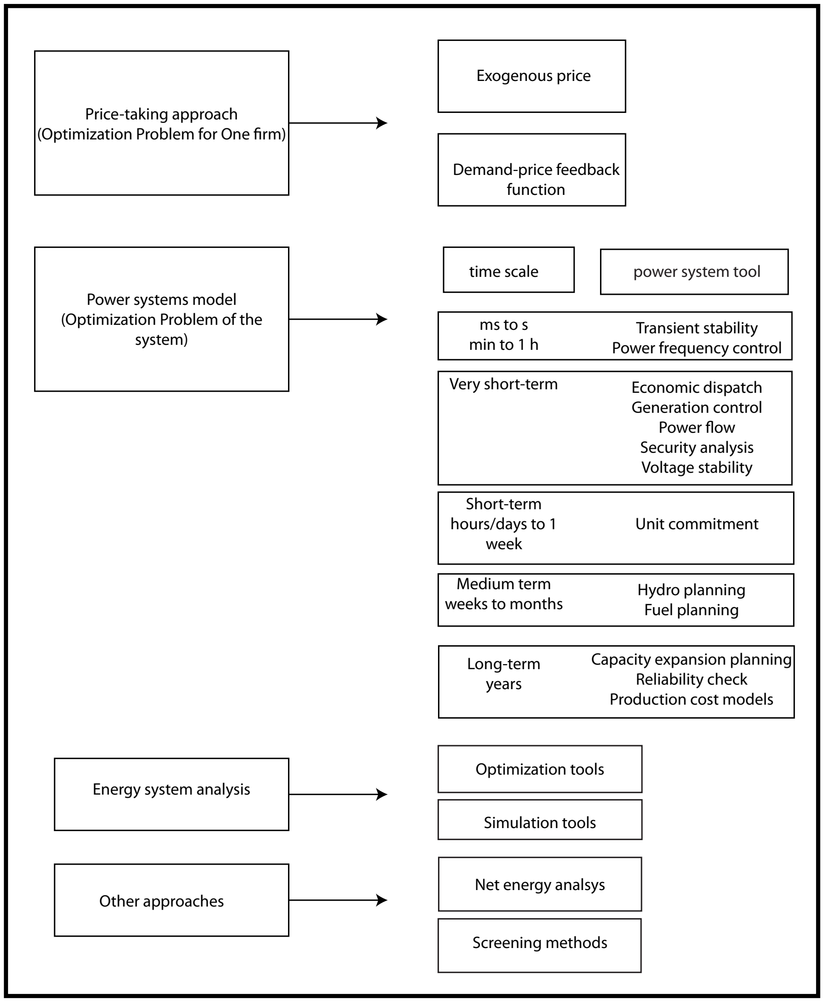

Figure 3-3: Synthesis of Modeling Approaches to Estimate the Value of Storage
Source: Author.

3.2 Storage technologies in climate change policy evaluation models

After the review of the value of storage currently found in the literature, I now turn to the discussion of methods used for long-term systems planning and climate policy evaluation, regarding to the incorporation of storage technologies. As I will briefly discuss, these models have not, to the present moment, incorporated electricity storage technologies and, for the most part, these models have also not included the analysis of the costs of transmission and distribution networks. Reliability, security and adequacy of electric systems is highly stylized in the models, if at all considered. Despite this, some of these models heavily rely on very large-scale penetration of renewable energy, finding solutions with more than 70% of the electricity mix coming from intermittent sources. In contrast, some models have almost no penetration of renewable energy even at very high carbon prices. This creates a problem for policy advice, since the real potential penetration of renewable energy is difficult to grasp from these models, which is a result of great interest as we craft climate mitigation policy.

To illustrate this problem, I show the different energy mixes for Mexico in 2050 provided by models participating in the Latin American Modeling Project (LAMP) – these models are representative of the state-of-the-art modeling techniques to evaluate climate policy in the region and in particular Latin American countries, including Mexico.

None of the participating models in LAMP – ADAGE, EPPA, POLES[21], TIAM-ECN, E3MG, IMAGE, and GCAM – represented storage technologies nor transmission and distribution costs explicitly [152, 136, 104, 105, 9, 19, 197]. However, all of them found that to reach deep mitigation in the economy (for example reaching the 50% economy-wide emissions reduction goal of Mexico's Climate Change Energy Strategy), a full decarbonization of the power sector was needed. Because these types

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[21] POLES model does consider a hydrogen technology, but does not model the services this technology provides for the management of the electric system.

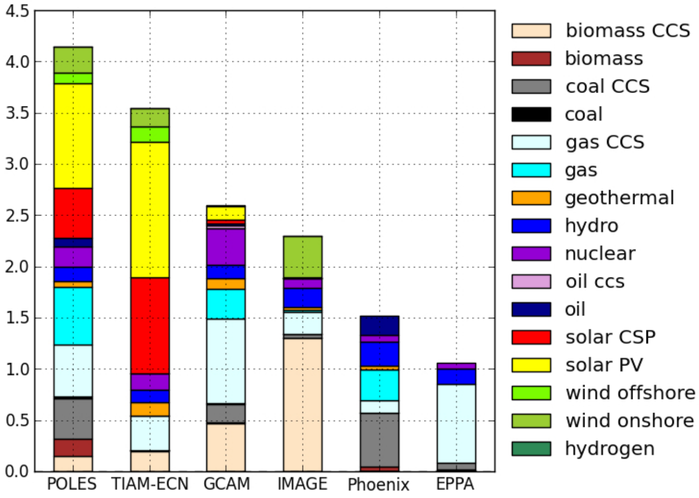

Figure 3-4: Mexico's electricity mix in 2050
under a 50% economy-wide emissions reduction goal
Source: Author with data from LAMP/ CLIMACAP project [144]

of models do not explicitly represent storage technologies, the value of storage has not been investigated using these methods. In this dissertation, I argue that investigating the value of storage, and other supporting infrastructure, to reach such ambitions mitigation scenarios and drastic changes in the electric sector would be a valuable contribution to the literature.

3.3 Storage technologies: review of costs and potential development

The goal of this research is to estimate the value of storage in terms of the willingness to pay for the services that these technologies provide. My study is designed to be technology neutral in order to fully explore the demand side in an evolving environment, where economic growth drives increases in electricity demand at the time that more renewables are introduced to the grid. In order to do so, I do not constrain the model to any specific storage technology cost specifications. Instead, I try to answer the question of what is the cost target to provide the services needed in the grid.

However, in order to provide some context on the state-of-the-art of technologies and future technological perspectives, I briefly describe the main technologies available, and potential technological pathways. The objective is two-fold, present some technological options and characterize some of the performance parameters, which are needed to model storage. The sensitivity to different parameters is presented in Chapter 6, where more explanations are given on the role of specific parameters.

This section does not pretend to provide an extensive survey, and even less an evaluation of each technology. For this I refer to the extensive literature in the matter, including the recent report of the International Energy Agency on the Technology Roadmap for Storage, the IPCC Special Report on Renewable Energy Technologies (with a description of storage services coupled with each type of renewable technology), as well as EPRI and the peer-reviewed literature[94, 91, 63, 29, 39, 182].

3.3.1 Classification of storage technologies

Electricity storage technologies can be classified by the type of energy they need to convert electricity to in order to store it– mechanical, chemical, electrochemical, electric field, magnetic or thermal. Pumped hydro, compressed air, and flywheels use mechanical energy; hydrogen converts energy into chemical form; batteries use electrochemical processes; double layer capacitors use electric fields; superconducting coils use magnetic energy; and molten salts store energy in thermal form (Figure 3-8).

As mentioned in the introductory chapter, at present pumped hydro storage (PHS) outweighs all other technologies in terms of installed capacity, followed by compressed air energy storage (CAES) and, in third place, on a much lower scale, different kinds of batteries. However, future scenarios of high penetration of renewable energy could demand services provided by a combination of different storage technologies. While PHS and CAES provide services to manage energy in long-periods of hours, days or even seasonal variations; batteries, hydrogen and capacitors could assist regulation and power quality control in very short-term periods of seconds and minutes due to their very fast response times. Hydrogen and thermal storage could also provide substitutions for mechanical options if economical, with the advantage of being more

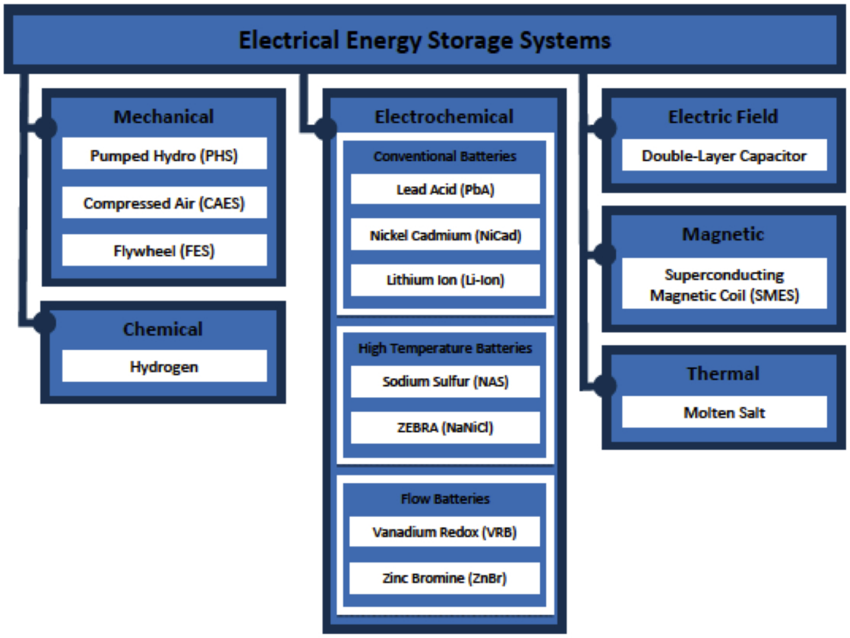

Figure 3-5: Electrical Energy Storage Systems
Source: Carnegie et al, *Utility Scale Energy Storage Systems*, p. 22 [23]

flexible in terms of location than PHS and CAES, which as of today are dependent on specific characteristics of the sites where they can be located in an economical way.

Two important characteristics of storage technologies make different applications more suited for some services: system power rating and duration of discharge time at rated power. The economic value of storage is highly dependent on both the total discharge capacity (in MW) and the energy storage capacity (in MWh). EPRI provides an illustrative comparison of current available technologies positioned considering their rated power against total storage capacity (see Figure 3-6). For bulk power management, CAES and PHS are the two technologies currently available identified by EPRI. For transmission and distribution grid support and load shifting, an array of different batteries, flywheels, super capacitors and superconductor magnetic energy storage applications could be used. For uninterruptible power supply (UPS) and power quality applications, high-energy supercapacitors could also play a role, in addition to batteries, flywheels, and supercapacitors. Because of the variety of services that the grid could require, there is no universal optimal size of storage, instead technology choice depends highly on the application and specific market environment where the service is provided.

PHS and CAES provide higher power rates in the order of hundreds of MW, and can respond in the hour time frame, while other technologies, for example high-energy super capacitors, could respond in minutes, but provide much lower power rate below 100 kW. High-power supercapacitors and high-power flywheels could provide power in seconds to a rated power of up to 1 MW, but typically are much smaller.

It should be noted, however, that fluctuations coming with renewables could result in operational conditions that require response in seconds to inject power for short periods of time, while other technologies come online for example, and in these cases there could be a market niche for short-term duration storage options. The operational characteristics of storage technologies are fundamentally different of that of power generating units, in that storage provides a two-way power flow. This characteristic could allow both the absorption of energy, for example when wind or solar energy could be produced in excess of demand, or injecting power in critical moments. In this regard, storage could provide unique solutions, for example to deal with curtailment issues.

Many other technical characteristics are important to assess storage solutions, among the most important are: efficiency, total cycles, minimum and maximum charge and discharge rates, total economic life, specific materials requirements, and of course total costs. The development status of technologies is also an important consideration, with PHS and CAES – the latter to a much less extent– being a mature technology and all other technologies transitioning from research and development stage to demonstration projects to commercial products. Figure 3-7 provides EPRI's summary evaluation of the costs and main features of currently available storage options.

While the EPRI report provides a review of the state-of-the-art on technologies available today and those with potential in the near future (5 years), other technologies could be developed in the long-run. The International Energy Agency's *Technology Roadmap for Energy Storage*[22] presents future prospects of technology

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[22] The IEA series of technology forecasts result from the Grenoble meeting where member countries

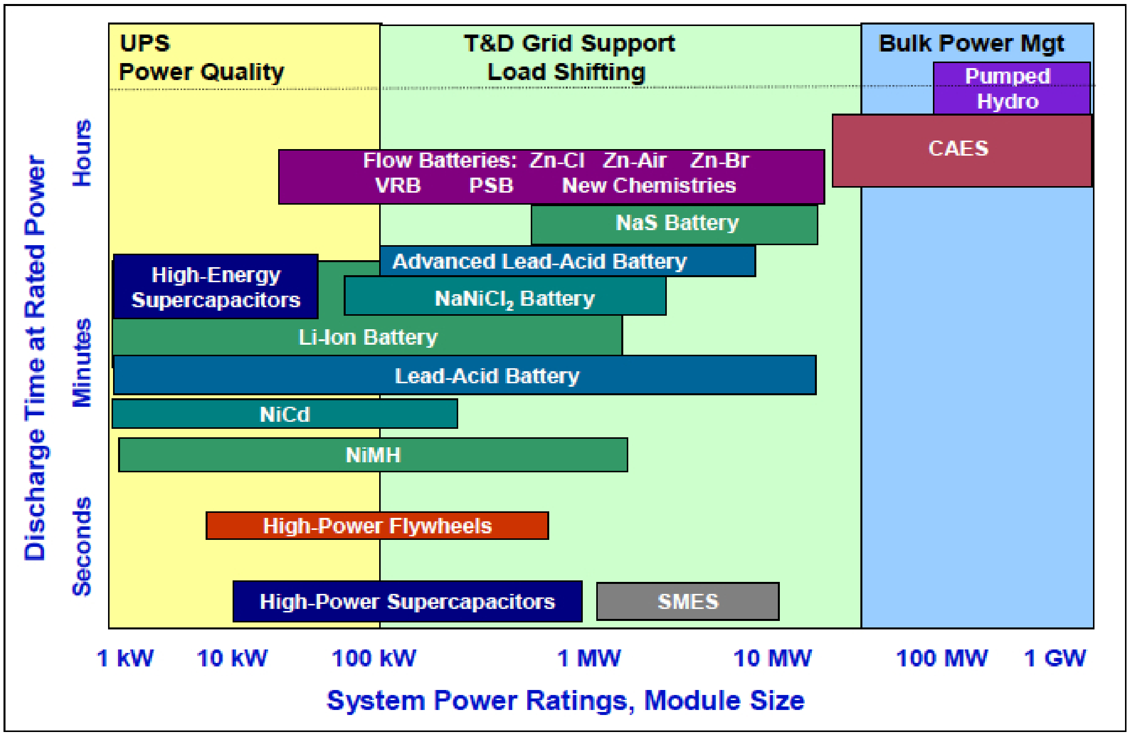

Figure 3-6: Positioning of Energy Storage Technologies
Source: Electric Power Research Institute,*Electricity Energy Storage Technology Options*, p.xiii, [63]

development up to 2050 [94]. A synthesis of the technology lifecycle curve identified by IEA, shows the maturity of different technology options, both for electric storage and for thermal storage (see Figure 3-8). As shown in the figure, in addition to the technologies surveyed in EPRI report, the IEA discusses potential developments in synthetic natural gas, hydrogen, and adiabatic CAES, all of them still in early stage of development.

In addition to classifying technologies in terms of energy type, and/or the specific applications they provide to the grid, it is possible to think about storage options alongside specific renewable energy applications. PHS, CAES and hydrogen have been proposed to pair with wind-farms, see for example [39, 13, 113], where many applications for solar energy are looking into thermal storage options such as molten-salts. The IPCC discusses storage technologies and their applications to specific renewable energy technologies in its recent Special Report on Renewable Energy [50].

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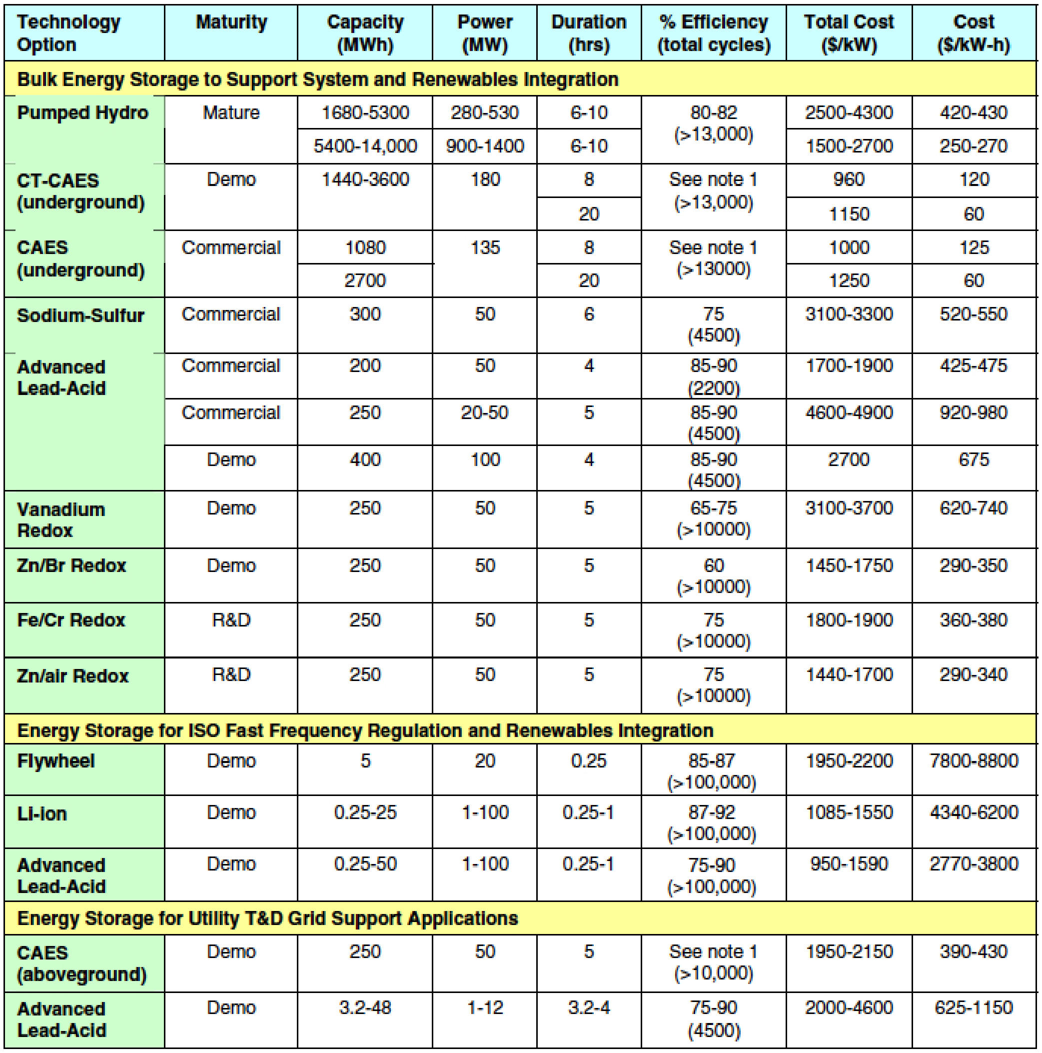
agree to evaluate energy technology solutions to the climate issue.



Technology Option	**Maturity**	**Capacity (MWh)**	**Power (MW)**	**Duration (hrs)**	**% Efficiency (total cycles)**	**Total Cost ($/kW)**	**Cost ($/kW-h)**
Bulk Energy Storage to Support System and Renewables Integration							
Pumped Hydro	Mature	1680-5300	280-530	6-10	80-82 (>13,000)	2500-4300	420-430
		5400-14,000	900-1400	6-10		1500-2700	250-270
CT-CAES (underground)	Demo	1440-3600	180	8	See note 1 (>13,000)	960	120
				20		1150	60
CAES (underground)	Commercial	1080	135	8	See note 1 (>13000)	1000	125
		2700		20		1250	60
Sodium-Sulfur	Commercial	300	50	6	75 (4500)	3100-3300	520-550
Advanced Lead-Acid	Commercial	200	50	4	85-90 (2200)	1700-1900	425-475
	Commercial	250	20-50	5	85-90 (4500)	4600-4900	920-980
	Demo	400	100	4	85-90 (4500)	2700	675
Vanadium Redox	Demo	250	50	5	65-75 (>10000)	3100-3700	620-740
Zn/Br Redox	Demo	250	50	5	60 (>10000)	1450-1750	290-350
Fe/Cr Redox	R&D	250	50	5	75 (>10000)	1800-1900	360-380
Zn/air Redox	R&D	250	50	5	75 (>10000)	1440-1700	290-340
Energy Storage for ISO Fast Frequency Regulation and Renewables Integration							
Flywheel	Demo	5	20	0.25	85-87 (>100,000)	1950-2200	7800-8800
Li-ion	Demo	0.25-25	1-100	0.25-1	87-92 (>100,000)	1085-1550	4340-6200
Advanced Lead-Acid	Demo	0.25-50	1-100	0.25-1	75-90 (>100,000)	950-1590	2770-3800
Energy Storage for Utility T&D Grid Support Applications							
CAES (aboveground)	Demo	250	50	5	See note 1 (>10,000)	1950-2150	390-430
Advanced Lead-Acid	Demo	3.2-48	1-12	3.2-4	75-90 (4500)	2000-4600	625-1150

Figure 3-7: Energy Storage System Costs
Source: Electric Power Research Institute, *Electricity Energy Storage Technology Options*, p.xxiii, [63]

Notes from EPRI report to the table:
1. All systems are modular and can be configured in both smaller and larger sizes not represented. Figures are estimated ranges for the total capital installed cost of “current” systems based on 2010 inputs from vendors and system integrators. Included are the costs of power electronics if applicable, and all costs for installation, step-up transformer, and grid interconnection to utility standards. Smart-grid communication and controls are also assumed to be included.
2. For all options, process and project contingency costs are included depending on technical maturity of the system.
3. Pumped hydro: Storage durations can exceed 10 hours. There is very limited new cost data on pumped hydro facilities. Costs vary significantly by site but values presented include project contingencies and substation and interconnection costs.
4. CAES systems: Sizes up to 400 MW to 2000 MW+ are possible, as are underground storage durations of 20 to 30 hours or longer. The incremental cost of an additional 1 hour of storage once the cavern has been developed is 1−5/kW. Data shown is only for the power and storage duration shown. CAES plants may have heat rates near 3850 Btu/kWh; energy ratios can range from 0.68 to 0.75. Estimates include process and project contingency and costs for NO$_x$ (SCR) emission-control technology. A storage cavern with salt geology is assumed; costs for other geologies can vary significantly and are site specific. Costs for siting, permitting, environmental impact studies and geological assessments are not included. Future system costs may be lower once standard, pre-designed systems are available.

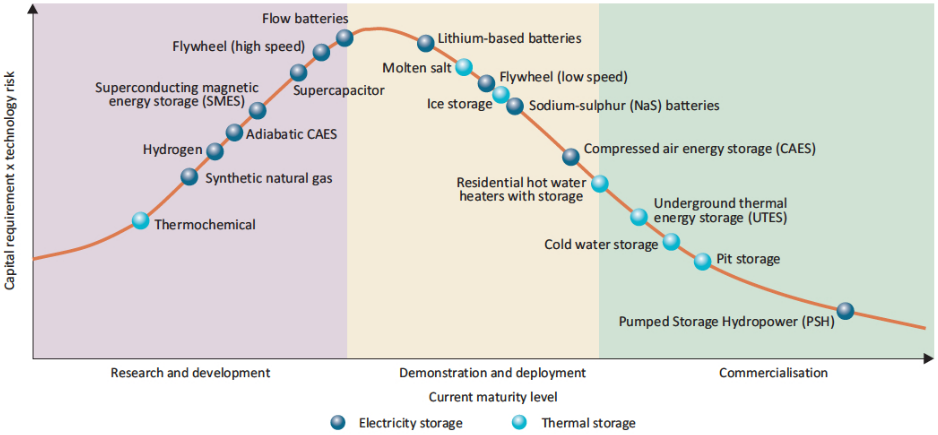


Figure 3-8: Maturity of storage technologies
Source: IEA, *Technology Roadmap. Energy Storage*, p.16. [94]

Finally, another important characteristic of storage technology is their modularity or location specificity. Storage could be located such that it charges from one single source or a variety of sources, and could likewise serve many different loads or be localized. Large storage facilities need to be planned within the transmission system while smaller sizes could be integrated into distribution networks. A single storage unit can provide multiple services, and thus while it is important to capture all of these services it is also important to avoid double counting, since in many cases the technologies would not be able to provide both at the same time. As highlighted by [3], some services could be well categorized in the ancillary services markets, while others are site-specific, and therefore will require an individual process to assess the peculiarities of a specific grid. Next, I briefly describe some of the technologies.

3.3.2 Pumped-hydro

PHS consists of a system of two water reservoirs, one at higher elevation. The system charges during low-price hours to pump water from the lower reservoir to the upper one, and discharges during peak-hours releasing water through an electric turbine into the low reservoir, generating electricity in a similar way to traditional hydropower plants [63]. It is a mature and proven technology, with high efficiency rates. The main constraints for this technology are site-specificity and high capital costs; however it has proven economical in many systems worldwide. As of today it can be practically sized up to to 4000 MW with efficiencies between 76-85% [63].

PHS systems can be closed loop (when the reservoirs are isolated from a flowing body of water), open loop (when the lower reservoir is a river) or seawater pumped storage (where the lower reservoir is the sea).[23]

A potential development for this technology is subsurface PHS [59]; in this variant one or two reservoirs are located underground. Abandoned mines, caverns or man-made reservoirs close to an upper reservoir could be used, creating an "artificial" location where the water can be pumped to and from. The advantage of this technology is that it eliminates the constraint of finding natural sites where two reservoirs are positioned in such a way that PHS is possible. The downside is that the underground excavation and infrastructure building costs are high.

Variable speed turbines for PHS applications are also becoming attractive for renewables integration. Most PHS facilities use a traditional pump turbine equipment which pumps in one direction and is a turbine in the other direction. A limitation of the traditional design is that frequency regulation while in pump mode is not possible and at turbine mode the unit cannot operate at peak efficiency when part-loaded. New variable speed equipment allows the units to do both, supporting stability and frequency regulation. New turbines have higher costs, including more technical controls. Variable speed equipment is already in place in Japan and Europe. [59]

3.3.3 Compressed Air Energy Storage

Lower-cost electricity is used to compress air and store it under pressure in underground caverns, or in pipes or vessels at ground level. Electricity can be produced back by heating the compressed air, expanding it, and directing it through a turbine. This technology is proven and a couple of plants have been operating in Germany and the US for some decades.

One of the problems of this technology is that some heat losses are involved in the process of compression and expansion of the air. During the compression process the

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[23] Only one plant currently exists in Japan.

air heats to very high temperatures, and needs to be cooled again before compression. Using the air to generate electricity requires an expansion process where the air needs to be heated again, in a combustor using natural gas or some other alternative fuel. In order to improve this technology, some developers are trying to capture the heat during the compression stage and thermally store it to be used in the expansion phase. These improvements to the technology are under development, and are commonly refer to as advanced-CAES or adiabatic-CAES[24]. Thermal oil and molten salts are currently under investigation for the thermal storage process. Some developers are proposing also the application of an isothermal process, which is complex since it requires controlling pressure with a constant heat trap and re-injection to maintain a constant thermal curve in the procedure minimizing heat losses [59].

Like PHS, underground CAES storage is site constraint, requiring geologic formations where air can be stored, and that comform to the necessary integrity conditions. The very low density of this process requires big installations, such as deep salt formations (salt caverns allow for storage without pressure losses or oxygen reactions). Depleted natural gas fields are also under investigation to serve as potential CAES sites (possible reactions with HC and other chemicals need to be investigated). Current storage capacities of CAES go up to 400 MW and discharge times between 8 to 26 hours.

3.3.4 Batteries

Batteries use electrochemical processes to transform energy; they differ on the elements use and the capabilities of different materials. In addition to EPRI and EIA, Divya et al provide a good overview of current battery systems for power systems [42]. Batteries specifications vary widely. Common challenges in battery deployments is that power output coming from these devices can be non-linear and life-time varies depending on the application, discharge rates, and the number of deep discharge cycles during use, which can reduce battery life significantly. A brief description of each

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[24] An adiabatic process occurs without the transfer of heat or matter between a system and its surroundings

battery type, as provided by EPRI and Divya et al., follows:

- *Lead-acid Batteries*: Most commercial batteries are manufactured with this chemistry, with low manufacturing costs, using a liquid electrolyte. This is the oldest type of battery with applications in many domains, but with current limited use in power systems, mostly for some applications for transmission and distribution. These batteries are slow to charge, cannot be fully discharged and have limited number of charge/discharge cycles. The lead and sulfuric acid use is highly toxic [63, 42].

- *Sodium-Sulfur*: Rechargeable high-temperature batteries, using metallic sodium, which can offer large-scale storage applications. The battery has high energy density, high efficiency of 75-86%, long cycle life, and materials are inexpensive. The problem with this type of battery is that because of the high temperature needed, and the corrosiveness of sodium polysulfide discharge products, the battery is constraint to specific non-mobile applications. This battery chemistry has an important participation in Japan, with 160 MW, and is present in many systems including the US. Installations of 2 to 10 MW are typical. Japan, Abu Dhabi, and France have projects to expand the use of these batteries in their power systems.

- *Sodium Nickel Chloride*: Made of a positive electrode with nickel oxyhydroxide as the active material and a negative electrode composed of metallic cadmium in sealed and vented designs. Because they can withstand high temperatures, applications for solar installations are of interest. These batteries do not perform well for peak shaving applications, and are mostly focused on providing energy management services [63, 42].

- *Vanadium Redox*: Flow battery type, which means the energy is stored as charged ions in two separate tanks of electrolytes. The electrochemical reaction can be reversed, as with conventional batteries, allowing the system to be repeatedly discharged and recharged. Like other flow batteries, many variations of power capacity and energy storage are possible depending on the size of the electrolyte tanks. They can provide from 2 to 8 hours of power and its lifetime is not strongly affected by cycling as other battery types [63].

- *Zinc-Bromine*: Also a redox flow battery, in a early stage of development. It has potential to reach efficiencies of 65 or 70% and longer cycle-life, and densities vary substantially between providers.
- *Fe/Cr and Zn/Air*: The lower cost of these systems have made them worth evaluating for grid storage solutions; however, they are still under development.
- *Lithium-Ion*: Batteries used in electrodomestic and portable consumer electronics, which have a big market in that domain providing 10 to 12 GWh of storage per year. Three types are available commercially based on cobalt, manganese and phosphate designs. Due to its high density, this battery type is attractive for vehicle applications and sites with space constraints. They can provide regulation services and be sped to run in minutes timeframe.

3.3.5 Hydrogen

Electricity is converted into hydrogen by electrolysis, stored, and then re-converted into the desired end-use form (e.g. electricity, heat, synthetic natural gas, pure hydrogen or liquid fuel). The interest in hydrogen has grown due to its potential for higher storage capacity, higher energy density, quicker response times than most batteries, PHS, and CAES, offering in theory potential of balancing seasonal variations in electric systems. However, currently the upfront costs are very high (particularly given the lack of infrastructure for large-scale applications), low efficiencies of the process (between 28 and 40% depending on the electrolyzer [76]) , and several safety concerns arise. As discussed by Green et al and Carton et al[72, 24], large-scale adoption of hydrogen storage could be transformative of current electricity choices solving many integration issues of renewables; however, as presented by the IEA assessment, this technology is still in a very early stage of development.

3.4 Thesis contribution to the literature

As a result of this literature review, I have found numerous studies investigating the value of storage from different angles. The vast majority of studies used price-taking approaches, which in my opinion, will be insufficient to assess the potential value of storage in future power systems with large-scale penetration of renewable energy. Therefore, systems level analyses will be required, both to assess very short-time scale dynamics and the long-term system expansion. My dissertation aims to contribute to the approaches that further investigate long-term system expansion benefits of the availability of storage, particularly for large-scale penetration of renewables. Because intermittent renewables disrupt the traditional operation of electric systems, the assessment of the system expansion needs to incorporate investment decisions and some critical operational dynamics, to assess the costs of system security and adequacy. I identified two studies, Stract et al. and NREL RE Futures. that have developed power systems tools with some of the desired characteristics to assess large-scale penetration of renewables for long-term systems expansion.

The vast majority of studies in the literature focused on analyzing storage value within the electricity sector, and two studies used a simplified tool to explore interactions within the energy sector. However, under deep mitigation scenarios, technologies assisting the transition of the power sector to low-carbon solutions – such as renewable energy technologies– could have value that derives from benefits (or costs) outside the energy sector. As identified by Sandia National Laboratory, there is a need to better “characterize, understand, and communicate the societal value proposition for storage”. By developing a new modeling framework that can assess the full interactions of a power system and the economy, and a experimental design to test the value of storage at increasing penetrations of renewable energy, this dissertation’s contribution to the literature is to estimate the economic value of storage for the economy, accounting for full feedbacks and price effects triggered by the penetration at scale of renewables and storage technologies.

A full assessment of emissions and prices for electricity and fuels is enabled by this modeling framework by adding the economy-wide interactions. The assessment is unique for its power to investigate the full social welfare implications of storage availability in power systems with large-scale renewables on the grid.

In addition to providing new insights on the value of storage, this thesis contributes too in advancing the literature of climate change policy evaluation, by incorporating storage technologies in sufficient level of detail, and to the literature investigating the penetration of renewable energy in developing countries, particularity in Mexico, where as of today, only simple screening methods have been applied to assess the value of storage.

In the following chapter, I describe the proposed modeling framework.

Chapter 4

Modeling and analysis framework

4.1 Hybrid modeling approach of this dissertation

The value of storage depends upon complex system-level interactions. The modeling strategy applied in this research consists of a full systems-level analysis including both the adjustments in a power system to new disruptive technologies – intermittent renewables and storage – along with the social and economic dynamics driving energy demand. In this chapter, I describe the economy-wide model used in this dissertation, the power systems model, and the integration of both in a fully consistent modeling framework.

Economy-wide models – often referred to as top-down models – represent the flow of goods and services in the economy and have the capability of assessing policy effects as they spread through different markets. General equilibrium models, in particular, are economy-wide models that simulate the market mechanisms triggered by movements in relative prices in multiple sectors of the economy under the implementation of specific policies.[1] As opposed to partial equilibrium models, where demand and supply in one market interact to reach a market equilibrium, general equilibrium models impose equilibrium conditions for all production activities and demand sectors for the entire economy. Founded on neoclassical economic theory, general equilibrium

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[1] Other economy-wide models that are not CGE models include statistical and econometric analysis, and agent based models.

models have been tools for applied economic analysis for over 50 years[2]; with the development of computer tools and improved algorithms, general equilibrium models have gotten more complex and have been extensively applied to understand real world issues including taxation, international trade, labor markets, social security, migration problems and climate policy, among others. Partial equilibrium models are insufficient to understand policy outcomes in these domains, which have ample economic and social repercussions. Because numerical methods and computer tools are required to solve these models, they are commonly known as computational general equilibrium, or CGE models. While these models are powerful tools to assess interactions between different sectors of the economy, they normally have stylized representations of specific production processes. These models place more emphasis on capturing the "top" or higher-level economic interactions and go "down" in a consistent fashion to individual agents' behavior. In this top-down process the models simplify specific processes. Thus, the representation of electricity production is too simple to capture the value of storage.

Power systems models – which I refer to in this dissertation as bottom-up models– are used to study specific activities of the value chain of electricity generation, transmission and distribution. These models are at the core of the planning, operation and regulation of these activities, and thus need to represent technologies and technical constraints of electricity systems in detail. As discussed in the previous chapters, power systems models have been widely used to investigate the value of storage.[3] These models often use optimization methods and include trade-offs between technologies in terms of their specific characteristics. For instance, technologies represent trade-offs in terms of capital and operational costs, efficiencies, and other parameters that become relevant when dealing with the problem of renewables integration, such as different technologies' capabilities to ramp up and down and their minimum ther-

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[2] The first CGE model was developed by Leif Johansen, and published in 1960 in a *Multisectoral Study of Economic Growth.*

[3] Within power systems models, electricity market models simulate the equilibrium of demand and supply in the electricity market. In some studies, welfare implications are assessed with these models, however, welfare here is computed from the partial equilibrium solution (only the electricity market) and should not be confused with welfare implications for the economy.

mal levels. Because of their detailed technological description, the literature normally refer to this analysis as built from the “bottom”, considering each component “upward” to the system-level description. Bottom-up models can analyze specific technologies in a power system; however, they cannot account for interactions with other sectors in the economy.

In the climate change literature, a divide between top-down and bottom-up models has been fairly studied, comparing different policy outcomes from CGE models and energy systems models. For a review on this discussion see Hourcade et al. [83]. In general, it has been acknowledged that hybrid modeling techniques are recommended when looking into problems that have both technical and economic ramifications.

The general equilibrium model I use in this dissertation has ample capability for analyzing climate policy. To improve this modeling tool to assess the value of storage under high penetrations of renewable energy, I integrate a bottom-up model to characterize electricity generation and capacity expansion. The power system model used in this dissertation represents in detail the technical characteristics of thermal technologies and renewables and includes a representation of the hydro-thermal coordination problem. Including the dispatch of hydro resources is important, because the current capacity to store energy in hydro reservoirs can compete with electricity storage technologies.[4] I incorporate electricity storage technologies with a sufficient level of detail to understand their value for long-term system expansion. The proposed integration method uses a “hard-link” approach, which represents an advanced hybrid modeling technique. The key innovation of this modeling strategy is that the electric sector optimization is fully consistent with the equilibrium response of the economy, which includes endogenously determined electricity demand and prices for fuels, goods and services. In this way, the integrated assessment provides theoretically sound welfare estimates that enable the assessment of the social value of storage.

In the following, I first describe the economy-wide model: the MIT Emissions Predictions and Policy Analysis (EPPA) model. Second, I present the new model

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[4] Big hydro reservoirs can have multi-annual storage capacity providing flexibility to the system; however, they do not use electricity to store energy (they depend on rainfall) and thus are a different type of storage.

built for this research, the Renewable Integration and Storage Assessment (RISA) model, a capacity expansion model to assess renewable electricity and supporting storage technologies. The chapter concludes with the description of the integration methodology. In the next chapter, I describe the experimental design and results for the value of storage.

4.2 The MIT Emissions Predictions and Policy Analysis (EPPA) model

The EPPA model is a multi-region, multi-sector recursive dynamic representation of the global economy developed and maintained by the MIT Joint Program on the Science and Policy of Global Change[5] [30, 136]. The model has been widely used for energy and climate change policy analysis, both for global policy evaluation [195, 96] and for analysis of specific countries, including the US, Europe, China, Mexico and Brazil, among others [137, 135, 191, 129, 31]. The model has also been used specifically to look into policies concerning the power sector in specific countries [134, 123].

The GTAP data set[6] provides the base information on the input-output structure for regional economies, including bilateral trade flows [80, 40]. I use EPPA-6, the most recent version of the model, calibrated to GTAP-8 database. As part of the work of this dissertation, the input-output table of Mexico was submitted to GTAP, in order to use updated statistics of the economic structure of Mexico, for details on the aggregation of Mexico's data see [116]. The data in EPPA-6 is aggregated into 18 world regions and 14 economic sectors. In addition, 14 backstop technologies, that while not competitive in the baseline year can become competitive under climate policy, are specified. Table 1 shows the details of EPPA model. For this dissertation, all regions were modeled as specified in EPPA, but I focus on the analysis of the results for Mexico.

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[5] For more information about the Joint Program and recent publications with the EPPA model see `http://globalchange.mit.edu/`

[6] For more information about GTAP see `https://www.gtap.agecon.purdue.edu/`

Table 4.1: EPPA Model Details

Country or Region	**Sectors**	**Factors**
Africa (AFR)	*Intermeditate & Final Demand:*	Capital
Australia & New Zealand (ANZ)	Agriculture (crops, livestock & forestry)	Labor
Brazil (BRA)	Services	Crude Oil
Canada (CAN)	Dwelling	Shale Oil
China (CHN)	Energy-Intensive	Conventional Natural Gas
Eastern Europe (ROE)	Other Industries	Unconventional Natural Gas
Europe (EUR)	Transportation	Coal
East Asia (ASI)	Household Transportation	Hydro
India (IND)	Other Household Demand	Nuclear
Indonesia (IDZ)	*Energy Supply*	Wind and Solar
Japan (JPN)	*Fuels:*	Nuclear
Mexico (MEX)	Coal	Land
Middle East (MES)	Crude Oil, Refined Oil	
Rest of Asia (REA)	Natural Gas	
Rest of Latin America (LAM)	Liquids from Biomass	
Russia (RUS)	Oil shale	
South Korea (KOR)	Synthetic gas from coal	
United States (USA)	Hydrogen	
	Electricity Generation:	
	Conventional Fossil	
	Hydro	
	Nuclear	
	Wind and Solar	
	Biomass	
	Gas combined cycle	
	Gas CCS	
	Coal CCS	
	Advanced Nuclear	
	Exogenous Electricity Generation in Mexico	
	Above technologies and:	
	Wind(hourly profile)	
	Solar (hourly profile)	
	Geothermal (total resource potential)	
	Electricity storage	

Table 1 presents the countries or regions in the model and broadly identifies intermediate and final demand and energy supply and conversion sectors considering advanced technologies. It also shows the breakdown of energy supply, which for the Mexico region has a special exogenous representation of the electricity sector. Final demand sectors include industrial sectors and household demands, including the dwelling sector to represent energy consumption for heating and cooling.

I used the EPPA model to evaluate future economic and energy scenarios. EPPA includes the main drivers of emissions: population growth, technology and GDP growth. Future scenarios are driven by economic growth that results from savings and investments and exogenously specified productivity improvements in EPPA for labor and energy. Growth in demand for goods produced from each sector, including electricity, occurs as GDP and income grow.

The model is calibrated to the latest UN data for population in each country [185]; for example, for Mexico in 2010 total population was 115 million and by 2050, the UN projects that Mexico will have a population of 152 million. Regarding economic growth the model uses available projections in each country, as well as information from the World Bank and other international institutions, to project growth trends. For instance, for Mexico EPPA assumes an average of 3.4% per year from 2015 to 2050.[7] Demand for energy, including electricity is also affected by a non-price induced efficiency parameter, the so-called autonomous energy efficiency improvement (AEEI).[8] For Mexico, we stipulate an AEEI of 1% improvement from the baseline per year which reduces GDP's energy intensity smoothly over time.

Stocks of depletable resources (like coal, oil and natural gas) fall as they are used, driving production to higher cost grades. These, together with policies, such as constraints on the amount of greenhouse gases, change the relative economics of different technologies over time and in different policy scenarios. The price of CO_2 and other GHGs in the model are obtained from emissions constraints as a shadow price. EPPA represents all of GHGs, and finds least-cost reductions for each gas in each sector. The model also has the capability of representing emissions trading, and can trade between different gas species using global warming potential weights.

For this dissertation I adjusted the EPPA model in the following way. First, the EPPA model was prepared to compute a solution using an exogenous representation of electricity generation for Mexico, which is read from the bottom-up model. The production block for electricity in Mexico was dropped from EPPA and total electricity supply in the country, expenditures for electricity generation in terms of capital, fuels, and other inputs to production, are computed in the bottom-up model. The exogenous electricity sector representation enters the model as a "special" type of agent, that mirrors the behavior of another consumer with an endowment of elec-

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[7] Growth is faster at the beginning of the period, and the economy keeps growing throughout the period but at decreasing rates, a trend normally observed as countries develop.

[8] As countries develop, greater efficiency in use of energy could be expected as better technologies are implemented. To capture this dynamic, EPPA scales energy use in production and consumption using a specific parameter for each country (or for groups of countries, i.e. developed, rapidly growing economies, least developed economies, etc.)

tricity and negative endowments (demands) for fuels, capital, labor and other inputs to production. Additional constraints in the model were needed to ensure that all markets keep in balance at the same time that the new solution is exogenously computed and incorporated into the EPPA solution. I add a constraint to ensure the zero profit condition, such that all rents are equal to all inputs to production of electricity. All electricity sector profits are added to the representative agent income, as are all the rents from vintaged capital in the sector and CO_2 emissions allowances. Also, I created a separate production block for electricity distribution, since costs for this service were not considered in the bottom-up model (this block is a small share of total production in the baseline year, and grows as a fixed share of total electricity generation). The calibration process between the models and the iterative solution algorithm are described in section 4 of this chapter. Following, I briefly explain the mathematical structure behind EPPA, with emphasis on the components of interest to understand the interactions with the bottom-up electricity sector.

4.2.1 Equilibrium conditions

EPPA is a very complex model that explicitly represents many sectors, agents and regions of the world. Also, EPPA models the full set of inter-industry transaction and explicitly represents international trade for each of the goods and services in the model. Despite this complexity, the mechanisms of Arrow-Debreu general equilibrium theory underlie the mathematical formulation of the model, in the same fashion that it does in a 2x2 sector illustrative model. For this reason, I first explain the equilibrium conditions in any CGE model, and then summarize the most relevant equations in the EPPA model to understand its interaction with the bottom-up model. My goal is not to provide a full mathematical formulation of the EPPA model, but rather to present formally the key linkages between the bottom-up model and the general equilibrium model– the main objective of this dissertation. Also, I provide some discussion on the mathematical approach that is undertaken to compute the solution in EPPA.

CGE models describe the behavior of consumers and producers in the economy, the structure of markets and institutions, and the relationships between them. CGE models assume that, in a given year, one possible equilibrium solution is observed from data as collected in the input-output matrices that describe the economic structure of a specific region. Input-output matrices record economic transactions throughout the economy, including inter-industry trade and international trade, and are the basis for a CGE model calibration, along with econometric studies that provide elasticities of substitution between different goods and services. Behavioral assumptions are drawn from microeconomic theory, and characterize consumer and producer choices, where consumers maximize their welfare (or minimize their expenditures given budget constraints), producers maximize profits (or minimize costs), and the government collects taxes, consumes and direct transfers.[9]

First order necessary conditions for each agent's minimization problem are derived. Based on microeconomic theory individual demand and supply functions describe how consumers and firms react to prices. Constant elasticity of substitution (CES) production functions are used to characterize the sectors in the economy – except for oil and agriculture which exhibit decreasing returns to scale. CES functions are smooth and capture substitution possibilities via elasticities. CES functions are calibrated using a single reference point to account for: value of output, relative prices of inputs, and the curvature of the isoquant; the latter is defined by the elasticities assumed for production technologies and consumer preferences. The optimizing behavior of agents is embedded in the equations describing optimal demands for inputs and final goods.

Numerically, the EPPA model is posed as a mixed complementarity problem (MCP). As proved by Mathiesen and Rutherford [114, 153], under perfect competition conditions, the general equilibrium problem can be solved as a MCP with three types of equilibrium conditions: zero profit, market clearance and income balance. [111]. MCP is a special kind of mathematical problems defined by a square system of nonlinear equations and inequalities. The condition that determines the *complementarity* is that the solution of the system of equations is a function of two vector

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[9] The rigorous micro-foundation of CGE models provides a key improvement over traditional Keynesian macroeconomic models and input-output models; by embedding agents choices triggered by price variations the CGE tools are more robust to study policy counterfactuals.

variables whose inner product must equal zero.[10] In brief, the *complementarity* characteristic of the general equilibrium problem derives from the economic behavior that characterizes agents in a perfectly competitive market. First, in any given market, if supply exceeds demand then the price must be zero. Second, if the marginal cost of production exceeds marginal revenue, then the activity level must go to zero. This *complementarity* characteristic of the general equilibrium problem allows the use of MCP methods which provide more efficient solutions for large-scale models.[11] Complementarity does not apply to income equations, which are enforced to balance the system.

In sum, the equilibrium conditions can be posed as follows [111]:

First

Zero profit condition: stating that unit cost of production must be greater or equal than unit revenue for each activity.

$$-profit \geq 0, \quad output \geq 0, \quad output^T(-profit) = 0 \tag{4.1}$$

Second

Market clearance: stating that supply must be greater than or equal to demand for each commodity.

$$supply - demand \geq 0, \quad price \geq 0, \quad price^T(supply - demand) = 0 \tag{4.2}$$

Third

Income balance: stating that consumer's expenditures must be less than or equal to total income, for each consumer.

$$income = value\, of\, endowments \tag{4.3}$$

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[10] For example, if we have vectors X and Y of i dimension, in each pair x_i, y_i, one must be zero; hence the term "complementarity". MCP problems result in a square system of weak inequalities, each associated with a non-negative variable.

[11] Smaller size models can be directly posed as optimization models; large-scale CGE models are more efficiently solved as MCP problems.

In EPPA, each of these conditions is operationalized by defining "blocks" of equations by type. First, we define all the equations for the zero profit condition which should be met in each of the *activities* represented in the model. The 3 main categories of *activities* are: transformation of goods into inputs, transformation of goods and services into utility, and trade activities (exports and imports).[12] All *activities* are represented as cost functions (the dual of the profit maximizing function) with constant returns to scale; the complementarity variable for each *activity* is the total quantity produced or utility level attained by consumers.

The second block of equations define the market clearance condition for each of the *commodities* in the model. The *commodities* are all the goods and services in the economy, factors of production, and the utility of consumers. For each commodity, supply must be greater or equal than demand and the complementarity variable for each commodity is the price of the commodity.

Finally, income balance equations are established to maintain equilibrium conditions expenditure must equal income for the representative consumer in each region of the model.

These equations and equilibrium conditions will apply to any CGE model; the number of equations grow as a function of the number of sectors, agents and institutions represented in the model. If we have i activities, j prices one per each commodity, and h income/expenditure per agent, the general equilibrium system consists of i $+j$ $+h$ unknowns. One price is fixed as a numeraire, following Walras law. Three sets of variables define the solution: a) a vector of prices, b) a vector of activity levels, and c) a vector of income levels. Table 4.2 presents a description of main indices, sets, decision variables and parameters in CGE models. In EPPA additional parameters are necessary, as inputs to the model, to account for time dynamics, resource depletion (for example fixed factor elasticities) and to represent backstop technologies.

The model is coded in GAMS using the Mathematical Programming System for General Equilibrium Analysis (MPSGE), and solved with PATH solver. For more

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[12] Domestic and foreign goods are "transformed" into an Armington composite, which means that imports are only imperfect substitutes of domestic production.

Table 4.2: Generalized indices, sets, decision variables, and parameters in CGE models

Indices and Sets	
$j \in J$	set of commodities
$i \in I$	set of activities
$h \in H$	set of agents
Decision variables	
p_j	vector of prices, including all final goods and services, intermediate goods and services and primary factors of production
y_i	vector of activity levels in each economic sector
I_k	vector of income levels for each household
Parameters	
$A_{a_{ij}}$	is technology matrix of input-output coefficients
E_k	endowments of labor, capital, and natural resources of each consumer
$ELAS\sigma_{ij}$	initial substitution elasticity matrix

details on the EPPA model calibration and equilibrium conditions see [30, 136]. Following, I describe some of the key interactions of EPPA with the bottom-up solution and how it enters the equilibrium calculation.

4.2.2 The electricity market

First, the equilibrium between supply and demand in the electricity market in Mexico is defined by:

$$ELE^{\text{Bottom-up}} = Demand_i^{\text{Ele}} + Demand_{h=MEX}^{\text{Ele}} \quad \perp \quad P^{\text{Ele}} \tag{4.4}$$

Where the total electricity supply coming from the bottom-up model, $ELE^{\text{Bottom-up}}$, must equal Mexico's demand for electricity of all productive activities i and the representative household h. In the model the price of electricity will be computed using an MPSGE routine that first reads the total electricity supply coming from the bottom-up model, and then finds the demands in all production sectors and final demands from consumers. It then applies Shephard's lemma[13] to all cost functions where electricity is used to compute optimal demands for each production sector and for each final demand. At last, MPSGE builds the supply/demand equation to clear the market by solving for the price. In equation 4.4 the complementary variable of this market clearance equation is the price of electricity, denoted by $\perp P^{\mathrm{Ele}}$, a notation I will use hereinafter to denote complementarity.

4.2.3 Capital, labor and fuel markets

Equilibrium interactions of the electricity sector in Mexico with the rest of the global economy are described by a set of market clearing conditions for capital, labor, and fuel markets. Both capital and labor are mobile between sectors within a region, but not internationally. Equations (4.5) -(4.6) give the capital and labor market equilibrium conditions, respectively, as follows:

$$K = D^{\mathrm{K}}_{bottom-up} + \overline{\theta}_{\mathrm{i}} \frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{K}}} \perp P^{\mathrm{K}} \tag{4.5}$$

$$L = D^{\mathrm{L}}_{bottom-up} + \overline{\theta}_{\mathrm{i}} \frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{L}}} \perp P^{\mathrm{L}} \tag{4.6}$$

where K and L are the capital and labor supply in the economy, $\mathrm{D}^{\mathrm{K}}_{bottom-up}$ and $\mathrm{D}^{\mathrm{L}}_{bottom-up}$ are the capital and labor demands for electricity generation coming from the bottom-up model, $\overline{\theta}_{\mathrm{i}}$ denotes the benchmark value of each production, and $\frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{K}}}$ and $\frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{L}}}$, denotes the change in the unit cost function given a change in the price of capital P^{K} and labor P^{L}, respectively, for each of i production activity.

It is worth mentioning that EPPA has an elaborated formulation of capital markets to account for non-malleability of capital in some sectors in the economy, such as the

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[13] By Shepard's lemma, the derivative of the expenditure function with respect to p_i is the compensated demand function for good i.

power sector, and also for capital accumulation as the model moves in time. Physical capital is captured through a vintage structure in some sectors of the economy. The model has different vintages, to account for the fact, that in some sectors capital investments have an economic life of many years. The accumulation of capital is calculated as investment net of depreciation, according to the standard perpetual inventory assumption.[14] Vintaged production in industry i that uses non-malleable capital is subject to a fixed-coefficient transformation process in which the quantity shares of capital, labor, intermediate inputs and energy by fuel type are set to be identical to those in the year where the capital was vintaged. For more details on capital market specifications see [30].

In the case of fuel markets for gas, oil and coal, EPPA treats these as commodities traded internationally. Each country has a given endowment of natural resources which is calibrated according to statistics of the International Energy Agency or country specific information. In the case of Mexico, for example, coal resources are very limited but oil and gas are significant. Market clearance conditions for fuels are shown in equations 4.7, 4.8 and 4.9, where supply for each fuel is a composite of domestic production and imports.

$$S^{gas} = D^{\mathrm{gas}}_{bottom-up} + \overline{\theta}_{\mathrm{i}} \frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{gas}}} \perp P^{\mathrm{gas}} \tag{4.7}$$

$$S^{coal} = D^{\mathrm{coal}}_{bottom-up} + \overline{\theta}_{\mathrm{i}} \frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{coal}}} \perp P^{\mathrm{coal}} \tag{4.8}$$

$$S^{oil} = D^{\mathrm{oil}}_{bottom-up} + \overline{\theta}_{\mathrm{i}} \frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{oil}}} \perp P^{\mathrm{oil}} \tag{4.9}$$

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[14] Net capital stock equals the sum of the net values of still lasting vintages of gross fixed capital formation in each period. Total investment of a particular asset does not deteriorate during the expected service life of that asset, and is discarded as a whole at the end of its economic life.

The market balance for coal, oil and gas considers total supply of each of the fuels– considering both domestic production and imports– and demand for each fuel for electricity generation, coming from the bottom-up model, $D^{\mathrm{gas}}_{bottom-up}$, $D^{\mathrm{coal}}_{bottom-up}$, and $D^{\mathrm{oil}}_{bottom-up}$, as well as from other sectors. The demand of other sectors is a function of the value share of each of the fuels on the sector's benchmark production, $\overline{\theta}_{\mathrm{i}}$, and the changes in the unit cost function of each of the sectors in the economy, as the price of gas, coal and oil changes, $\frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{gas}}}$, $\frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{coal}}}$, $\frac{\partial \pi^{\mathrm{i}}}{\partial P^{\mathrm{oil}}}$. The price of fuels is the complementarity variable of each of the market clearance condition.

4.2.4 Electricity Demand

The demand for electricity is modeled in each of the production activities and in the consumption of the representative consumer. As mentioned, production activities are characterized by CES production functions, as are consumer preferences. Electricity enters the production of almost all activities in the model, with a significant contribution in some industries, for example in energy intensive industries. Sectors with higher value share coming from electricity, will be generally more impacted by changes in its price. Firms and consumers can substitute electricity to various degrees depending on the industry, and will shift away from electricity if its price increases relative to other energy commodities. In contrast, if electricity becomes relatively less expensive, electricity demand will grow as firms and consumers shift towards more electricity use.

The decision to use electricity or other energy types is one of the many decisions that firms and consumers face in the production of goods and services and in final energy demand. In EPPA, the different levels of decisions and possible substitutions are structured in so-called "nested" production or consumption functions. As an example, I show in Figure 4-1 and Figure 4-2 an illustration of the consumption preferences nest and the production function for energy intensive industries, focusing on the nests' levels that represent the consumption and production of electricity. The latter illustrates the decision making of firms, and there is a specific nest for each of the production sectors in the model. In reality, the nests in EPPA are more complex than the ones shown in the figures, for example the utility nest has 8 levels; however, I illustrate only the top level and the details of the level on the demand for energy. In a similar way, in EPPA the structure of energy intensive industries has 8 nested levels, to account for each of the GHGs and the Armington transformation; however, I only show the levels of interest for energy demand, where the impacts of changes in electricity prices will be captured. For a full detail of the nesting structure in EPPA6 see [30].

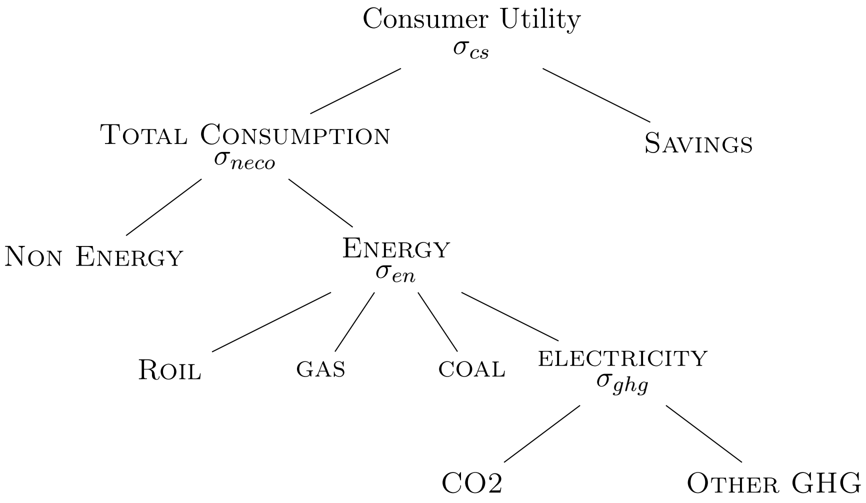

Figure 4-1: Nesting structure consumption
Source: Author based on [30].

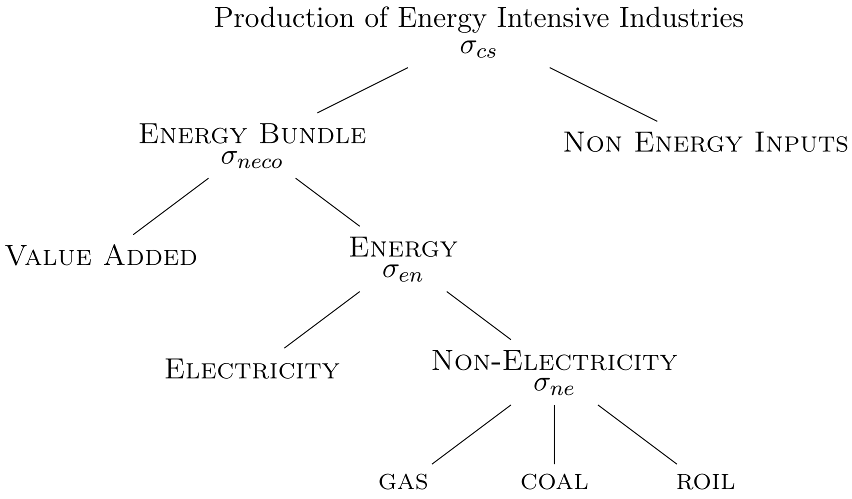

Figure 4-2: Nesting structure of Energy Intensive Industries.
Source: Author based on [30]

In the case of the consumer, as shown in 4-1, the representative agent decides between savings and consumption of goods and services, then between consumption of non-energy and energy goods. For the latter, the consumer can decide among refined oil, gas, coal and electricity. For all of the energy products, CO_2 and other GHGs penalties would enter the costs in the case of climate policy (last nest level shown only for electricity). Equation 4.10 presents formally the decision between energy commodities. The substitution of fuels takes place as prices of refined oil, P^{Roil}, gas, P^{gas}, coal, P^{coal}, and electricity, P^{ELE} move relative to one another, and is a function of the initial share in consumption of each of the fuels refined oil θ_h^{Roil}, gas θ_h^{gas}, coal θ_h^{coal}, and electricity θ_h^{ELE}. All fuels are substituted with the same elasticity σ_{en}. The unit cost function for the consumer's energy bundle, π^{EN}, is derived as follows:

$$\begin{aligned}\pi^{\text{EN}} = \text{P}^{\text{EN}} - \Bigg(\Bigg(& \theta_h^{\text{Roil}} \left(\frac{P^{\text{Roil}}}{\overline{P}^{\text{Roil}}} \right)^{1-\sigma_{\text{EN}}} + \theta_h^{\text{gas}} \left(\frac{P^{\text{gas}}}{\overline{P}^{\text{gas}}} \right)^{1-\sigma_{\text{EN}}} \\ & + \theta_h^{\text{coal}} \left(\frac{P^{\text{coal}}}{\overline{P}^{\text{coal}}} \right)^{1-\sigma_{\text{EN}}} + \theta_h^{\text{ELE}} \left(\frac{P^{\text{ELE}}}{\overline{P}^{\text{ELE}}} \right)^{1-\sigma_{\text{EN}}} \Bigg)^{\frac{1}{1-\sigma_{\text{EN}}}} \Bigg)\end{aligned} \tag{4.10}$$

In the case of production of energy intensive goods the structure of the nest is slightly different. In this case, the firm chooses between non-energy inputs and the energy bundle, with a substitution elasticity for non-energy commodities, σ_{neco}. Energy goods can be substituted between electricity and non-electricity goods, which includes gas, coal, and refined oil. Electricity and non-electricity energy commodities are substituted with an elasticity of σ_{en} and non-electricity energy commodities are substitute with σ_{ne}. This reflects the fact that it is easier in industries to substitute between the fossil energy bundle, but shifting to electricity would require additional modifications in the production process. Equation 4.11 shows the decision for electricity demand and other types of energy for the sector, and similar equations will be derived for each of the production activities in EPPA. The unit cost function for the producer's energy bundle, π^{EN}, is derived as follows:

$$\pi^{\mathrm{EN}} = \mathrm{P}^{\mathrm{EN}} - \left(\left(\theta_{Eint}^{\mathrm{Nele}} \left(\frac{P^{\mathrm{Nele}}}{\overline{P}^{\mathrm{Nele}}} \right)^{1-\sigma_{\mathrm{EN}}} + \theta_{Eint}^{\mathrm{ELE}} \left(\frac{P^{\mathrm{ELE}}}{\overline{P}^{\mathrm{ELE}}} \right)^{1-\sigma_{\mathrm{EN}}} \right)^{\frac{1}{1-\sigma_{\mathrm{EN}}}} \right) \tag{4.11}$$

4.2.5 International Trade

With the exception of crude oil, which is a homogeneous good, intermediate and final consumption goods are differentiated between domestic and foreign markets, with an Armington specification of international trade. The model is calibrated to reflect the baseline statistics on trade among the different regions in the model. For example, it accounts for the energy trade between Mexico and the US, and other regions in the EPPA model. While there is an small share of electricity trading between Mexico and the US and Central America, the electricity trade was set to zero for the EPPA-RISA model iterations; however, gas and coal remain as tradable commodities. EPPA treats all foreign goods as imperfect substitutes for domestic goods, and computes a terms of trade variable to estimate impacts on international trade.[15] If electricity becomes more expensive, this can make exports less competitive and affect the trade balance. International trade of electricity is very low; however, movements of the electricity price could lead to trade effects due to multi-market interactions. International trade of fuels can also be important, for example, if less or more natural gas is used in the country resulting from renewables integration assisted by storage.

4.2.6 Income Balance equation

Finally, the income of the representative consumer is the sum of wages, capital gains, returns on investment, transfers and rents from natural resources, which needs to match total consumption and savings in each period, as shown in Equation 4.12.

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[15] The terms of trade variable measures the relationship between prices of exports and prices of imports; one is interested in this indicator since an improvement of terms of trade implies that for a given quantity of exports a larger volume of imports could be achieved potentially increasing standards of living in the country [138].

Under policy scenarios, income effects can reduce consumption of goods and services, since the consumer needs to allocate some income to pay for carbon penalties.

$$Consumption_h + Savings_h = L_h \; P_h^L + K_h \; P_h^K \; + I_h \; P_h^I + r_h \; P_h^R + transfers_h \tag{4.12}$$

4.2.7 Summary of EPPA model and linkages with electricity bottom-up model

In sum, the EPPA model was modified to read an exogenous electricity supply for Mexico from a bottom-up model, and to consider as exogenous the parameters for expenditures of capital, fuels and other inputs to production of electricity. The EPPA model is a large-scale global model with many features to evaluate climate policy; the new modifications allow investigating impacts in the electricity and fuels markets in Mexico resulting from structural changes in the power sector while capturing economy-wide interactions. The critical links between EPPA and the inputs from the bottom-up model were described, as well as the fundamentals of the mathematical structure and equilibrium conditions of the model, highlighting the conditions that change due to the coupling with the bottom-up electricity model. In the next section, I present the bottom-up model.

4.3 Renewable Integration and Storage Assessment (RISA) Model

The Renewable Integration and Storage Assessment (RISA) model is a recursive-dynamic linear programming model that simulates the least-cost expansion of electricity generation capacity under high levels of penetration of intermittent renewable electricity in Mexico. Investment in electricity technologies is portrayed by a cost minimization problem which includes important operational constraints to capture the impacts of intermittency in the overall system configuration. The model builds on the previous formulation presented by [117] for Spain, and adds renewable energy resources, storage, and transmission to the analysis, in addition to calibrating it to the Mexican power system. The model considers the current structure of the power sector in Mexico, as described in Chapter 2, as well as the renewable energy resources available in the country. In order to consider the fluctuating nature of renewables, the model incorporates a full year chronology of hourly demand, as well as resource profiles. It also optimizes the use of hydro resources, since, under high levels of renewables, these resources can provide flexibility to the system and also can compete with storage. A generic storage technology is modeled to capture its role as the system expands. Constraints to account for both security[16] and adequacy of supply[17] are modeled. Since an hourly time-scale is considered, shorter time-scales balancing needs are outside the scope of this research.

Investment costs and technical parameters come from the most part from CFE's planning documents, the main utility in Mexico [27]. When information was not available for specific parameters, the input data was complemented with international studies or data for the US [92, 54]. In particular, the investment costs of renewable energy were parameterized to follow a cost reduction curve with data of the International Energy Agency [92]. Renewable energy potential comes from Mexico's National Inventory of Renewable Energy[18] [169], the MERRA dataset for wind and solar hourly profiles [149], and hydro resources come CFE planning documents [27]. Hourly demand profiles by region come from the system operator, CENACE [26]. Annex 1 presents summary tables of the parameters used. Next, I present the mathematical formulation of the model.

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[16] System security is "the capability of the power system, using existing resources, to maintain reliable supply in the face of unexpected shocks and sudden disruptions" [90].

[17] System adequacy is "the capability of the power system, using existing and new resources, to meet changes to aggregate power requirements in the present and future, through timely and flexible investment, operational and end-use responses" [90].

[18] Tidal and biomass resources are not considered.

4.3.1 Mathematical formulation

The RISA model uses linear programming to minimize total generation cost subject to constraints, which I group in 4 classes: operational, renewable resources, hydropower and storage modeling. Generators are grouped by technology type. First, I present the nomenclature for indices and sets, decision variables, and parameters, and then I describe in detail each of the constraints.

Indices and Sets

$c \in C$	set of wind classes
$d \in D$	set of days in a year
$h \in H$	set of hours
$l \in L$	set of transmission lines
$r \in R$	set of regions in the electric system
$t \in T$	set of thermal technologies
$y \in Y$	set of years

Decision variables

$g_{y,h,r,t}$	thermal generation per year, per hour, per region, per technology in GWh
$h_{y,h,r}$	hydro generation per year, per hour, per region in GWh
$so_{y,h,r}$	solar generation per year, per hour, per region in GWh
$w_{y,h,r,c}$	wind generation per year, per hour, per region, per class in GWh
$nse_{y,h,r}$	non-served energy per year, per hour, per region in GWh
$ic_{y,r,t}$	new installed thermal capacity per year, per region, per thermal technology in GW
$icw_{y,r,c}$	new installed wind capacity per year, per region, per wind class in GW
$ics_{y,r}$	new installed solar capacity per year, per region in GW
$p_{y,h,r}$	power available per year, per hour, per region
$dw_{y,d,r,t}$	shut-down power per year, per day, per region, per thermal technology in GW
$up_{y,d,r,t}$	start-up power per year, per hour, per region, per technology in GW

$lf^{IN}_{y,h,r}$	energy flow into each region over transmission lines per year, per line, per hour in GWh
$lf^{OUT}_{y,h,r}$	energy flow out of each region over transmission lines per year, per line, per hour in GWh
$ste_{y,h}$	stored energy per year, per hour in GWh
$stw_{y,h,r}$	stored energy in catchment basin of hydro-generator in GWh
$s_{y,h,r}$	water spill per year, per hour, per region in GWh
$in_{y,h}$	energy inflow into new storage technology per year, per hour in GWh
$out_{y,h}$	energy outflow from new storage technology per year, per hour in GWh

Parameters

AF_t	availability factor of each thermal technology in percent of hours in a year
BG_r	capacity of the biggest generator per region in GW
CC_c	capital cost for wind technology per class, per kWyr
CC_t	capital cost per thermal technology in dollars per kWyr
CC_s	capital cost for solar PV technology per class per kWyr
EF_t	emissions factor per thermal technology in ton per MMBtu
EFF	efficiency of generic storage technology as percent of total energy charged
$FP_{y,r,t}$	fuel price per year, per region, per technology in dollars per MMBtu
GEO^{MAX}_r	Geothermal potential in GW
HC_r	total hydro capacity in each region in GW
HR_t	heat rate per thermal technology in MMBtu per kWh
$HWP_{r,c,h}$	hourly wind profile per region per class per hour
$HSP_{r,h}$	hourly wind profile per region per class per hour
$ICs^{OLD}_{y,r}$	Initial solar capacity each year in GW
$ICt^{OLD}_{y,r,t}$	Initial thermal capacity each year in GW
$ICw^{OLD}_{y,r,c}$	Initial wind capacity each year in GW
L^{MAX}_r	capacity of the hydro reservoir per region per hour in GWh
L^{MIN}_r	minimum level of the hydro reservoirs per region, per hour, in GWh
$LD_{y,r,h}$	load per year, per region, per hour, in GWh

MR_r	marginal reserve requirement per region in percent of peak demand
OR_r	operating reserve requirement per region in percent of load
PCO_2	price CO_2 in dollars per ton
$PMIN_t$	minimum stable load in per cent of rated capacity
SCA	storage capacity in the system in GWh
SC_t	start-up costs for each thermal technology in dollars per kW
$SMIN$	storage minimum charge
SCV	solar capacity value in percentage of total solar capacity
SP	maximum output power of storage in GW
SR_r	total solar resource per region in GW
TC_r^{IN}	maximum transmission capacity of lines transporting into region r
TC_r^{out}	maximum transmission capacity of lines from region r
$VOLL$	value of lost load in dollar per kWh
VOM_t	variable operation and maintenance cost in dollar per kWh
WCV	wind capacity value in percentage of peak demand
WFE	wind forecast error in percent of wind in each hour
$WIN_{h,r}$	water inflow per hour, per region, in GWh
$WR_{r,c}$	total wind resource per region, per class, in GW

4.3.2 Objective Function

The objective function minimizes total system costs, which are the sum of investment, variable and emissions costs, expenditures for starting-up capacity, the social cost of non-served energy, and the payments for emissions, if there is a cost for emissions.

$$\begin{aligned}\min_{\substack{ic,icw,ics\\ g,w,s,h\\ s,in,out,p\\ lf,ste,stw\\ nse,dw,up}} CC_t ic_{y,r,t} + CC_c icw_{y,r,c} + CC_s ics_{y,r} + (FP_{y,r,t} HR_t + VOM_t + PCO_2 EF_t HR_t) g_{y,h,r,t} \\ + SC_t up_{y,d,r,t} + VOLL nse_{y,h,r} \quad (4.13)\end{aligned}$$

4.3.3 Operational Constraints

Subject to:

a. Supply-Demand Balance

Demand must be met every hour of the year. In every region, generation from thermal, hydro, wind and solar along with storage outflow, energy coming from other regions, and non-served energy should equal load, energy inputs to the storage device, and transmission flows to other regions, for every hour of the year.

$$\begin{aligned}\sum_t g_{y,h,r,t} + h_{y,h,r} + w_{y,h,r,c} + so_{y,h,r} + out_{y,h,r} + lf^{IN}_{y,h,r} + nse_{y,h,r} \\ = LD_{y,r,h} + in_{y,h,r} + lf^{OUT}_{y,h,r}\end{aligned} \tag{4.14}$$

b. Maximum transmission capacity

Transmission flows are represented with a simple transport model. Total energy flows between regions are limited by maximum transmission capacity between any pair of contiguous regions, which characterizes the main interconnections between regions.

$$lf^{IN}_{y,h,r} \leq TC^{in}_{r} \tag{4.15}$$

$$lf^{OUT}_{y,h,r} \leq TC^{out}_{r} \tag{4.16}$$

c. Total available thermal capacity

Total thermal capacity is the sum of installed capacity at the beginning of the period, which enters as a parameter, and the new capacity of each technology, which is a decision variable. Thermal capacity is adjusted by an availability factor that considers the probability of failure and required maintenance by technology.

$$p_{y,h,r} \leq (IC^{OLD}_{y,r,t} + ic_{y,r,t})AF_t \tag{4.17}$$

d. Maximum generation from thermal technologies

In each region, thermal generation is limited by total available thermal capacity.

$$g_{y,h,r,t} \leq p_{y,h,r} \tag{4.18}$$

e. Start-up decision

Each day a decision to start-up thermal generation is taken.[19] Available thermal capacity is equal to thermal capacity on-line the previous day and the capacity that is started-up less the capacity that is shut-down each day.

$$p_{y,d,r} = p_{y,d-1,r} + up_{y,d,r,t} - dw_{y,d,r,t} \quad \forall h \in d \tag{4.19}$$

f. Operating reserves

According to the North American Reliability Corporation, operating reserves are “that capability above firm system demand required to provide for regulation, load forecasting error, equipment forced and scheduled outages and local area protection. It consists of spinning and non-spinning reserve" [126]. Systems around the world use different classifications of reserves, and have different regulatory frameworks for markets for ancillary services. In Mexico, the regulation of these markets is still under development, and different terminologies could be adopted; therefore, I do not use any specific terminology to classify reserves.[20]

In the model reserves can be provided by thermal generation and by storage facilities. The thermal capacity margin and the storage capacity available to provide reserves should be greater than a specified reserve margin. This reserve margin is determined as a percentage of total load and a wind forecast error in each hour multiplied by the total wind production in each hour, to provide load-following services, and the capacity of the biggest generator in each region to account for contingency reserves. I include upward and downward reserves. I used a 20% forecast error, 1365 MW that corresponds to the largest unit currently in the system (Laguna Verde

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[19] The first hour of the year the system starts-up the capacity needed for the first day and then adjusts each 24 hours.

[20] In Europe, reserves are generally classified as primary, secondary and tertiary; in North America different classes exist including regulation, load-following, spinning and non-spinning, voltage control, etc.

nuclear power plant), and 2% of electricity demand as reserves.

$$p_{y,h,r} - \sum_t g_{y,h,r,t} + SP - out_{y,h,r} + in_{y,h,r} \geq OR_r LD_{y,r,h} + WFE \sum_c w_{y,h,r,c} + BG_r \tag{4.20}$$

$$\sum_c g_{y,h,r,t} - p_{y,h,r} + SP - in_{y,h,r} + out_{y,h,r} \geq OR_r LD_{y,r,h} + WFE w_{y,h,r,c} \tag{4.21}$$

g. Reserve Margin

In addition to the operating reserves, the system is planned considering a reserve margin to meet peak demand. Total system capacity should be greater than a regionally specified reserve margin, which defines a capacity margin above peak load.

$$\begin{split} ICt^{OLD}_{y,r,t} + ic_{y,r,t} + (ICw^{OLD}_{y,r,c} + icw_{y,r,c})WCV + (ICs^{OLD}_{y,r} + ics_{y,r})SCV + SP \\ \geq MR_r \max LD_{y,r,h} \end{split} \tag{4.22}$$

Wind and solar capacity is adjusted by a capacity value, to account for its intermittency. It is worth mentioning that the parametrization of renewables' capacity value is currently a subject of much research. These values are system specific, since they depend on the regional dynamics of the resources and the current configuration of electricity networks. Probabilistic methods to determine wind and solar production during peak demand are recommended. A key finding from the literature currently available is that the capacity value of renewables is a function of the total level of renewables on the grid, and without storage, the capacity value of renewables decreases as wind and solar penetration increases. For this research, I use the mean value of the probability density function for wind capacity value estimated for Mexico by Yañez et al. in their *Assessment of the capacity credit of wind power in Mexico* [200]. No assessment of the capacity credit of solar in Mexico was found. To parameterize the capacity credit of solar, I use the review of different systems by Helman, who examined reliability benefits of large-scale solar plants [79]. I will further discuss this issue in the presentation of results.

4.3.4 Renewables modeling

h. Total wind installed capacity

Total installed capacity of wind is the capacity at the beginning of the year, which enters as a parameter, and the new capacity, a decision variable. Wind capacity is limited by the total resource availability in each region.

$$ICw^{OLD}_{y,r,c} + icw_{y,r,c} \leq WR_{r,c} \tag{4.23}$$

i. Wind generation

Wind generation is equal to the total wind installed capacity times the hourly wind profile.

$$w_{y,h,r,c} = (ICw^{OLD}_{y,r,c} + icw_{y,r,c})HWP_{r,c,h} \tag{4.24}$$

j. Total solar installed capacity

Similar to wind, solar installed capacity is the capacity at the beginning of the year and the new installed capacity. Solar capacity is limited by solar resource availability in each region.

$$ICs^{OLD}_{y,r,c} + ics_{y,r,c} \leq SR_r \tag{4.25}$$

k. Solar generation

Similar to wind, solar generation is equal to solar installed capacity times the hourly solar profile.

$$so_{y,h,r} = (ICs^{OLD}_{y,r,c} + ics_{y,r})HSP_{r,h} \tag{4.26}$$

l. Maximum geothermal capacity

Capacity of geothermal is bound by total resource potential in each region.

$$ic_{y,r,t=geothermal} \leq GEO^{MAX}_r \tag{4.27}$$

4.3.5 Hydropower

m. Management of hydro reservoirs

Only big hydro reservoirs, which have storage capacity, are modeled.[21] The management of the reservoirs considers the balance between energy stored in previous periods, the energy released each hour, and the natural water inflows into the reservoir. There is also the possibility of spilling water.

$$stw_{y,h,r} + h_{y,h,r} = stw_{y,h-1,r} + WIN_{h,r} - s_{y,h,r} \tag{4.28}$$

n. Limits of the hydro reservoir

Upper and lower bounds are considered for stored energy in the reservoirs. Maximum capacity of the reservoir provides the upper limit; the minimum limit considers regulatory restrictions, either environmental or other, in different seasons of the year. An additional constraint, to ensure the model reproduces a realistic water dispatch, requires total energy stored at the beginning and at the end of the year to be equal. In addition, a set of constraints is introduced so that the model follows by month historical patterns of energy stored in the reservoirs. In Chapter 6, I present a detailed description of the modeling of hydropower with a sensitivity analysis of the value of storage.

$$L_r^{MIN} \leq stw_{y,h,r} \leq L_r^{MAX} \tag{4.29}$$

$$stw_{y,1,r} = stw_{y,8760,r} \tag{4.30}$$

o. Maximum hydro generation

Total hydro generation is bound by the total capacity of hydroelectric plants. No capacity expansion of big hydro is considered.

$$h_{y,h,r} \leq HC_r \tag{4.31}$$

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[21] I do not consider run-off-river hydro generation, which is small in Mexico.

4.3.6 Modeling of Storage

p. Stored energy

A generic storage technology that charges and discharges from and to the grid is modeled. Importantly, the analysis of storage is done at the hourly time scale, a time resolution that few models capture, since many formulations rely on time blocks. Total energy stored is equal to the level of energy stored in the previous period, the energy inflows to the storage device penalized by an efficiency loss, less the energy outflows from the storage device.

$$ste_{y,h} = ste_{y,h-1} + EFFin_{y,h} - out_{y,h} \tag{4.32}$$

q. Maximum stored energy

Total energy stored is limited to the total capacity of the storage technology.

$$out_{y,h} \leq SCA \tag{4.33}$$

r. Minimum stored energy

Total energy stored has a minimum to ensure that the facility can provide power for peak demand. SMIN was defined as SCA/8, considering a generic storage technology with 8 hours duration (so that it could provide one hour).

$$out_{y,h} \geq SMIN \tag{4.34}$$

s. Maximum storage output

Total energy outflow from the storage device is restricted to its rated power.

$$out_{y,h} \leq SP \tag{4.35}$$

Finally, the model considers as positive variables the installed capacity, generation, storage level, storage flows, and non-served energy.

4.4 Integration of the power systems model and the General Equilibrium Model

There are different approaches to integrate top-down and bottom-up models. A simple form of hybrid modeling is to use engineering studies in economic models or vice versa to use economic information to parameterize demand in engineering models. For example, information regarding the specific costs of different technologies in one sector can help parameterize production functions in top-down models. In the case of bottom-up models, demand representation can be improved by incorporating elasticities available in the literature to parameterize demand. This simple approach is the most commonly used, since it allows maintaining the main structure of the top-down and bottom-up models with only some changes in specific parameters.[22] The limitation, however, is that some of the problems that prevent the analysis of technologies or demand remain in the models. For instance, while incorporating more data on costs of technologies is valuable in CGE models, maintaining a smooth production function such as the CES function limits the analysis of technological changes that do not comport to a constant substitution rate. In the case of bottom-up models, incorporating elasticities will improve the representation of demand changes in one market, but will disregard the general equilibrium effects.

A second approach is to integrate models loosely. In this case two models are used and the information of one of the models is passed to the other model through a “soft-link”. In this way, the output of one of the models is considered in the second model, but there is no “feedback” or consistency check between the two models; it works as a one-way loop. For example, Schäffer and Jacoby linked a transportation model to EPPA [155]. This approach improves the characterization of one sector in the top-down model, but does not incorporate the impact of demand changes into the bottom-up model, which could be substantial, particularly under policy scenarios and thus could change the bottom-up output.

A third approach, put forward by Böhringer and Rutherford [17], is to integrate

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[22] In fact, this is the current approach used in EPPA.

models so that the solutions from both, the bottom-up and the top-down models, converge. This last approach is known as “hard-link” between models. One possible avenue to integrate models with a “hard-link” is to cast both as MCP and solve them in a single system of equations. For this, the bottom-up model needs to be reformulated using the Karush-Kuhn-Tucker (KKT) conditions and embedded into the top-down MCP formulation. While theoretically consistent, there are practical limitations to integrate large-scale models into one single MCP problem. As explained by Böhringer and Rutherford in a following paper [18], in addition to the difficulties of posing the problem properly, when both primal and dual relationships double the number of equations needed to represent the bottom-up system, there is also a problem of tracking income effects when lower and upper bounds are imposed to many variables in a large-scale bottom-up problem. Thus, to integrate large-scale models the authors propose a block decomposition algorithm.[23] I use this block decomposition methodology in my modeling framework: the integrated EPPA-RISA model. Both models are solved in a single consistent framework, while preserving in full the strengths of both modeling approaches.

The integration is done by a number of links between the top-down and the bottom-up models for the variables of interest: electricity demand, expenditures on capital, fuels, and other inputs needed for electricity generation. Prices for electricity, fuels and capital are determined in the CGE. The bottom-up model RISA provides the equilibrium supply for electricity, as well as total energy use for electricity generation by type: natural gas, coal and oil. The availability of total renewable energy resources by region is represented in the bottom-up model, including wind, solar, geothermal and hydro. Emissions from electricity generation are estimated also from the resulting dispatch in the bottom-up model and are considered in EPPA with the inputs coming from the bottom-up model. Figure 4-3 shows the iterative procedure

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[23] The block decomposition algorithm of Böhringer and Rutherford (2009) exploits the block-diagonal structure of the Jacobian matrix of the problem. The name block decomposition is used by Böhringer and Rutherford since it provides a method to solve the top-down bottom-up problem maintaining the structure of the models through several iterations instead of solving them as a big optimization problem that would require recasting the bottom-up model as an MPC problem and embedding it within the CGE solution. In this study, each of the models will represent a block of the iterative algorithm. See discussion in [18, 17].

between the models.

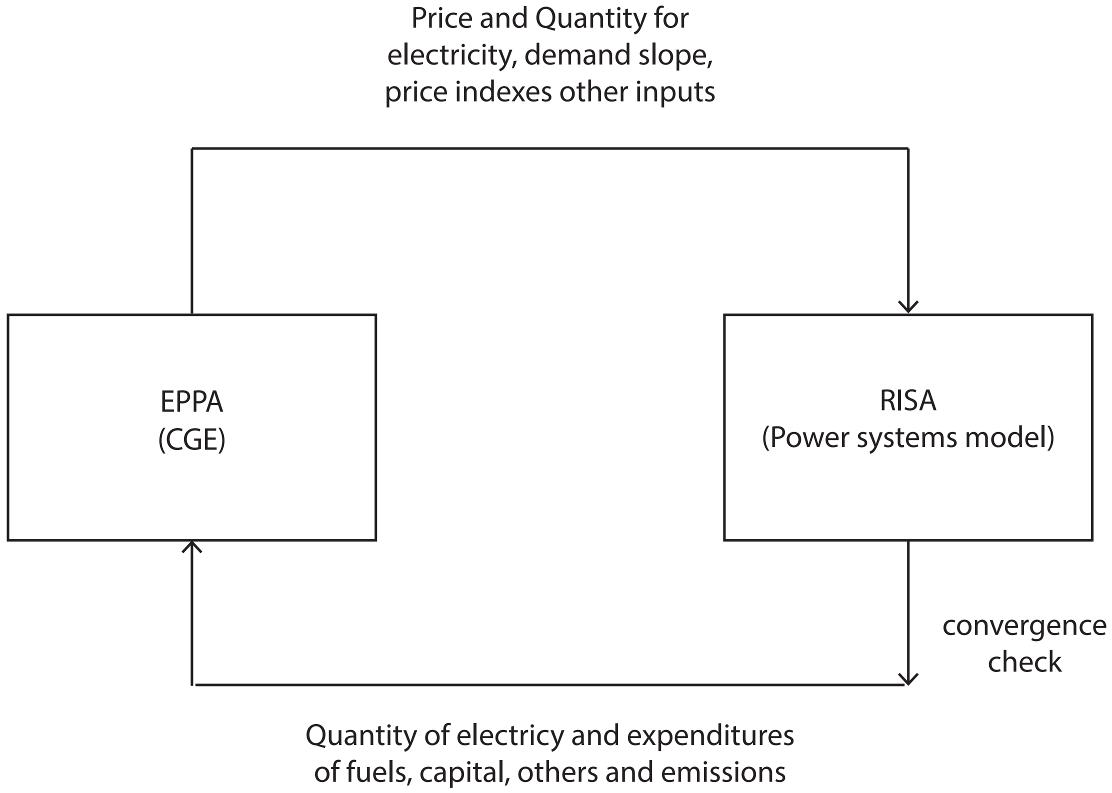

Figure 4-3: Iterative algorithm - Model interaction
Source: Author based on [18]

Both models are written in GAMS; the CGE model is solved using PATH and the electricity model is solved using CPLEX. The iteration routines are written in bash. Following, I describe in more detail the three main steps followed for the integration.

4.4.1 Benchmark equilibrium

The first step for coupling the models is the calibration of EPPA and RISA to a consistent benchmark equilibrium. Total generation and energy use in the bottom-up model is made consistent with the base year data in the Social Accounting Matrix[24] (SAM) that underlines the EPPA model. This initial treatment of the data allows the

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[24] A Social Accounting Matrix (SAM) is a presentation of a country's National Accounts in a matrix that elaborates the linkages between a supply and use table and sector accounts. For more information on SAMS see the World Bank "Impact Analysis: General Equilibrium Models" website: http://go.worldbank.org/IGGYGPFP60

models to replicate the benchmark equilibrium in the absence of policy shocks, which is necessary in CGE models to correctly evaluate policy counterfactuals (otherwise policy effects could be confounded with adjustments in the iterations driven to initial data disparities).

The benchmark procedure is the following. First, the RISA model computes a solution of the bottom-up problem considering total electricity generation and historical prices for fuels for the baseline year 2007, the same year of the calibration of the EPPA model. The solution of the bottom-up model (without iterations with EPPA) provides initial data to parameterize the EPPA model's benchmark solution. I used least-square optimization techniques to estimate a new SAM holding fixed the results that come from the bottom-up model for the electricity sector. This is needed to ensure that the models start from the same equilibrium in the electricity sector and that all other sectors are balanced.

Also, as part of the benchmark calibration, transmission and distribution services are separated from the original production block. Because RISA does not include distribution and transmission costs, a share of the value of the electricity sector is specified separately considering these costs in the baseline.

4.4.2 Iteration in each period

Each iteration in the solution algorithm comprises two main steps that are repeated until the models converge. First EPPA model is solved, with exogenous electricity production where electricity sector outputs and input demands are parameters that come from the solution of the RISA model. As explained in section 4.2, these parameters enter in the equilibrium conditions for each of the markets and production activities where electricity is used as an input to production or to satisfy final demand of consumers. Also, the demands of fuels and capital enter the clearing of these markets, along with demands from all other production sectors. After solving the model, EPPA passes total electricity demand and price, elasticity of demand in the electricity market, and fuel prices to RISA. Next the RISA model is solved. The electricity model computes the optimal capacity expansion of the system and dispatch based on total electricity demand coming from EPPA and fuel prices. Following Böhringer and Rutherford's decomposition algorithm [17], the price-quantity point and the elasticity of substitution are used to construct a Marshallian demand, which serves as an approximation of the local representation of the general equilibrium demand (see Figure 4-4). The demand of the electricity sector for capital, fuels and other materials is computed in the bottom-up model. The new supply of electricity and new expenditures are passed to the EPPA model, which solves the general equilibrium problem with the updated inputs from the bottom-up (see Figure 4-5). A convergence test takes place after step 2, and if the supply of electricity provided by the bottom-up model and the demand from all sectors in the top-down are in equilibrium, and if all other markets are in equilibrium, the models have converged. Otherwise, the iterative algorithm restarts until convergence is reached.

Because the electricity sector is a small share of the economy, convergence between the two models is achieved in a relative small number of iterations, supporting Böhringer and Rutherford expectation that the algorithm would behave well for cases where the bottom-up model represents a small part of the top-down problem. By passing a reference point and demand elasticity in each iteration, the bottom-up model can approximate the general equilibrium demand and progressively.

4.4.3 Disaggregation of demand to hourly profiles in the bottom-up model

Because the EPPA model advances in steps of 5 years, I provide some details of how the time dynamics are treated in the bottom-up RISA model. As shown in Figure 4-6, on one hand EPPA provides a total annual electricity demand to RISA. On the other hand, hourly profiles of demand by region are inputs to the RISA model. First, total demand coming from EPPA is disaggregated by region proportionally to demand in each region in the baseline year. Second, using regional demand and the hourly profiles, demand is scaled to match hourly data. The RISA model solves the minimization problem using hourly demand data. The resulting generation in each

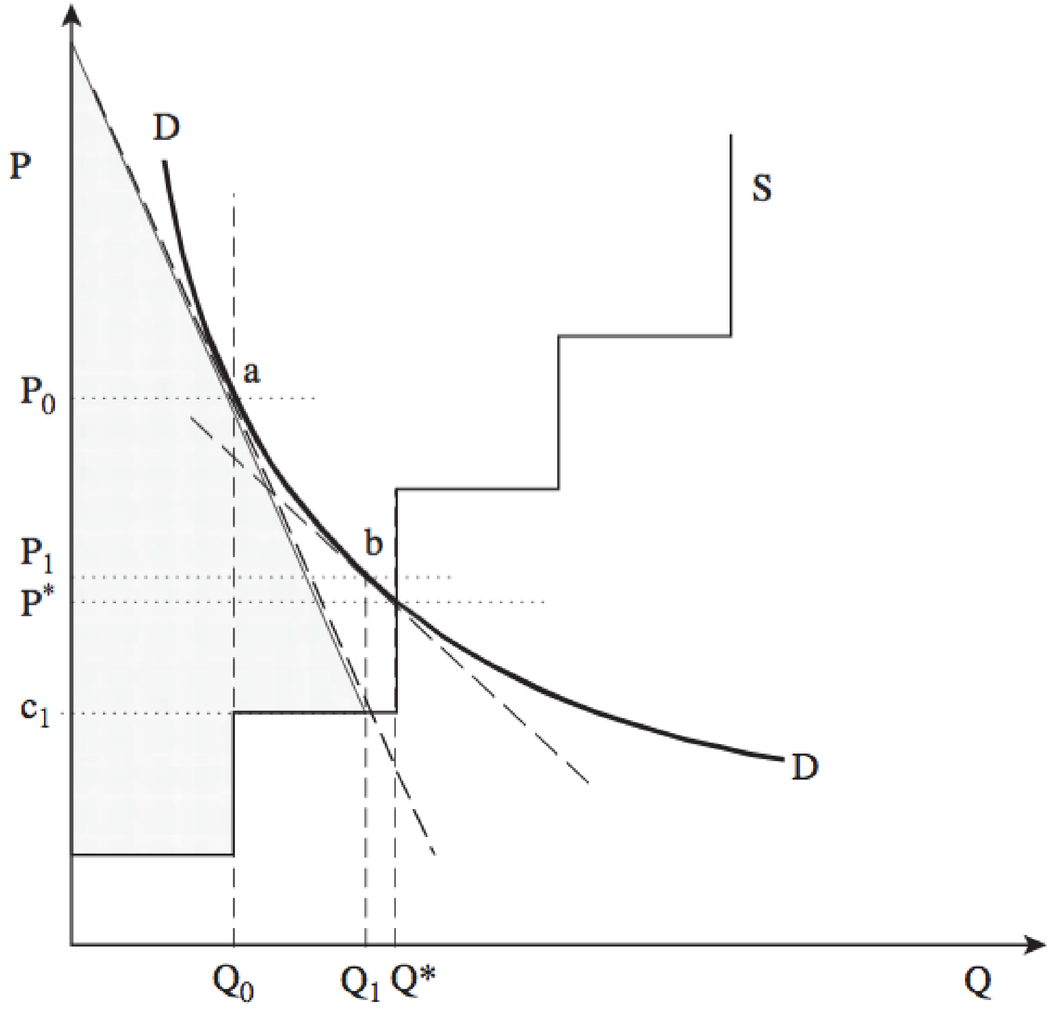

Figure 4-4: Iterative algorithm - Electricity market
Source: Böhringer and Rutherford [18]

Note: In the figure, the market for electricity is depicted to illustrate the problem solved by the RISA model. Electricity generation is characterized by a piecewise linear supply curve (S), and demand of electricity is a non-linear curve (D), which is linearly approximated (dotted lines) to reach the market clearance point. The equilibrium point is gradually achieved through a series of internal iterations that move supply from the initial point (Q_0, P_0) to the equilibrium point (Q^*, P^*). The initial quantity-price point coming from EPPA, *a*, is not on the bottom-up supply curve. At this point, the willingness to pay from consumers for electricity is higher than in the equilibrium point and marginal cost is lower; therefore, more electricity could be supplied. A first solution of the RISA model using a linear approximation of demand curve provides point (Q_1, P_1), with marginal cost c_1. The algorithm is repeated until the equilibrium reaches the intersecting point of supply and the non-linear demand. In this way, the algorithm maps the Marshallian to the Hicksian demand, as it moves through the price vector on the same indifference curve.

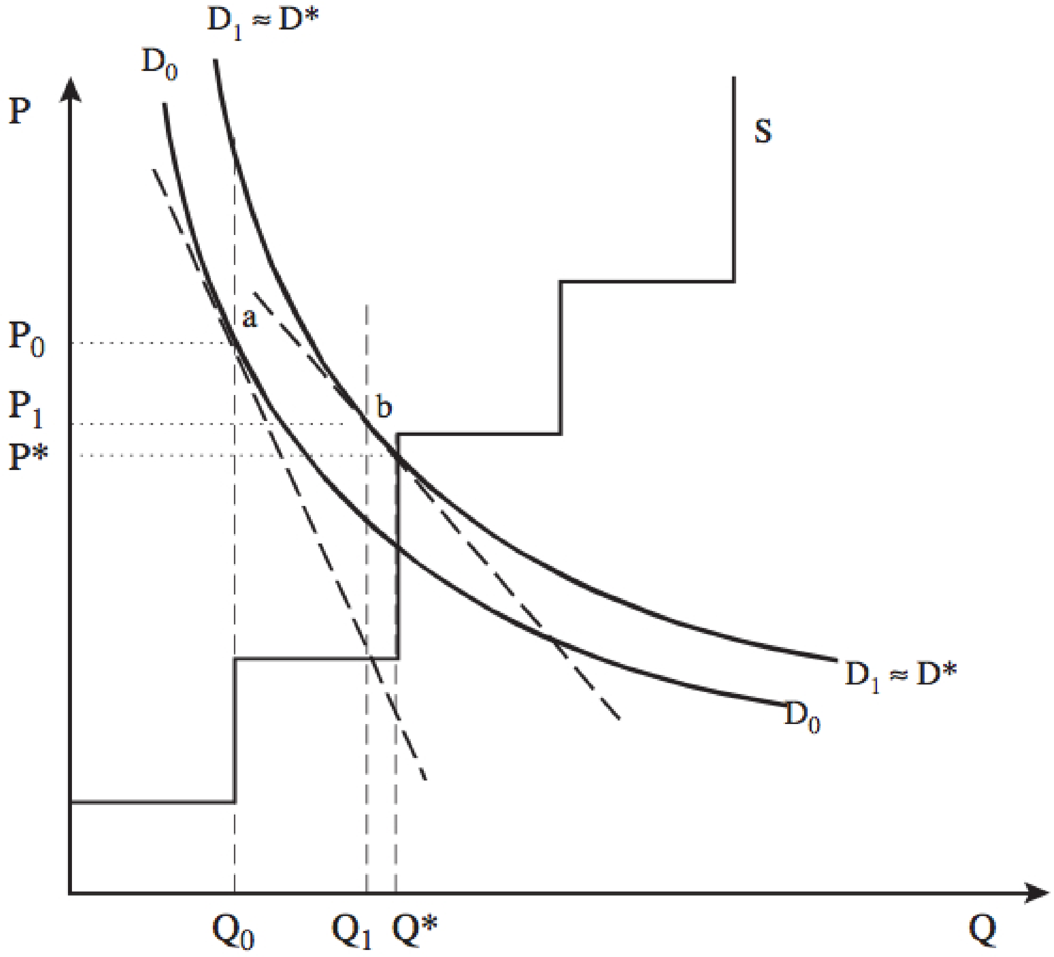

Figure 4-5: Iterative algorithm - Economy-wide adjustments
Source: Böhringer and Rutherford [18]

Note: In the figure, the multi-market equilibrium is depicted to illustrate the problem solved by the EPPA model for the electricity market. The initial guess of the EPPA, point a, is not on the supply curve of the bottom-up model. In the first iteration with RISA, EPPA updates Q_0 to Q_1 (the dotted line shows the linear approximation of demand made by the bottom-up model). The new quantity of generation represents a new equilibrium of the electricity market and has general equilibrium income and cross-market price effects, since it affects both consumers and other productive activities, as explained in Section 2. These effects combined shift the non-linear demand curve from D_0 to D_1 level. The new solution of EPPA model, (Q*,P*) provides the new equilibrium, where both substitution and income effects are taken into account.

region is processed again, to an annual level, to be sent back to EPPA.

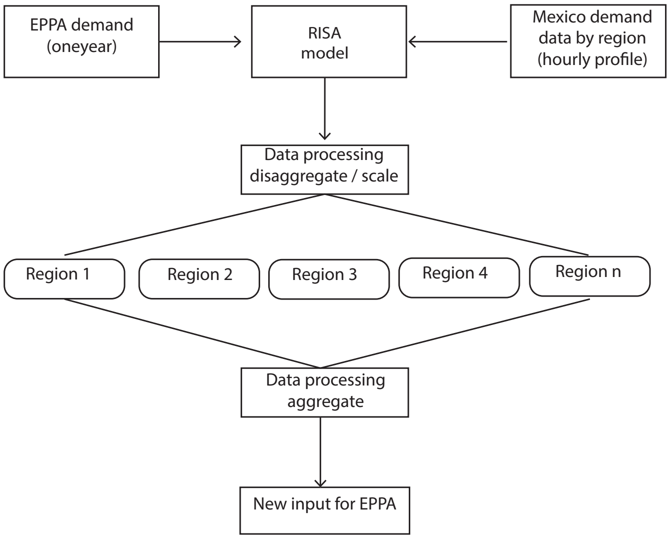

Figure 4-6: Treatment of demand dynamics between EPPA and RISA
Source: Author

4.4.4 Recursive dynamics

Both models follow the recursive dynamic formulation of the standard version of the EPPA model, taking decisions with information from the current period, as opposed to a forward-looking inter-temporal optimization. In general, there is a trade-off between the number of constraints and detail that can be incorporated in a forward-looking model versus the details that can be considered in a recursive dynamic model. This is true both in the case of CGE models and detailed electricity models, and for energy systems models more generally as well. While ignoring future periods is a strong assumption of the recursive-dynamic formulation, such is the perfect information assumption in the forward-looking approach, since in real world there is uncertainty in critical variables that determine investment decisions. In general, new approaches need to be developed to better assess uncertainty and inter-temporal decisions in detailed economic and technology-rich models [78, 122].

As discussed by Babiker et al., the recursive dynamic formulation has implications in the overall policy costs estimates, in particular “macroeconomic costs are substantially lower in the forward-looking version of the model, since it allows consumption shifting as an additional avenue of adjustment to the policy" [6].[25] However, in order to be able to solve the forward-looking version of the model, perfect information is assumed, along with several important simplifications of the EPPA model. For example, the forward-looking version of the model disregards the vintage structure of the capital stock and the number of available technological options in order to be able to solve the model inter-temporally, both of which are important for policy costs. I use the recursive dynamic most updated version of the EPPA model, and made several modeling considerations in the RISA model to consider the capacity installed in previous periods and technology costs trends as explained below.

EPPA6 is solved for the baseline year 2007, and then at 5-year intervals from 2010 onwards up to 2100. To move in time, both models iterate following EPPA's growth trends, including economic and population growth. Each period has a number of internal iterations until they reach a solution. The solution from the last iteration is used by EPPA in its projection of next period growth, which results in a new demand of electricity for next period. The process is repeated in subsequent periods computing a series of equilibria, as shown in Figure 4-7.

The RISA models takes investment decisions to expand the capacity of the different technologies, and keeps track of the total capacity that is installed for each technology, which depreciates linearly based on the life-time of each of the different technologies, as specified in Annex 1. Each period, the model considers the extant capacity (the sum by technology of all the capacity installed in previous years that has not been depreciated) and expands the system with the information provided by the EPPA model regarding costs of capital and fuels in the period. In addition to the prices and electricity demand coming from the EPPA model, the RISA model considers exogenously trends of decreasing costs in renewable energy technologies, as specified by the International Energy Agency [92].

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[25] By developing a forward-looking version of the EPPA model, and performing computational analysis with both versions the recursive dynamic and the forward-looking version benchmarked to the same growth pattern, the authors explored the effects of the different formulations on energy sector outcomes, emissions and policy costs.

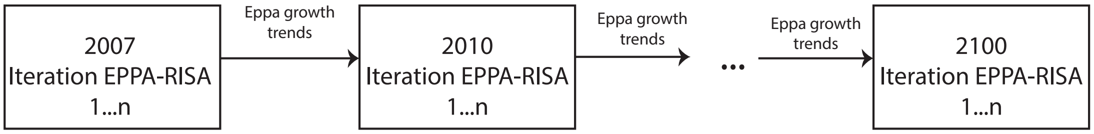

Figure 4-7: Recursive dynamics of the integrated EPPA - RISA model
Source: Author

4.5 Final remarks regarding the new modeling framework

While electricity contributes generally a small share of total GDP, its contribution to CO_2 emissions is substantial. At the same time, electricity availability and quality is essential for the correct functioning of modern nations, it enters in the production of almost all goods and services in the economy and powers many of human activities from refrigeration of food to personal computers and other appliances. Therefore, the role of storage technologies and other supporting infrastructure that can firm power coming from renewables is an important economic question with many ramifications. As the economy develops, the future of electricity demand can be expected to diversify and increase both because developing countries will demand more electricity and due to increased demand to power information technologies and transportation in developed and developing nations [97]. In particular, the future of electricity demand – and the future operation of electricity generation – interlace as we advance in decarbonization pathways. Modeling tools with the capability of assessing both dimensions, demand and supply in sufficient detail, will be important to understand the consequences of deployment of new electricity technologies. The modeling framework presented in this chapter has ample capacity to explore questions regarding renewable electricity and climate policy, with both technical and economic detail. In the next chapter, I focus in one of these questions, the social value of storage under large-scale penetration of renewable energy.

Chapter 5

The role of electricity storage under increasing penetration of renewables

In this chapter, the modeling framework described in Chapter 4 is used to elicit the value of storage using a reverse engineering approach. First, I describe what is reverse engineering and the computational experimental design. Second, I present results on the value of storage, and compare them to current cost estimates. Third, I describe the mechanisms that determine storage value in terms of its impact on investment decisions and operations of the electric power system. Fourth, I discuss the implications of economic storage availability from a social point of view presenting the general equilibrium effects. The chapter concludes with policy implications regarding costs of climate and renewable energy policies with and without the availability of storage technologies.

5.1 Experimental design

The modeling framework described in Chapter 4 is used to elicit the value of storage using a reverse engineering approach. Reverse engineering is a technique widely used in engineering design, financial analysis and in software development. When applied to engineering design it can be defined as the "process of creating a similar device, object, or system after examining the original and discovering its technological principles through analysis of its structure, function, and operation" [57].[1] In financial analysis, reverse engineering is an analytical approach through which one can deduce the value of an asset by “reversing the valuation process” using information available in the market and assumptions regarding key variables, such as expected profits, growth rates and risk-adjusted discount rates.[2]

In this dissertation, I use reverse engineering to analyze the performance of a hypothetical volume of storage technology deployed in a power system with renewables and to recover information about its operation and theoretical remuneration at different levels of storage capacity to estimate the system's storage value. Thus the reverse engineering method is used to understand both the operation of storage in a specific system through a computer model simulation (and how the physical system's structure and operation change as the amount of storage changes), and to estimate the economic value of that amount of storage.

Why is a reverse engineering approach needed? Currently, the high cost of storage technologies has resulted in very limited use of these technologies in most power systems worldwide.[3] The reverse engineering methodology allows for a technology neutral estimation of the value of storage. Instead of constraining the optimization problem to costs parameters of specific storage technologies, the reverse engineering experimental design evaluates the use of storage given some storage capacity in the system. First, a small capacity of storage is added to a system (at no cost) and we compare the system's performance with and without storage. For example, we investigate what would happen if the system were to have 5% of storage capacity,

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[1] Reverse engineering applied to system design can rely on computer modeling prototypes.

[2] Many times in financial analysis one is interested in finding out what is the right value for stocks, considering information about the firms independently of the prevailing market value. Financial investors are always looking for firms whose market value does not properly reflect their real value, since those that are undervalued constitute good investment opportunities. As explained by Wahlen et al [193], the valuation process of firms is characterized by four main key variables: expected future profits, expected long-run future growth, expected risk-adjusted discount rates, and current firm value. One can make assumptions about any three of the four values and solve for the fourth value. The method of reverse engineering allows to ask questions such as what should the rate of return of this asset be, in order for the stock to be priced at fare value. The investor then can compare her own expectations regarding the rate of return with those implicit in the stock market price and decide whether a stock is correctly valued, undervalued or overvalued.

[3] This with the exemption of PHS which is used economically in some systems.

how much we would pay for this specific amount of storage considering the services it provides to the system. Second, we add more storage to the system, and again observe the system changes and the value of storage. A series of scenarios is specified to estimate the marginal value of storage as we add more and more capacity of storage to the system.

Table 5.1: Experimental Design to Elicit the Value of Storage

Storage capacity*	**Renewable energy targets per year (% of total generation in GWh per year)**								
	2010	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	0%	5%	20%	25%	30%	35%	40%	45%	50%
10%	1a	2a	3a	4a	5a	6a	7a	8a	9a
15%	1b	2b	3b	4b	5b	6b	7b	8b	9b
20%	1c	2c	3c	4c	5c	6c	7c	8c	9c
25%	1d	2d	3d	4d	5d	6d	7d	8d	9d
30%	1e	2e	3e	4e	5e	6e	7e	8e	9e
35%	1f	2f	3f	4f	5f	6f	7f	8f	9f
40%	1g	2g	3g	4g	5g	6g	7g	8g	9g
45%	1h	2h	3h	4h	5h	6h	7h	8h	9h

*Storage capacity is specified as a percentage of renewables generation.

Future energy scenarios are designed using the economic and population growth assumptions that determine electricity demand in the EPPA model. Table 5.1 summarizes the family of scenarios explored for each of the periods of the EPPA model between 2015 and 2050. A full trajectory of the system expansion can be read in each row, each cell representing the solution of the integrated model for each year, at a given level of storage capacity in the system. Thus, the family of scenarios 1a, 2a, .., 9a represent a full trajectory from 2010-2050 with 10% of storage capacity in the system (as a share of total renewable electricity generation). A policy that requires renewable electricity to increase its share of total generation gradually from 5% in 2015 to 50% in 2050 is mandated, thus as we advance in time we also increase the renewable penetration in the system. For example, in 2010 zero per cent renewable penetration is assumed in the system, but it gradually grows to 25% in 2025 and reaches 50% in 2050. Ten different levels of storage capacity as a percentage of total renewables generation are modeled, from 10% storage as a percentage of renewables in the system to 45%. I scale the total capacity of storage as a percentage of total renewables penetration so that I can assess later the potential range of storage capacity that seems suitable to accompany renewables penetration. The result scenario setting is an ensemble of 72 full runs of the iterative modeling framework.

Each of the iterations requires in itself between 5-7 runs of each of the models. For each year, the initial pair of price and quantity of electricity and inputs to production comes from the EPPA model to the RISA model. RISA model optimizes the system expansion and dispatch considering this demand level, as well as price indexes coming from the EPPA model for all inputs to production. The models iterate as explained in Chapter 4 (Section 4.4) to find a consistent solution that satisfies both the general equilibrium in the economy and the cost minimizing solution in the electric power sector.

5.2 Value of storage

Based on the economic marginal principles for electric power systems [139], the value of storage can be computed as the remuneration that the providers would obtain for the provision of four distinctive services to the system: energy supply, upward operating reserves, downward operating reserves and capacity reserve.[4] From the cost minimization problem, the Lagrangian multipliers associated with each constraint – when active– result in the prices that consumers should pay for these services. For each hour of the year, the shadow price for each of these constraints is used along with the corresponding level of storage service for that hour. The aggregate of the remuneration for each of these services (hourly price times quantity supplied) provides the value of storage for the system. Equation 5.1 shows the calculation of the value of storage. The prices for each of the services are endogenously computed in the

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[4] This payment is not a capacity mechanism; it is associated to the constraint for reserve margin. The shadow price of this constraint is used to remunerate storage for its contribution to meet peak demand. To be sure that the storage facility can provide this reserve a minimum requirement of stored energy is also imposed as a constraint to the model. While this is a way to ensure that this minimum level would be available to meet peak demand, it induces some inefficiencies in storage operation (since it forces storage to maintain a reserve of energy.)

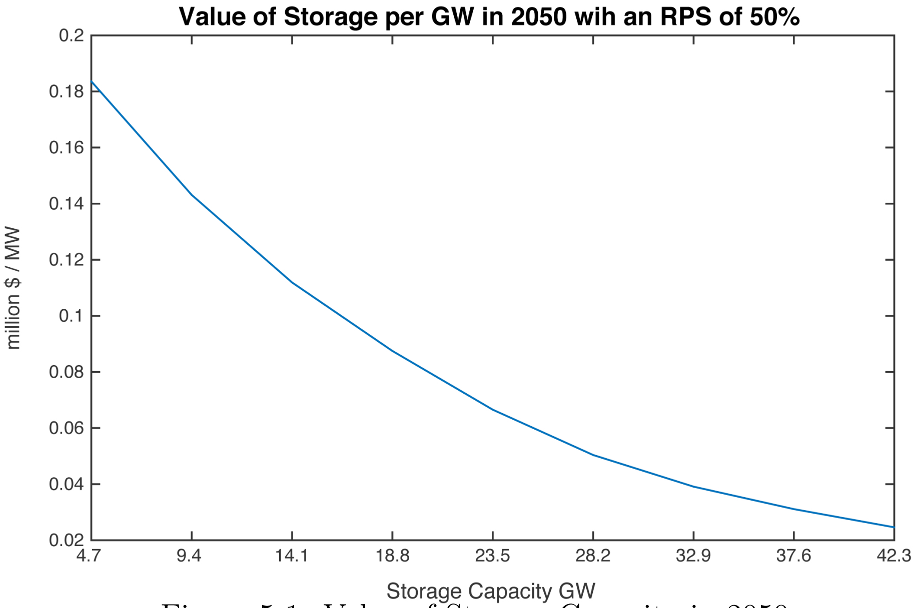

Figure 5-1: Value of Storage Capacity in 2050
Source: Author Modeling Results

model and are a function of total capacity and use of storage in the system. As opposed to other studies that use the price-taking approach, storage technologies can be important in the price formation process.

$$VoS = \sum_h \rho_{t,h}\,\mathrm{Out}_{t,h} - \rho_{t,h}\,\mathrm{In}_{t,h} + \sigma_{t,h}^{UP}\,\mathrm{OR}_{t,h}^{UP} + \sigma_t^{DW}\,\mathrm{OR}_t^{DW} + \tau_t\,\mathrm{P}_t \qquad (5.1)$$

Where the Value of Storage, *VoS*, is computed using information for each year t and each hour h of the following variables. $Out_{\mathrm{t,h}}$ is the energy outflow from the storage device when storage is discharging, $In_{\mathrm{t,h}}$ is the energy inflow when storage is charging, $\rho_{\mathrm{t,h}}$ is the *hourly electricity price*, $\sigma_{\mathrm{t,h}}^{\mathrm{UP}}$ is the *upward operating reserve price*, $\sigma_{\mathrm{t,h}}^{\mathrm{DW}}$ is the *downward operating reserve price*, $OR_{\mathrm{t,h}}^{\mathrm{DW}}$ is the level of downwards reserve provisions, and $OR_{\mathrm{t,h}}^{\mathrm{UP}}$ is the level of upward reserves provision, $\tau_{\mathrm{t,r}}$ is the *capacity reserve price* and P is storage rated power.[5]

The value of storage is the remuneration that the system would allocate for storage services; I explore how the value changes by testing how the remuneration changes as the capacity of storage in a system increases. Figure 5-1 shows the value of storage estimated for the year 2050, resulting for the family of scenarios 9a-9h as shown

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[5] A constraint is imposed such that the minimum level of energy stored in the system must allow the provision of energy for one hour at rated power.

in Table 5.1. The value of storage is equivalent to the "willingness to pay" for the services storage could provide. For example, as shown in the graph, in 2050 with a 50% penetration of intermittent resources, a 10% storage capacity in the system would be valued in 0.17 million $ per MW. If we increase the capacity of storage in the system to 20% the value drops to 0.07 million $ per MW. At 45% storage capacity as a percentage of total renewables in the system, the value has decreased to 0.02 million $ per MW. We can observe that as we add more storage to the system, its value decreases.

The evolution of the value of storage under large-scale renewables penetration is presented in Figure 5.2a and 5.2b. The surface represents the results from the experimental design ensemble and shows the value of storage from 2015 to 2050. As shown in the figures, at very low penetrations of renewables and under the current configuration of the system, the value of storage is very low. However, the value of storage increases in time as renewables expand. The surface represents the growth of storage value as a function of total renewables in the system and total capacity of storage. The second observation is that in each year, storage value is maximal at low capacity, but as we add storage to the system the value declines. We can infer from the figure a pattern suggesting that, as renewables penetration increases, a storage capacity between 10% to 25% presents consistently higher values across scenarios. Figure 5.2b presents the same information in two dimensions showing the value scale in color. We can infer that penetrations of storage above 35% would probably exhaust the value of storage.

Once we estimate the value of storage in a particular system, we can compare this value to the cost of providing the service. Storage providers will supply this service only if their cost structure allows them to break-even, otherwise storage would not be supplied in the system. In a perfectly competitive environment, the price that the market is willing to pay for a service should be equal to its marginal cost. The application of reverse engineering allows exploring the target technology cost of storage indirectly: since supply and demand would be equal at an equilibrium point, the value that we are willing to pay must be equal to the cost of producing one more

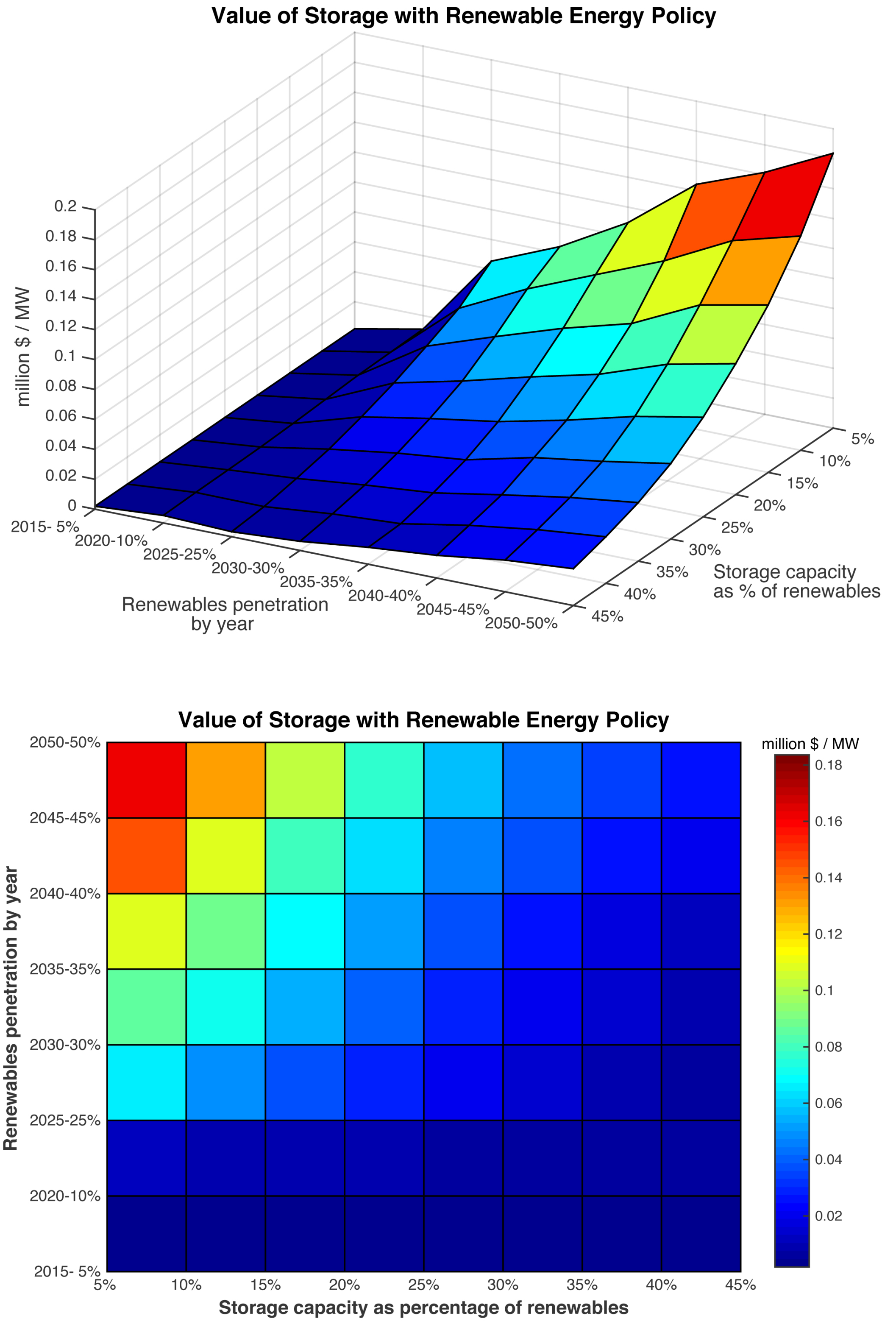

Figure 5-2: Value of Storage under Large-Scale Penetration of Renewable Energy
Source: Author Modeling Results

unit of storage. I am not providing information on the cost directly (i.e. I am not performing any cost analysis of different technologies and this is not a parameter in the model). However, any provider could look at the curve of the value of storage and decide whether the value proposition is interesting to participate in the market.

A reasonable question to ask now, is whether current storage technologies will be deployed given the estimated value of storage and their current cost. Figure 5.3a and 5.3b show the comparison of the estimated value of storage against the current cost of different storage technologies, as surveyed by the Electric Power Research Institute in 2011 [63]. To provide this comparison, I first compute the present value of storage considering the annual cash flow revenues that a provider would receive for the operation of a storage device in this system for 30 years, considering a 6% discount rate.[6] The present value is represented in the graph by two horizontal lines: one is the value resulting from the installation of storage at a 10% of total renewables in the system and the second represents the installation of storage at 25% of total renewables in the system. These lines relate to the family of Scenarios a (2a,...,9a) and Scenarios h (2d,...,9h) as specified in Table 5.1.

As shown in the graph, if we consider capacity costs at 10% capacity of storage, CAES technologies, two battery chemistries (ZnBr and ZnAir) and a few PHS designs would be economical at today's costs if we consider a very large future expansion of renewables in the system. At 25% capacity of storage, only CAES remains economical. If we combine this with the cost per kWh, only CAES is economical. This means that most technologies will have to further decrease costs, even if we expect very large-scale renewables penetration. As explained in Chapter 4, there is much on-going research of new storage technologies that aim to drastically reduce their cost. Of course, there is nothing preventing the adoption of higher shares of storage technologies if the cost declines even below the value levels I present. Whether we could expect drastic cost

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[6] The present value calculation was done in MATLAB. First an annual stream of cash flows is estimated using the spline function to interpolate from the value estimates every 5 years. The scenarios imply that capacity additions will have to occur in time (i.e. storage capacity is expanded to provide a constant 10% as share of renewables in the system); however, for the present value calculation only the cash flows occurring within the period between 2020 and 2050 were considered and normalized by \$/kWh or \$/kW. MATLAB's present value function (pvvar) is used with 6% discount rate.

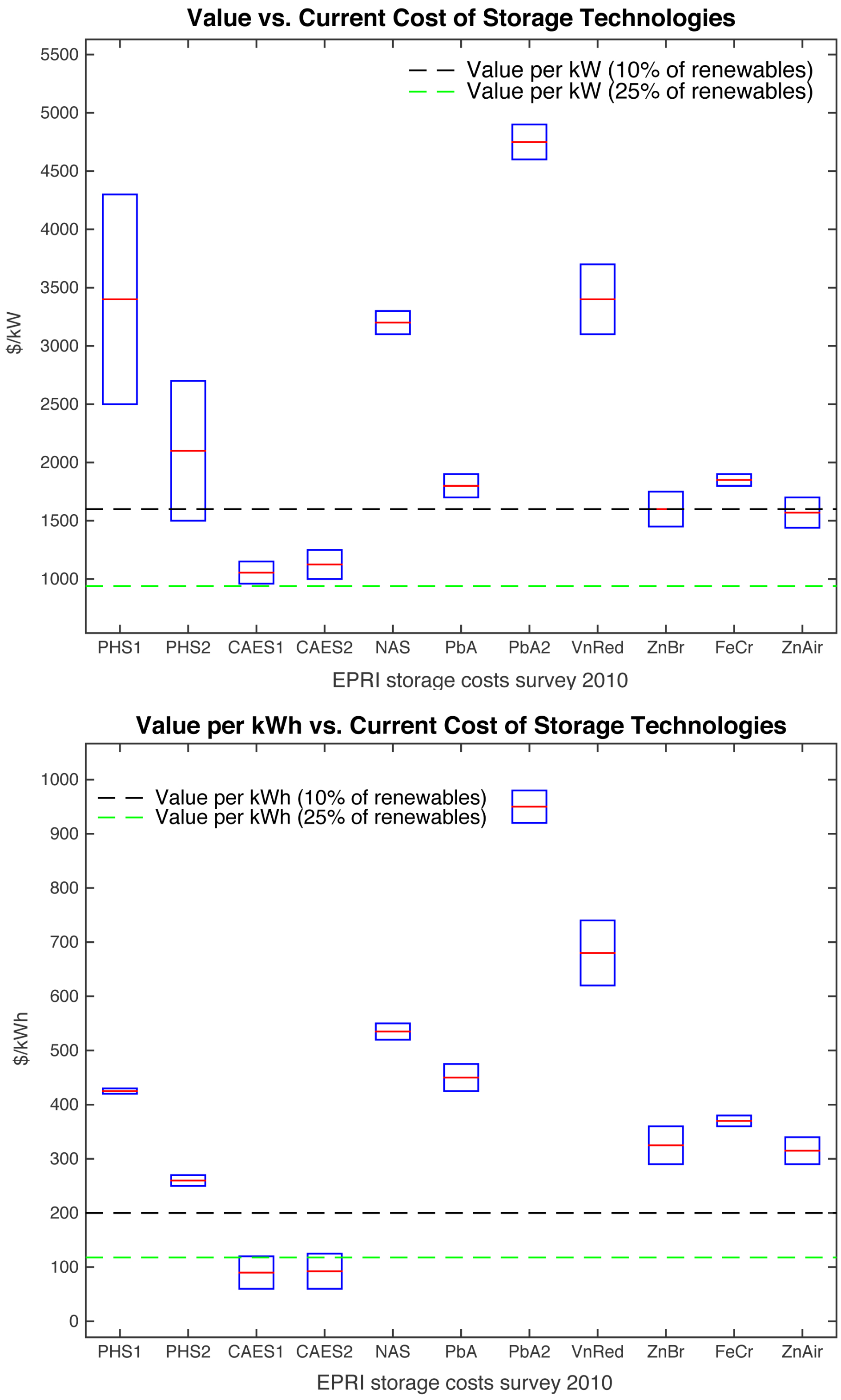

Figure 5-3: Value of Storage Compared to Current Technology Costs
Source: Author with Modeling Results and Information on Technology costs from EPRI [63]

reductions in the next decades below these levels is an open question. The value of storage calculated here provides a good insight of the level of cost reductions needed considering a future with large-scale renewables technologies roll-out.

In the next section, I explain the mechanisms that determine storage value and further decompose this value to understand its impact on renewables penetration and in other electricity generation technologies.

5.3 Mechanisms that determine storage value

One can decompose the value of storage into the different services it provides to the electric power system. Figure 5-4 shows the split between the revenue from the energy market and the one from the ancillary services market. In 2015, storage remuneration sums 6.3 million dollars; 56% coming from the energy market, 43% ancillary services provision and 1% from capacity payments. In this year, only 5% of the energy comes from renewables. By 2050, when 50% of generation comes from intermittent renewables, the remuneration for storage provision grows 3.9 times to reach 24.43 million; 58% of it is associated with energy management services, 22% with ancillary services and 18% with capacity payments.

Market dynamics are profoundly modified with the introduction of renewable energy and storage technologies. The changes are disruptive, because they force other electricity technologies in the system to change their operation drastically, and as a result the economics of extant technologies are impacted.

First, I explain the operational conditions changes driven by renewables and storage in the system. Figure 5-5 illustrates the economic dispatch of different generation technologies in 2030, using results from the RISA model. A sample week was selected to illustrate conditions where increased cycling of thermal generation is observed due to variable wind profiles. The figure shows at the top demand, wind and the resulting net demand. Net demand is met by the other electricity technologies. In this week, nuclear, geothermal and coal are at the base followed by combined cycle units as shoulder generation. As shown in the figure, hydro and storage outflows are provid-

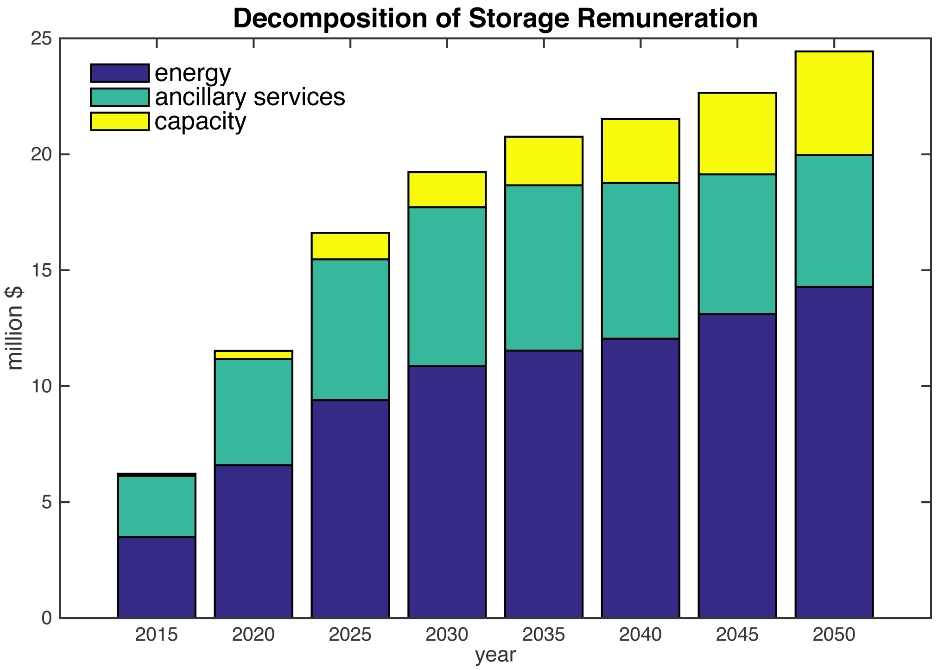

Figure 5-4: Decomposition of the Value of Storage
Source: Author-modeling results

ing peak generation to meet net demand. At the bottom of the figure, the hours where storage is charging are shown. One can see that storage is charging to avoid wind curtailment while allowing combined cycle natural gas units operation. Although fairly variable, this wind profile combined with this week's demand level allowed for a stable base load generation, with hydro and storage providing power such that not too much disruption in the thermal technologies operation is experienced this week.

However, wind profiles in other weeks demand more changes from the thermal fleet. Figure 5-6 shows a sample week, also in 2030, during a very windy period with some hours of low demand. As shown in the figure, during this week for many hours net demand goes negative. During these hours storage charges energy, avoiding wind curtailment and allowing nuclear to continue its operations. The minimum levels of hydro and some thermal technologies can be maintained by storing their energy production during these hours. Several days of this week, however, coal and combined cycle units need to shut down completely and restart. Peak net demand is met with storage, hydro and open gas turbine units. Storage during this week provides critical services both during charging and discharging hours.

A third example of difficult operational conditions brought about by renewables

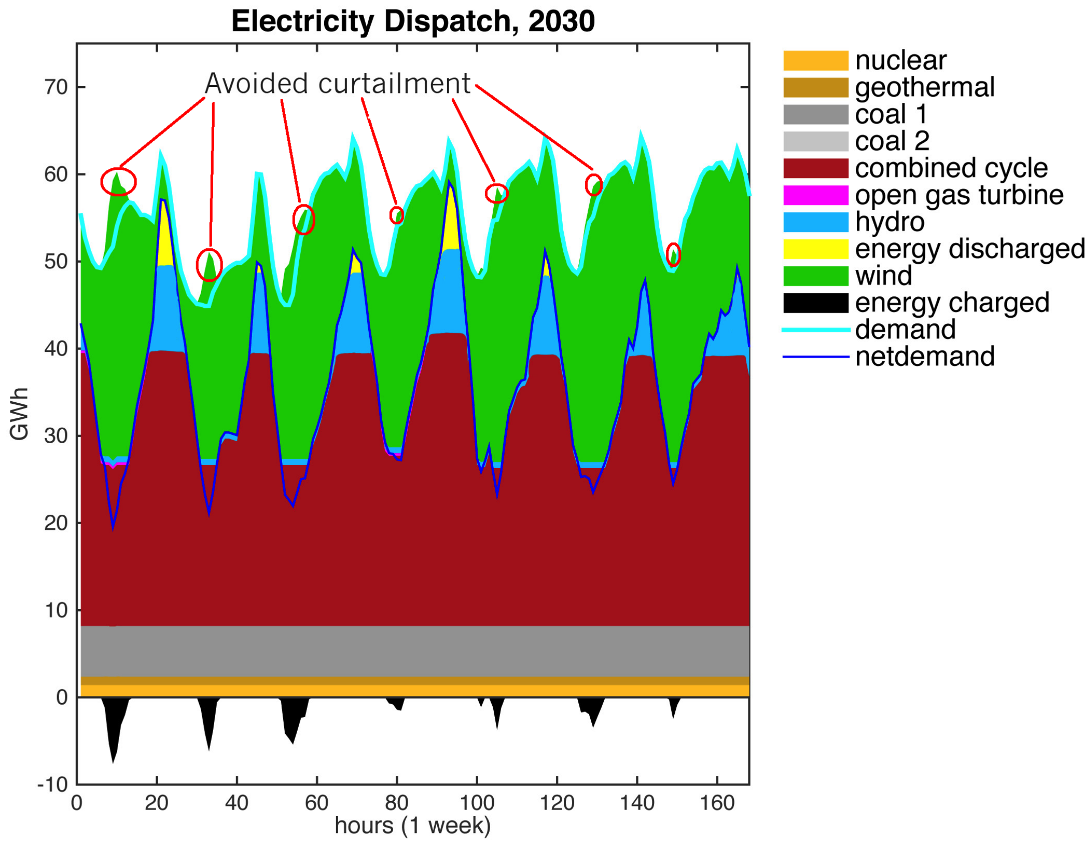

Figure 5-5: Electricity dispatch - one sample week in 2030
Source: Author-modeling results.
Note: As shown in the graph, there are some hours where wind exceeds demand. Without storage wind would be curtailed (or the operation of thermal units must be stop to allow wind to serve demand.)

penetration is illustrated in Figure 5-7. Another sample week of 2030 is shown to illustrate the situation when the system experiences an episode of transition from very high wind to almost null. As shown in the figure, storage charges during negative net demand periods and discharges during the periods where not enough thermal capacity has yet been connected. Hydro and open gas turbine units also assist the transition until more thermal generation is called into the system. As shown in the figure, at the end of the week the wind is almost zero, with hydro and storage outflows serving net load peaks during this low wind episode.

A final example of an important operational moment is provided in Figure 5-8. The figure illustrates the dispatch during the week when peak demand occurs. In traditional systems, this is the week where most stressful operational conditions

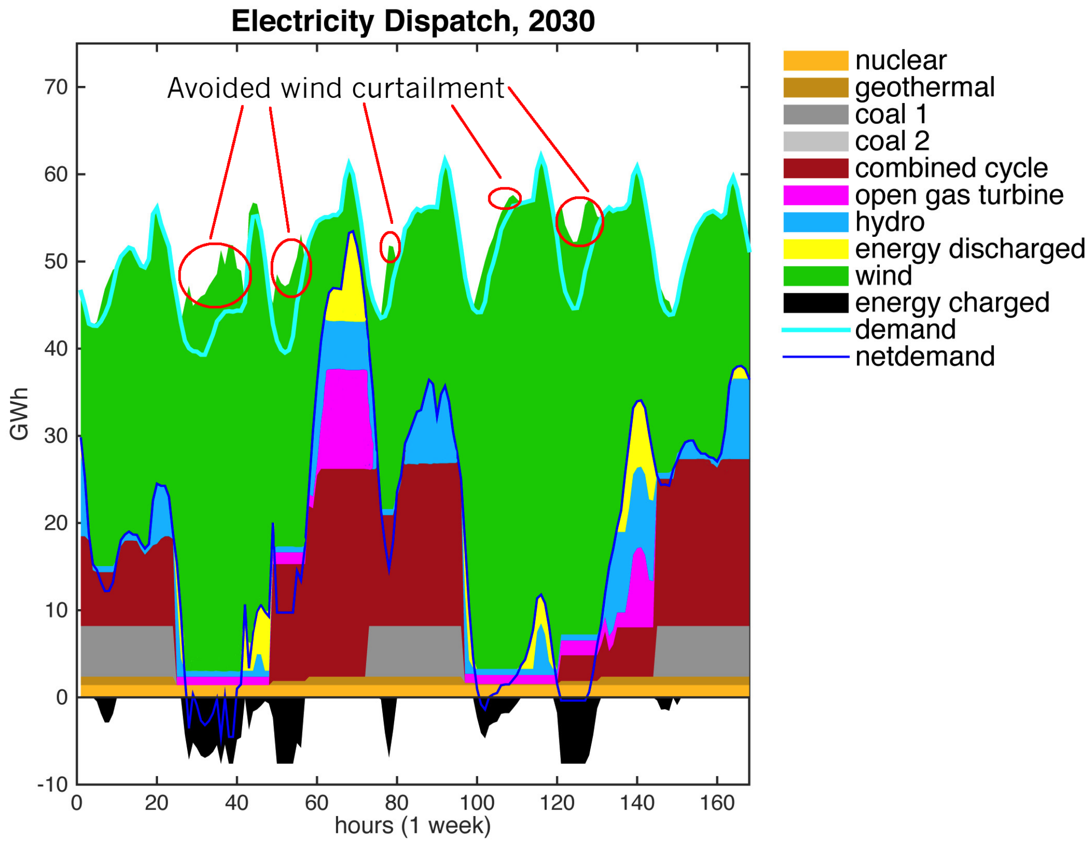

Figure 5-6: Electricity dispatch in a windy week in 2030
Source: Author-modeling results

could occur, since most of the capacity in the system is in operation and any forced outages could be stressful if the system does not have enough reserves, requiring power transmission from neighboring systems, or even not serving demand. The results of the model show that during this week (in July for Mexico's peak) the system has relatively low wind levels. Nuclear, geothermal, coal and combined cycle generation are connected and operating base loaded. Net load fluctuations are met with hydropower and with storage outflows.

The above examples illustrate some of the new conditions for power system's operation. Although I present only four weeks representing particular situations of interest, it is clear with these few examples that increased operational flexibility would be valuable for the system. The examples also highlight how storage could assist providing flexibility to the system. One would like to explore what is the effect in the market of having flexibility or not. In particular, it would be important to

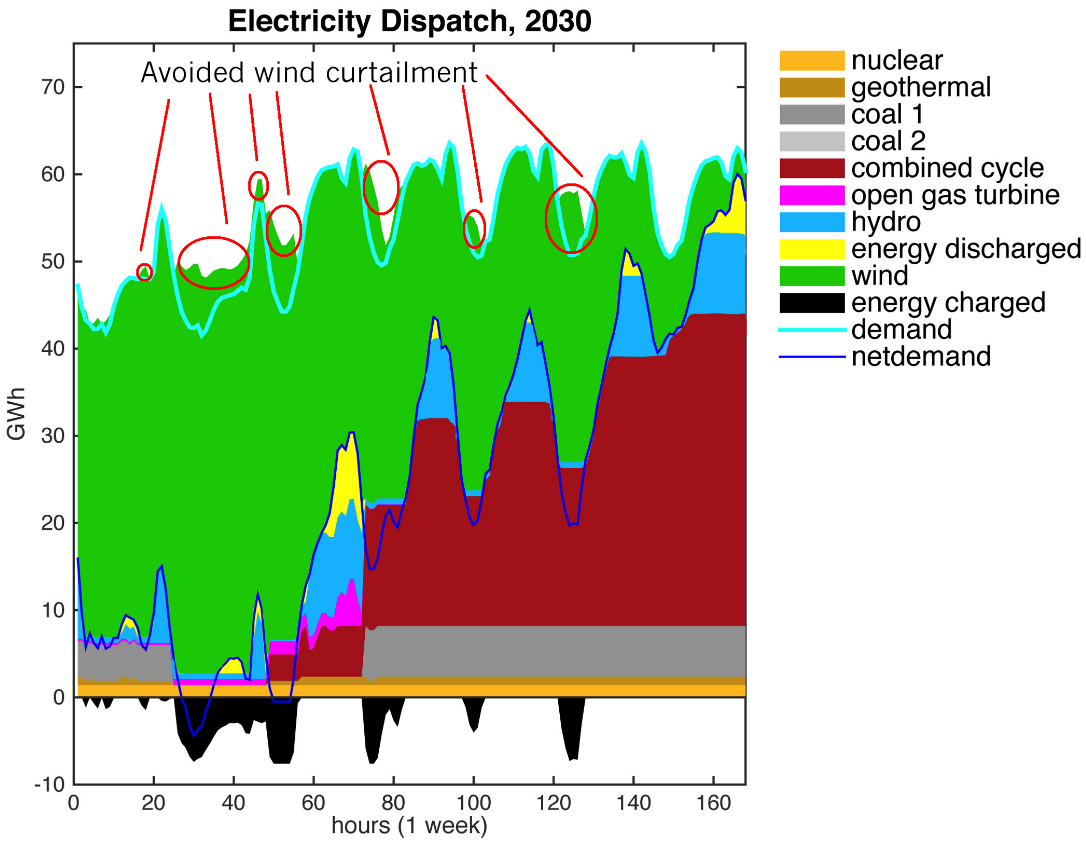

Figure 5-7: Electricity dispatch in a high wind to no wind episode in 2030
Source: Author-modeling results

know: a) how do renewables affect prices and b) whether the capacity of storage changes price dynamics in markets with large renewables penetration.

In the energy market two different activities occur regarding storage. First, storage needs to charge energy at an hourly price. Second, storage discharges energy and gets a payment for the energy provided also at the hourly price. The spread between the charging and discharging prices is what traditionally has made the business case for storage through price arbitrage. As the system evolves towards higher penetration of renewables, the new net demand (demand minus wind) is highly variable, and the spread between the new valley hours and peak hours expands. Figure 5-9 shows the distribution of prices at different levels of renewables penetration resulting from our model.

As shown in the figure, as larger shares of renewables enter the market, price volatility increases. The price spread increases from \$130 in 2020, to \$270 in 2030,

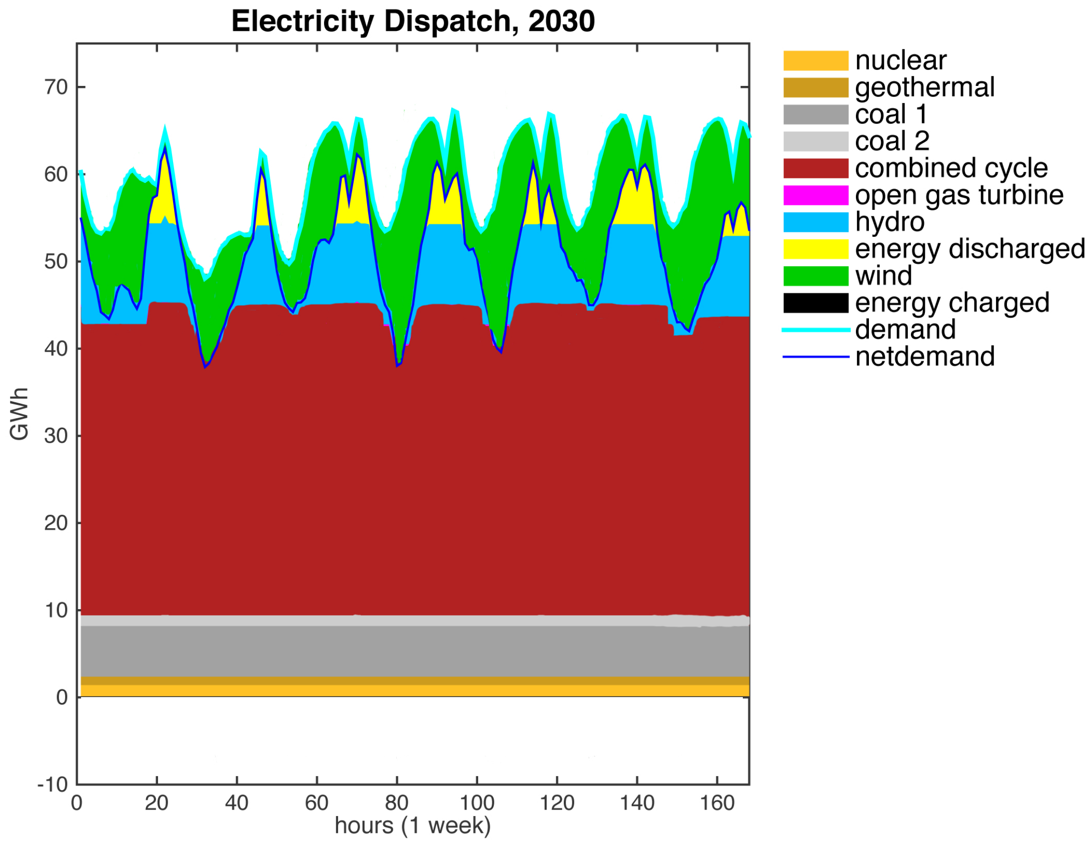

Figure 5-8: Electricity dispatch during demand peak week in 2030
Source: Author-modeling results

and \$575 in 2050. The volatility, as measured by the standard deviation of prices, in 2015 is 9 \$/MWh, and increases to 29 \$/MWh in 2030, and 48 \$/MWh in 2050. Due to larger shares of zero-variable-cost generation entering the market, a lower mean value of electricity prices results. At the same time, however, some hours of the year will present very high price spikes, i.e. those with very low or no wind and coincident high demand. Technologies with the capacity to arbitrage this difference, like storage devices, could find these new market dynamics attractive.

Storage capacity reduces price volatility: by charging during low-price hours it increases the prices in those hours, closing the gap between peak and valley. Figure 5-10 shows the effect of increasing capacity of storage on the energy component of electricity prices. The price distribution in 2030 is shown for different levels of storage capacity. We can observe that the price range decreases as storage capacity increases.

There is a new market dynamic that requires further explanation: as renewables

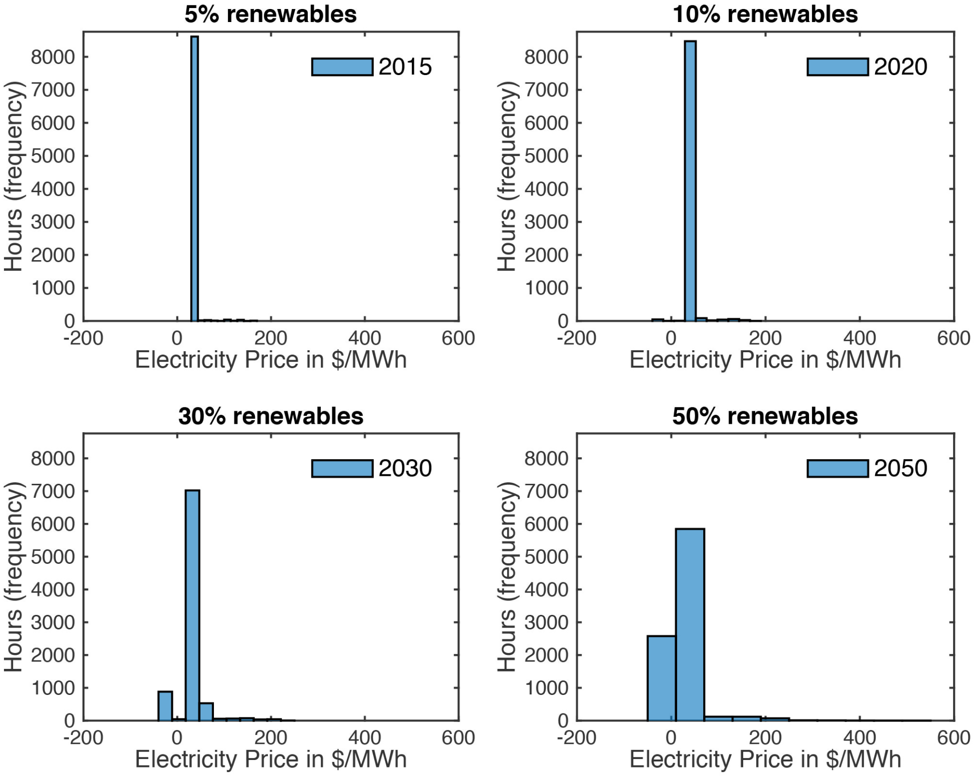

Figure 5-9: Distribution of Electricity Prices at
Different Levels of Renewables Penetration
Source: Author-modeling results

penetration in the system increases, prices can be negative for many hours of the year. The explanation of these “negative price” hours has to do with the inflexibility embedded in the system. At very large penetration of renewable energy, the fluctuation of net load could require very low levels of operation of the thermal fleet, potentially pushing some technologies to their technical minimum or forcing them to shut down. Some of these situations were illustrated in Figures 5-6 and 5-7. Negative prices occur when the system has units that are inflexible and cannot change their production levels as demanded by the market for technical reasons. In this case, some generators could bid negative prices so they are dispatched. Avoiding the shut-down and start-up costs is cheaper for some generators than paying a negative price for some hours (so they opt to pay to produce).

We observe that in 2015, when renewables penetration is assumed to reach just 5% of total generation, electricity prices never reach negative levels, but in 2030, when we mandate 30% renewables penetration, 10% of the hourly prices are negative. By 2050,

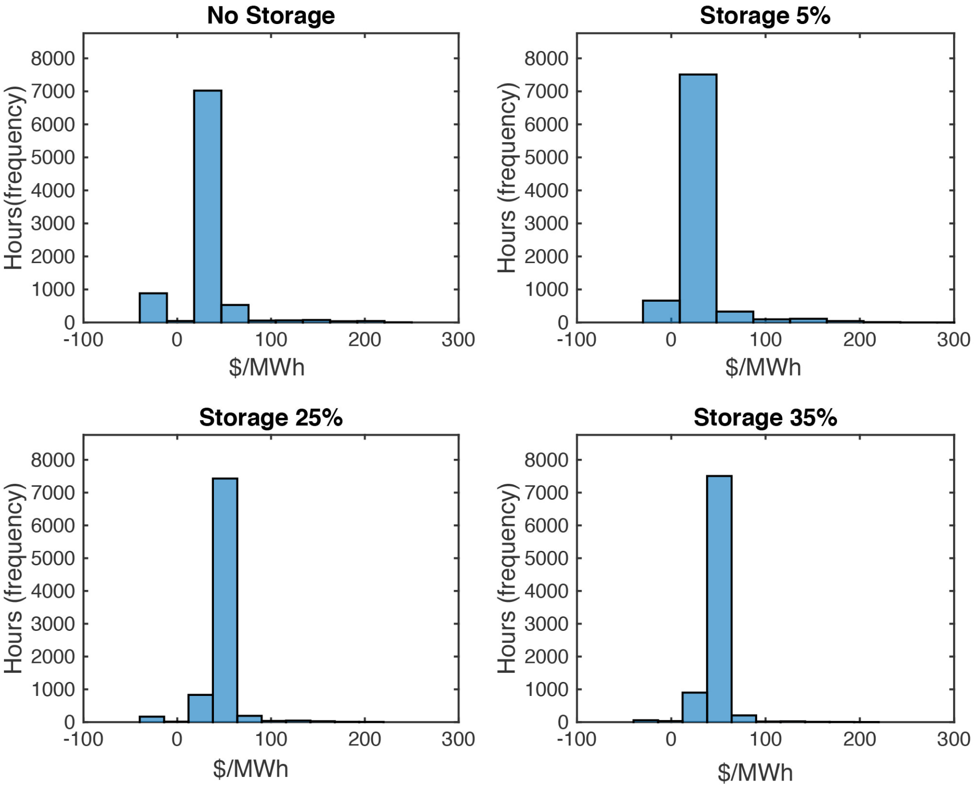

Figure 5-10: Impact of Storage on Electricity Price Volatility.
Prices in 2030 at different levels of storage.
Source: Author-modeling results

when a 50% penetration of intermittent renewables is modeled, 29% of the hours of the year are at negative prices. The occurrence of negative prices is for sure one of the new dynamics that captures the attention of electricity market experts and the industry more generally. Negative prices have occurred in markets with important shares of intermittent renewables in the grid and could arguably be important to provide flexibility to the system, by allowing some generators with technical constraints to avoid shut-downs during temporary net demand fluctuations. In some countries, however, negative prices have been associated with wind and solar generators under a feed-in tariff (FIT). The FIT creates an incentive to generate electricity under negative prices for wind and solar generators that would find economic to bid negative prices up to the size of the FIT, since they would make a profit for the difference.[7] New

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[7] For example, if a FIT of 150 $/MWh for wind generators is in place, then these generators will make a profit of 5 $/MWh if they bid -145 $/MWh. Since renewables marginal cost is for practical purposes zero, they could bid up to -150 $/MWh.

measures are put in place to ensure that generators have no incentive to generate electricity under negative prices, but allow negative prices otherwise for generators that are not under FIT [186].

In Europe, for example, negative price bidding is allowed both in the day-ahead and in the intraday markets of the European Power Exchange (EPEX).[8] In 2013, with a 13.7% renewables penetration, Germany's market experienced 56 hours of negative prices [60, 21]. Negative prices can actually reach very important levels; for example, in France during two summer days of 2013 prices reached a low peak of -200 Euros/MWh [12]. In the US, negative prices have occurred in the wholesale market of the Pacific Northwest, where environmental constraints to hydropower, technical constraints to nuclear and wind technologies conflict [56] and in Texas electricity market, where a combination of transmission constraints, inflexibilities in the system along with the production tax credits (PTC) resulted in many hours of negative hours during 2011 and 2012 [55, 86].[9] We will return to the discussion of the impacts of renewables and storage on the electricity wholesale price, and potential regulatory ramifications in Chapter 7.[10]

I have explained so far the mechanisms driving the price of electricity, focusing on the energy market. I turn now to the discussion of the value of storage derived from the provision of ancillary services. As Hummon et al [85] discuss, reserves result in a cost to electric power systems in order to maintain the ability to face contingencies and variations of net demand. To this day, the main providers of this service in most power systems are hydroelectric plants and thermal units.[11] For storage to participate in this market, it needs to compete with other potential reserve providers.

As shown in Figure 5-4, our modeling results for Mexico indicate that ancillary services constitute an important share of the value of storage. The value of ancillary

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[8] Currently, 28 EU countries trade under a common platform.

[9] After the "competitive renewable energy zones" (CREZ) transmission expansion program, wind curtailment and the occurrence of negative prices have decreased significantly in ERCOT. Huntowski et al argue that the PTC played an important role in the occurrence of negative prices in ERCOT as well, given the incentive that wind producers have to bid negatively up to the size of this subsidy to production, distorting market dynamics.

[10] For instance, the impact of feed-in tariffs, production tax credits and priority rules.

[11] Demand response is today limited, but could also be a very important competitor in the future.

services increases with renewables penetration. For example, in 2030, the prices ranged from 0-200 MW-h, and in 2050, the prices ranged from \$0-1176 MW-h (the last value occurred only in one hour).[12] Total annual remuneration of storage for ancillary services more than doubled in 2050 compared to 2015, going from 2.5 to 5.6 million. However, despite this trend, the value of storage coming from reserves does not escalate with renewables as the value of energy management services does. In fact, reserves provision decreases from 43% to 22% as percentage of the value of storage. This finding suggests that as renewables penetrates the mix, storage services for energy management become more valuable compared to reserves provision.[13]

Similar to the findings of Hummon et al. [85], I find that while wind increases reserves requirements, it frees up proportional generation capacity from other units and thus the additional cost for reserves provision does not involve building new capacity at the beginning of renewables deployment when a system is transitioning to higher shares of renewables. The cost of providing reserve involves the operating costs of connecting power to be ready to provide reserves.

In addition, the price of reserves quickly decreases as more storage is added into the system. Figure 5-11 shows the weighted average price for operating reserves, as a function of total storage capacity. The first observation from this graph is that, in 2015 without renewables in the grid, the average price of reserves is relatively low, but it increases dramatically as more renewables are deployed. The price in our case study goes from an average of 5 \$MW-h in 2015 to an average of 135 \$MW-h in 2050. A second finding is that, while in 2015 the relationship between storage and reserves price results in a flat curve, the relationship in all other years presents a downward sloping curve.

In 2015, without renewables, the presence of storage does not change the price of reserves. The reason is that in that year current installed capacity in the system

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[12] I follow the convention of representing reserves provision with units of MW-h, which represent a unit of capacity (MW) held for one hour. This is a capacity unit as opposed to MWh which is an energy unit.

[13] Reserves provision at finer time-scales than an hour are not considered in this study and could increase the value of some storage technologies that could provide this service at time-scales where thermal generators could not be connected fast enough.

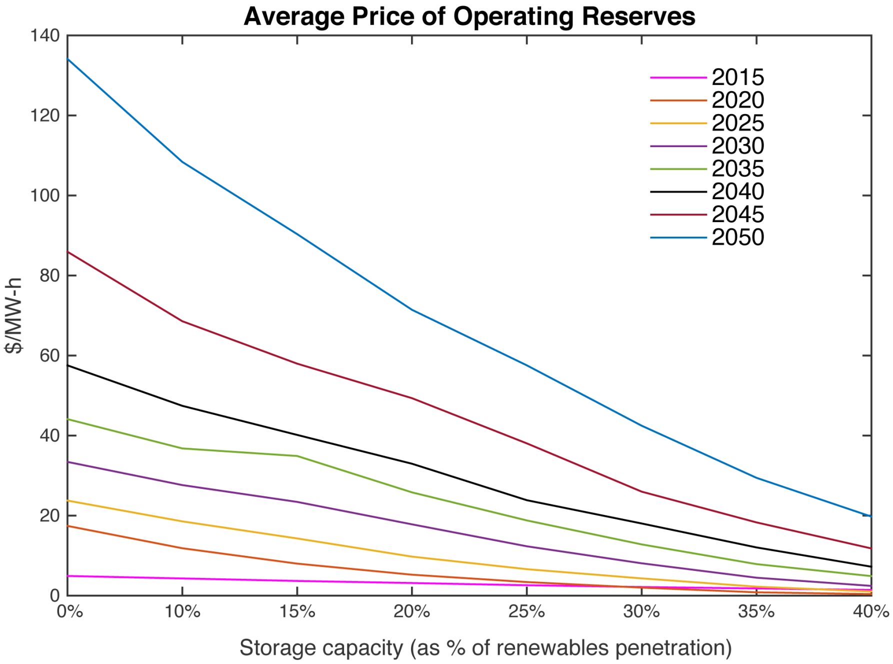

Figure 5-11: Reserves Prices
Source: Author-modeling results

can provide reserves less expensively, and therefore hydro and thermal generation outcompetes storage. Even though storage capacity is made available at no cost to the system, there is a cost of charging and discharging energy due to efficiency loses. However, one can observe that as more renewables enter the system, the capacity of storage changes the price of reserves drastically. As more storage is added into the system, the average price of reserves quickly declines. This is because storage can use very low -even negative -cost electricity and, by managing this energy and making it available in critical hours, it changes the dynamics in the ancillary services market, becoming an important player in price formation. Studies that use the price-taking approximation to value storage services miss this important market dynamic.

Now that I've discussed the mechanisms that derive the value of storage under large scale penetration of renewables, I provide some indicators in terms of energy managed and storage capacity in the system. For this, I use the family of scenarios in the experimental design 1b-9b, where 15% storage capacity is built in the system as renewables penetrate. This assumption is based on the results of Figure 5.2 that shows that most of the value of storage will be obtained at this level.[14] Total energy

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[14] I use this family of scenarios only as a working example. Of course, if storage were to be very cheap in the future, there is no reason why larger penetration could not be reached.

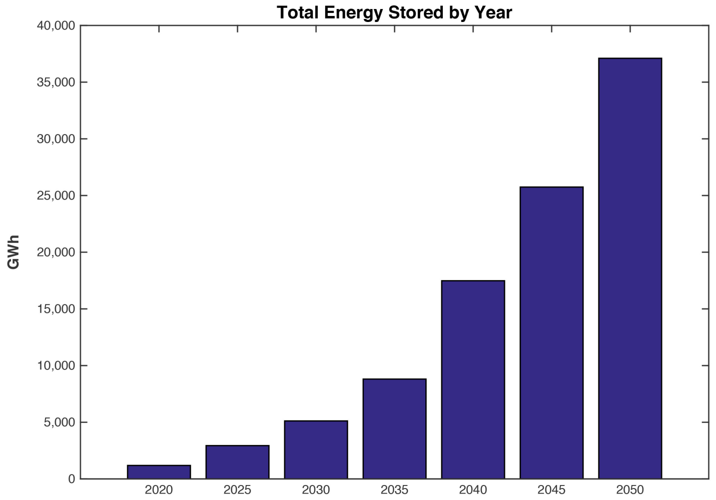

Figure 5-12: Total Energy Stored by Year

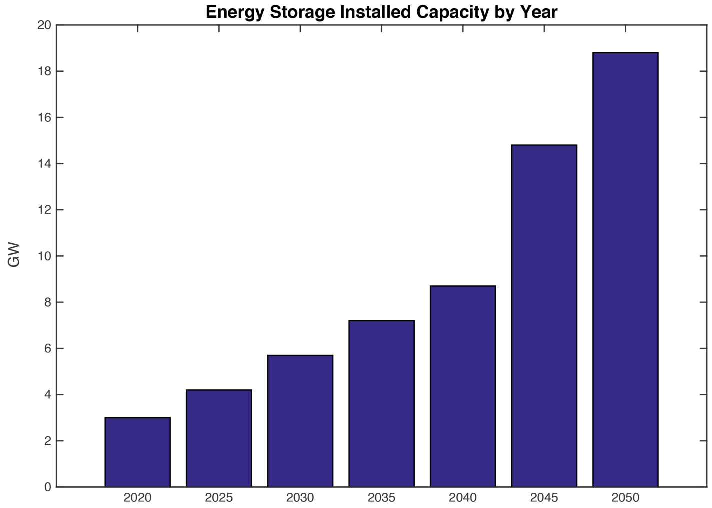

Figure 5-13: Storage Installed Capacity
Source: Author-modeling results

stored by year is shown in Figure 5-12, where we see that energy stored grows as renewables penetrates, from 2,940 GWh in 2020 to 37,103 GWh, which represents 1% of the generation in 2020 and 5% in 2050.

Total storage installed capacity is shown in Figure 5-13. By construction, total available capacity increases as renewables and demand increase. As a share of total installed capacity in the system, storage technologies represent 4.8% in 2020, and 7.5% in 2050.

The present value of storage capacity expansion by year is shown in Figure 5-14. The present value calculation represents the value of the cash-flows of the extant capacity and the new capacity additions in that year, considering an economic life of

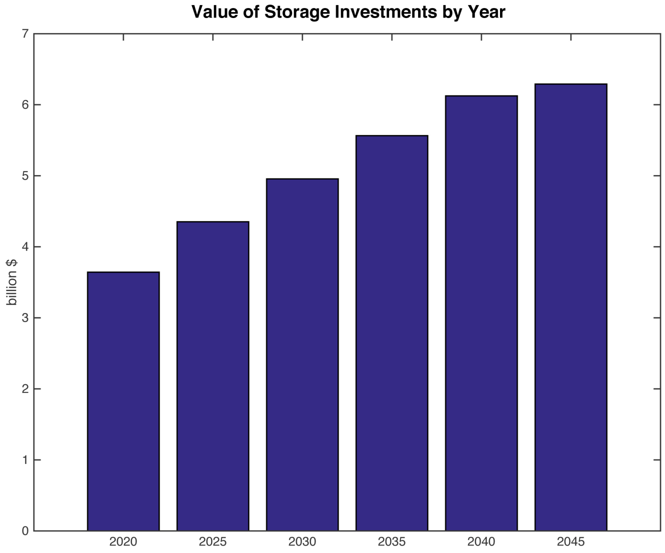

Figure 5-14: Present Value of Storage by Year
Source: Author-modeling results

30 years. I assumed that the cash-flows after 2050 remain constant at 2050 levels. We can see that as the value of storage increases in time, capacity additions in 2020 are less valuable because they operate at lower levels of renewables penetration for the first decades. Additions in later periods are more valuable, as shown in the figure.

Finally, one is interested in understanding the changes in investments and generation decisions driven by storage. Figures 5-15 and Figure 5-16 show the generation mix and the capacity expansion of the system every five years up to 2050 with storage. Compared to a scenario without storage, the modeling results indicate that the generation of thermal technologies decreases: open gas turbine units generate 80% less electricity compared to a system where no storage capacity is available and natural gas combined cycle units reduces 18% their generation, and 1% for coal. System capacity expansions also change due to storage capacity. Compared to the expansion without storage 35% less capacity of new combined cycle is built into the system, and less wind capacity is needed as well to provide the same amount of wind, 7% less wind is built. More open cycle gas turbines are added to the system, 9% more than in the case without storage. Since open gas turbines generation is reduced, the results show that this technology is built to provide reserves to the system.

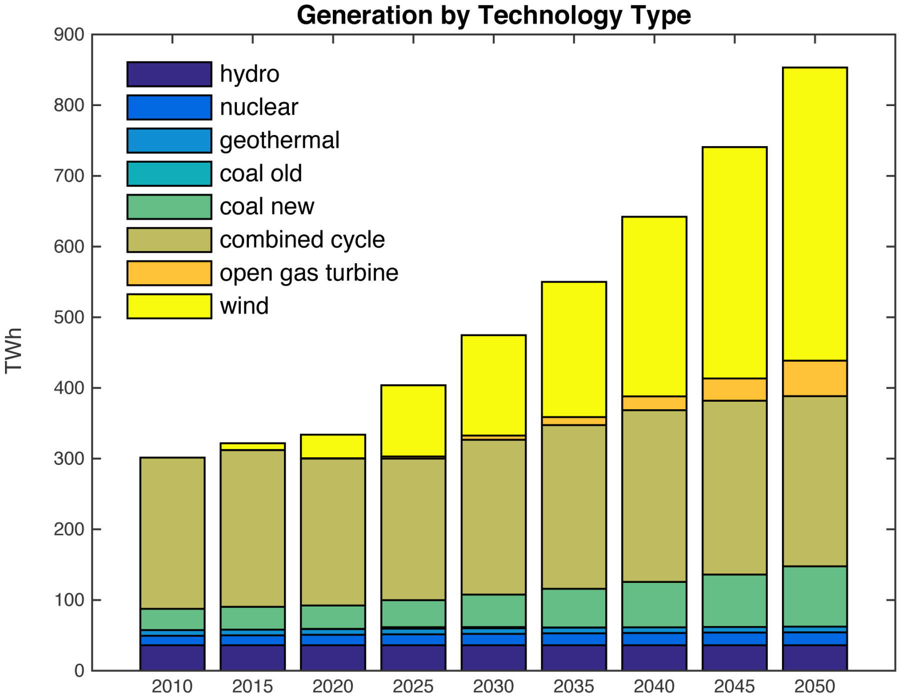

Figure 5-15: Electricity Generation by Year with Storage
Source: Author-modeling results

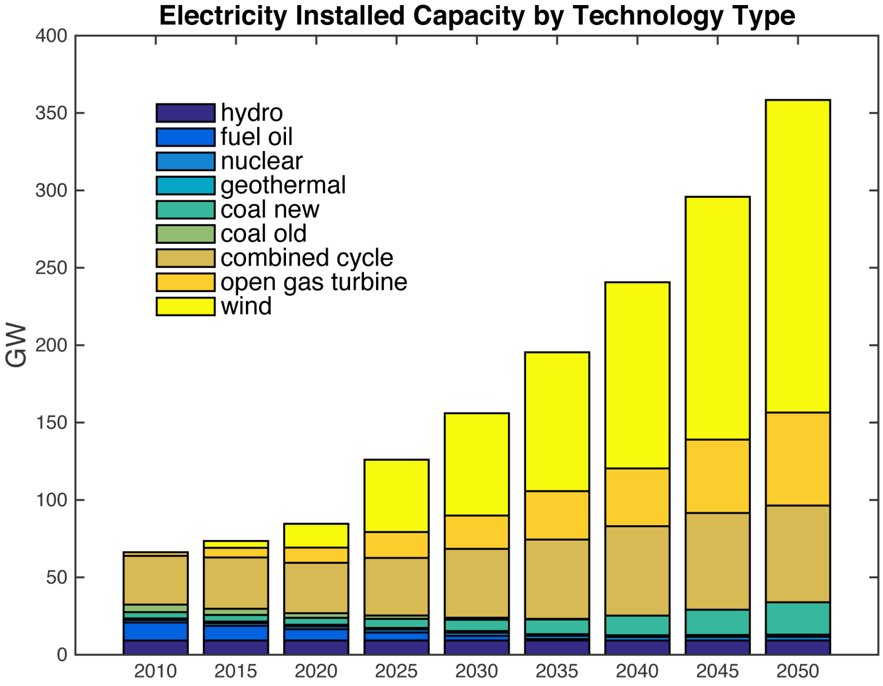

Figure 5-16: Capacity Expansion with Storage
Source: Author-modeling results

5.4 Optimal Level of Renewables Penetration with and without Storage

In the experimental design used to elicit the value of storage, specific renewable energy targets per year are set to evaluate the performance of storage technologies in a system with high renewable penetration. By 2050, as shown in Table 5.1, 50% of renewables penetration is mandated as a policy constraint in the model. While this allows one to elicit the value of storage if such a policy were pursued in Mexico, two important questions arise:

- What is the optimal level of renewables penetration without any policy constraint on total renewables target?
- Would the availability of storage allow higher penetrations of renewable energy?

In this section, I explore these questions to complement the analysis of the value of storage from the perspective of renewables integration with a set of two additional scenarios: a case that allows the model to optimize the share of renewables in the system without imposing any specific target for renewables nor considering storage, and a case that optimizes the share of renewables considering storage capacity. In these two cases, the model considers the cost of renewable technologies today in Mexico and projected decreasing cost trajectories. Considering the information used by the Federal Commission of Electricity in Mexico (CFE), I use a capital cost for wind onshore technology of 1,718 $/kW, for solar photovoltaic 3500 $/kW and for geothermal 2,105 $/kW [27].[15] Projected cost trajectories are estimated using costs decreases forecasted by the International Energy Agency [92].[16] Figure 5-17 shows the generation between 2015-2050 without specific targets for renewable energy deployment.

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[15] The IEA estimates differentiated costs for several regions of the world for renewable energy technologies; for reference the cost estimate for wind in the US is 1890 $/kW and 1300 $/kW in China, and for PV 4450 $/kW in the US and 2050 $/kW in China. The IEA does not report costs for Mexico.

[16] Learning rates used by the IEA are 5% for onshore wind and geothermal, 18% for large scale PV. I consider a cost reduction of 15% for wind by 2050 and of 54% for solar technologies consistent with the IEA estimates of a no policy scenario (values are dependent on the total projected installed capacity which is a function of policy constraints on CO_2 emissions.)

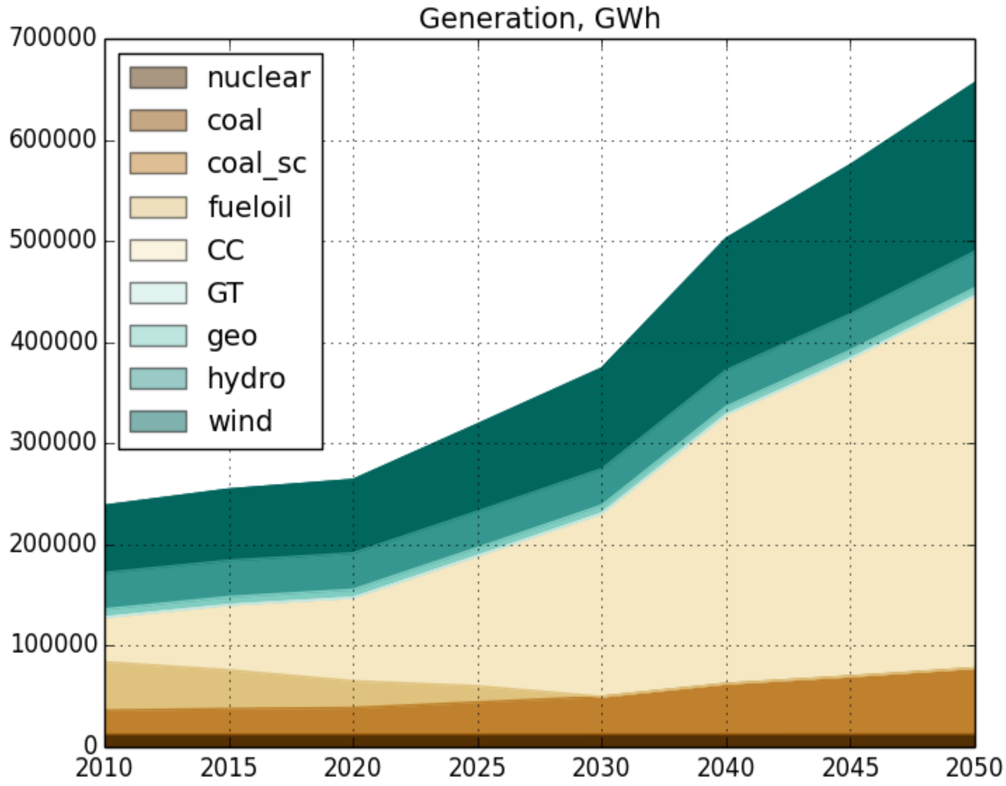
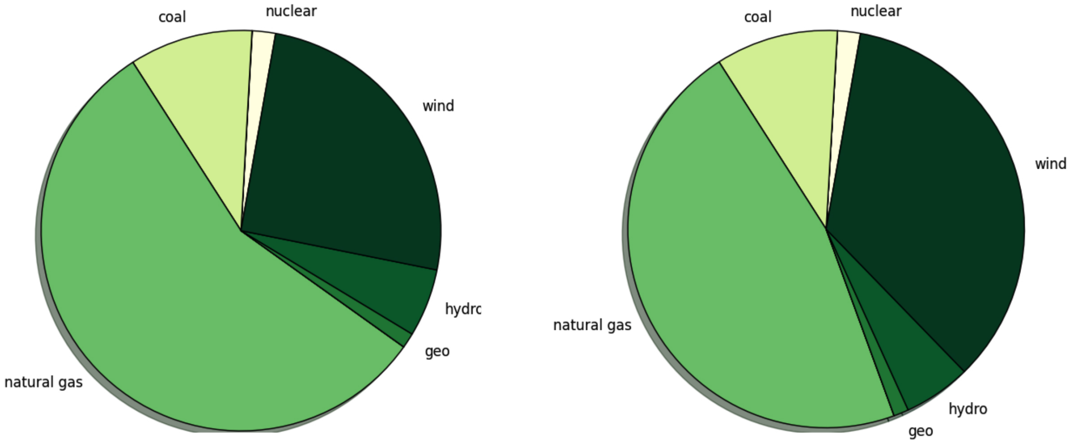


Figure 5-17: Generation Mix 2010-2050 - Optimal Wind Penetration
Source: Author-modeling results

The mix is dominated by the expansion of natural gas generation, which grows from 49% of total generation to 56% in 2050. An optimal penetration of wind by 2050 reaches 25% of generation.

When storage is available, the generation mix changes. As shown in Figures 5-18 wind share of total generation expands when storage capacity is available in the system. Wind participation in the generation mix grows from a 24% share of total generation to 35%. Wind displaces natural gas generation, which reduces its participation in total generation from 56% to 46%. Coal reduces 1% of its share. These results suggest that storage technologies can be important in supporting higher penetrations of renewables in the grid without forcing renewable energy into the system.

The capacity expansion decisions are also affected by the introduction of storage technologies. Figures 5-19 and 5-20 show the differences in investment decisions triggered by the capacity of storage in the system. As storage capacity increases,



(a) Generation mix in 2050 - no storage (b) Generation mix in 2050- storage

Figure 5-18: Generation Mix with and without Storage

more wind capacity is installed. More wind drives investment in greater capacity of open cycle gas turbines (GT) serving peak demand and reserves provision. This expansion of wind and open gas turbines displaces combined cycle units. It is worth explaining that in the previous section, storage allows less installation of wind while in this section storage results in more installation of wind. For any given target of renewables penetration, storage allows using that capacity more efficiently, and in the first case it allows meeting the target with fewer units, reducing policy costs. When no target of renewables is imposed, only the capacity that is cost minimizing is installed in the system. With storage capacity, more wind is economical to the system, and thus more wind capacity is installed.

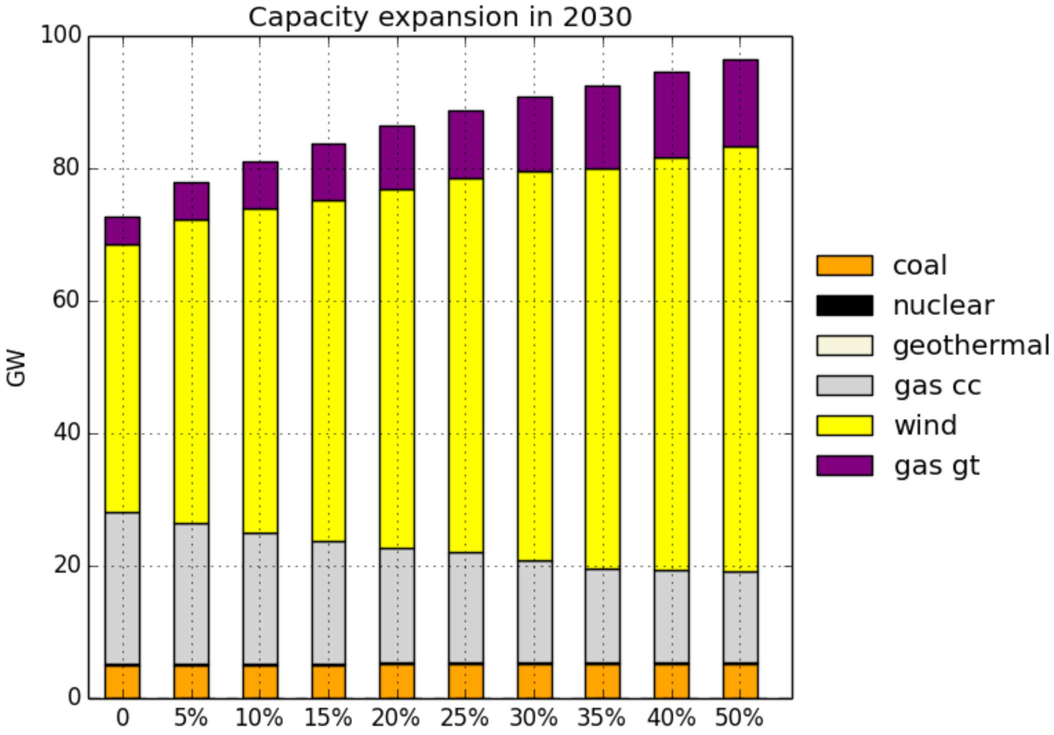


Figure 5-19: Capacity expansion in 2030 at Different Levels of Storage Capacity
Source: Author-modeling results

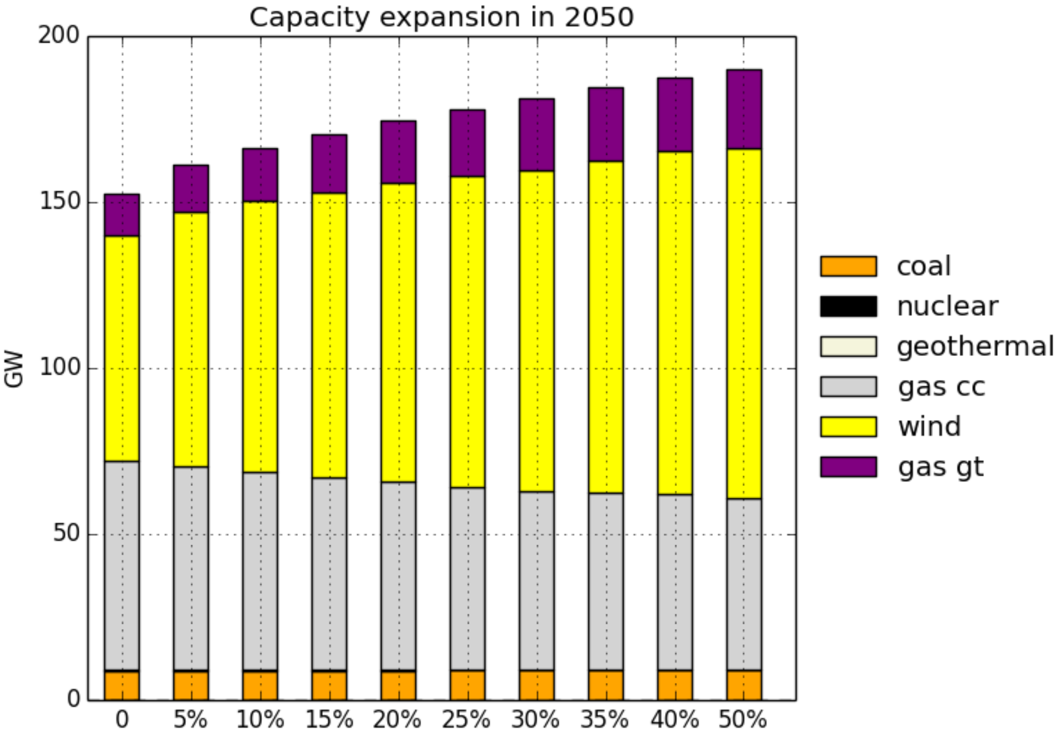


Figure 5-20: Capacity expansion in 2050 at Different Levels of Storage Capacity
Source: Author-modeling results

5.5 General Equilibrium Effects

The introduction of renewables and storage in electricity generation results in several changes in different markets in the economy. First, it changes the demand of inputs to production of the electric sector. Figure 5-21 shows the different shares of inputs to production as we add more renewables to the system.[17] As shown in the figure, the system becomes more capital intensive. In 2015, annual expenditures for capital[18] are less than 20% of the annual cost of inputs to production, fuel expenses account for 70%, and other inputs to production represent 10%. By 2050, the capital expenditures share expands to more than 70%, fuel costs are 26% and other inputs to production are 2%.

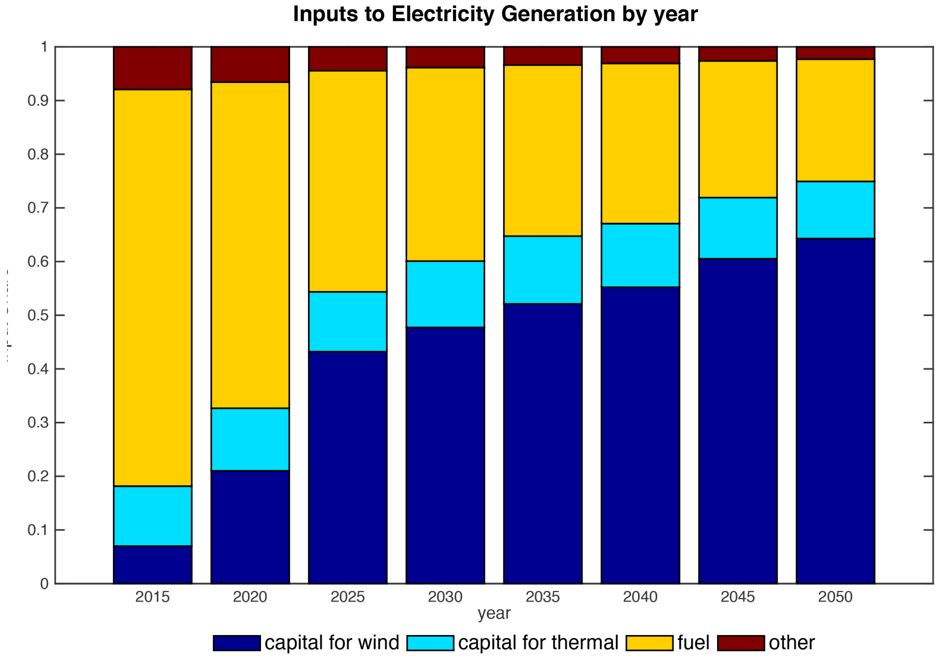


Figure 5-21: Changes in the Inputs to Electricity Generation
Source: Author-modeling results

The main driver of changes in the structure of inputs to production for electricity generation is the renewable energy policy. The use of fossil fuels is substituted away

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[17] These results correspond to the family of scenarios 1d to 8d when we allow a 25% of storage capacity as share of total renewables penetration in the system.

[18] These are the payments to capital that are due each year as an annuity, the so-called capital rents.

with wind, but capital requirements increase for installing wind turbines and additional thermal units to meet growing demand while maintaining system security and adequacy. Changes of inputs to production result in variations in the price of electricity and electricity demand. Figure 5-22 shows the overall effect of the renewable portfolio standard on the price of electricity and on electricity demand by sector. As shown in the figure, the price of electricity increases causing some sectors to reduce demand for electricity. Since electricity is used in almost all activities in the economy, the effects of changes in the price of electricity propagate throughout the economy, both due to substitution and income effects.

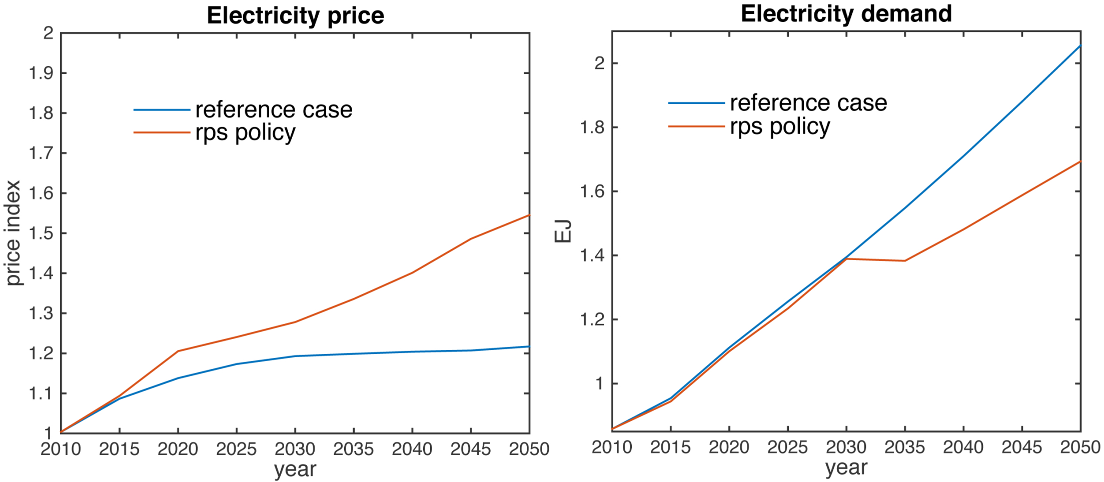

Figure 5-22: Electricity Price and Demand
Source: Author-modeling results

Since consumers face an income constraint, if electricity prices (and other prices) move as a result of the renewable energy policy and/or storage deployment plan, then welfare implications can result from the policy implementation. If the price of electricity is higher, resulting for example from policies that push renewables penetration above the "optimal level", then industries and consumers can substitute away from their use of electricity, either by reducing demand (i.e. taking some energy efficiency or conservation measures) or by using other energy sources. If the price of electricity is lower, for example because economic storage reduces the overall system cost, then the opposite effect takes place. I will further discuss welfare implications in the next section.[19]

The changes in the electricity sector demands for inputs to production drive responses in other markets of the economy. The importance of the general equilibrium effects highly depends on the size of the electric sector demands in specific markets. To illustrate the general equilibrium dynamics in other sectors, I describe the changes in the natural gas market resulting from the renewable energy policy. The electric sector in Mexico consumes 47% of total natural gas in the country; therefore, changes in its demand of natural gas as an input to production can impact the market for natural gas [166].[20] Figure 5-23 shows the movements in the price of natural gas and demand changes in the economy resulting from the implementation of a renewables portfolio standard.

To explain the changes it is useful to understand the different market mechanisms triggered by the policy. First, the electric sector reduces its demand for natural gas, which results in a reduction of the domestic price of natural gas. This reduction triggers increases in demand for gas from other sectors of the economy. In particular, energy intensive industries use more gas after the introduction of the renewables portfolio standard. This change is driven by two effects: a) an increase in the price of electricity that incentivizes substitution away from electricity, and b) a decrease in the price of natural gas that incentivizes switches to natural gas. The adjustments result in an overall increase of natural gas use in the economy. Coal decreases its use because its share in the benchmark data in other sectors of the Mexican economy is relatively small compared to natural gas use.

Finally, there are also general equilibrium effects regarding emissions associated with the policy implementation. Figure 5-24 shows total emissions reductions from the electric power sector and economy wide emissions. Total emissions reductions in the economy are lower than the absolute emissions reductions in the power sector. In the absence of policies targeting emissions reductions in the overall economy, the

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[19] In the EPPA model we consider only the long-term elasticity of demand, with an elasticity of substitution of 0.5 between electricity and fossil energy bundle for the aggregated energy good.

[20] 34% of natural gas demand was from the oil sector, 18% from industry and 1.7% from residential and services.

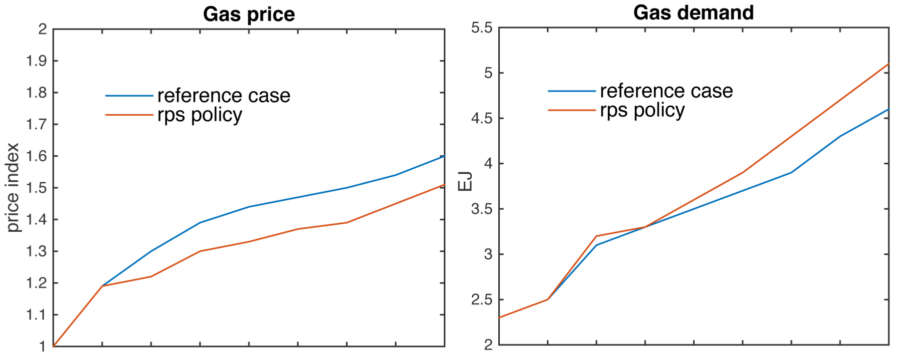

Figure 5-23: Natural Gas Price and Demand
Source: Author-modeling results

emissions reductions achieved by the implementation of policies in the electric sector are partially offset by increases in other sectors, due to general equilibrium effects. A fraction of the fuels not used in the power sector are used by other sectors in the economy in the absence of policies that penalize emissions; however, not all emissions are offset because there is no perfect substitution among fuels. In all, the availability of storage accompanying the renewable portfolio standard is able to reduce 3% economy-wide emissions by 2050, compared to the scenario without storage.

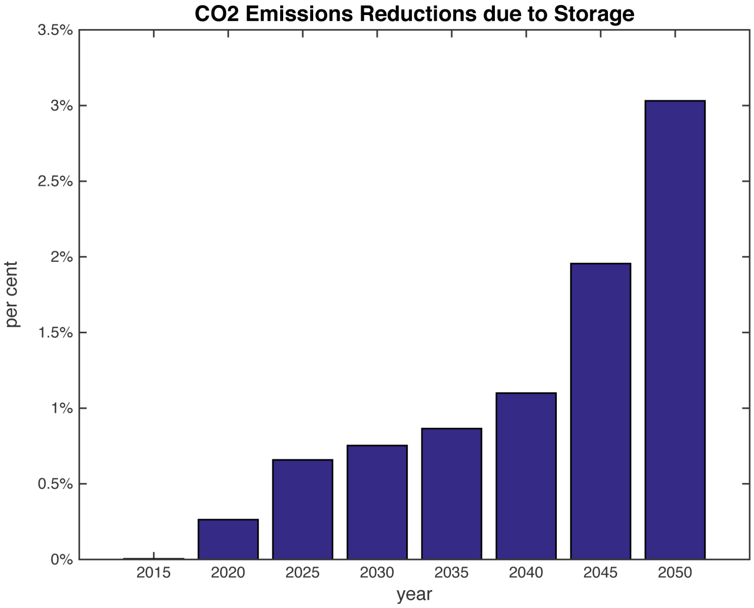

Figure 5-24: CO_2 Emissions
Source: Author-modeling results

5.6 The Value of Storage in the Context of Climate Policy

In this section, I present the economy-wide implications of the availability of storage in the context of climate mitigation. Up to this point, I have been discussing the value of storage in a world where policies are implemented to reach higher shares of deployment of renewable energy. First, in section 5.2 a full exploration of the value of storage was conducted with increasing levels of storage availability and mandates regarding total renewables penetration. In section 5.4, I analyzed the optimal penetration of renewables without specific renewables penetration targets, but with increasing levels of storage capacity. As discussed earlier, these policies have general equilibrium effects since they affect the markets of electricity and fuels. However, I have not yet discussed the introduction of a carbon price in the economy. I turn now to the discussion of the general equilibrium effects of storage availability in the broader context of national climate policy.

As discussed in Chapter 2, Mexico's climate policy has the ambitious target of reducing emissions 50% by 2050, provided that similar targets are pursued by developed economies and international cooperation for mitigation action helps finance emissions reductions. To describe the value of storage considering this economy-wide climate policy target, I simulated three policy scenarios as follows:

1. **The reference case**. The business as usual evolution of the economy without climate policy. In this case, renewables enter the power mix only if economical, and there is no storage capacity in the system.[21]

2. **Climate policy without storage**. Represents a 50% emissions reduction for the overall Mexican economy without storage capacity in the electricity system. All other regions of the world are assumed to follow strict mitigation policies.[22]

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[21] This scenario corresponds to the "optimal wind penetration without storage" case discussed in section 5.4. I use this scenario as a reference case, since it corresponds to the business as usual (economic) expansion of the electricity system without storage or climate policy.

[22] Developed economies have differentiated targets from developing countries; all countries together reach a 50% reduction by 2050 as compared to global emissions of 2010. There is no international

3. **Climate policy with storage**. Represents a 50% emissions reduction for the overall Mexican economy with 25% of storage capacity in the electricity system. All other regions of the world are assumed to follow strict mitigation policies.

The integrated modeling framework allows us to explore the policy costs and emissions outcomes using economic welfare analysis. The emissions baseline trajectories for all activities in the economy are projected using the EPPA model, with the emissions from electricity coming from the bottom-up RISA model. Figure 5-25a shows the economy-wide emissions trajectories in the reference case. As shown, without climate policy, total emissions of the country are expected to almost double from 2010 to 2050, reaching 1126 million ton per year by 2050. With a 50% emissions reductions goal, mitigation needs to occur in all sectors of the economy. Figure 5-25b shows the emissions reductions required by sector in the *Climate policy without storage* scenario: the power sector reduces 94% from the reference 2010 emissions, refined oil activities 51%, transportation 52%, other industries 51%, and households 13%. The only sector that increases emissions is energy intensive industries that have 18% more emissions compared to 2010.[23]

The total emissions constraint has an implied carbon price in the economy. Introducing a carbon price results in increased costs for the electricity sector; meeting demand is 2.4 times more expensive than without a carbon price. The electricity generation mix in 2050 under the *Climate policy without storage* is 69% wind, 10% coal with carbon capture and storage (CCS), 9% from open gas turbines, 5% natural gas combined cycles, 4% hydro, 2% nuclear and 1% geothermal. This leads to an increase in the price of electricity, and consequently decreases electricity demand. As shown in Figure 5-26, in the *Climate policy without storage* scenario, electricity use decreases due to increased electricity cost and the overall slow-down of economic activity resulting from carbon policy.

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emissions trading in the policy. While I will not discuss the results for the rest of the world, the specification of emissions reductions targets for other countries is important to properly assess national policy considering the international economic dynamics resulting from a global climate policy.

[23] Emissions in this sector increase compared to 2010, but drastically decrease if compared with the business as usual scenario, therefore mitigation also needs to occur in this sector.

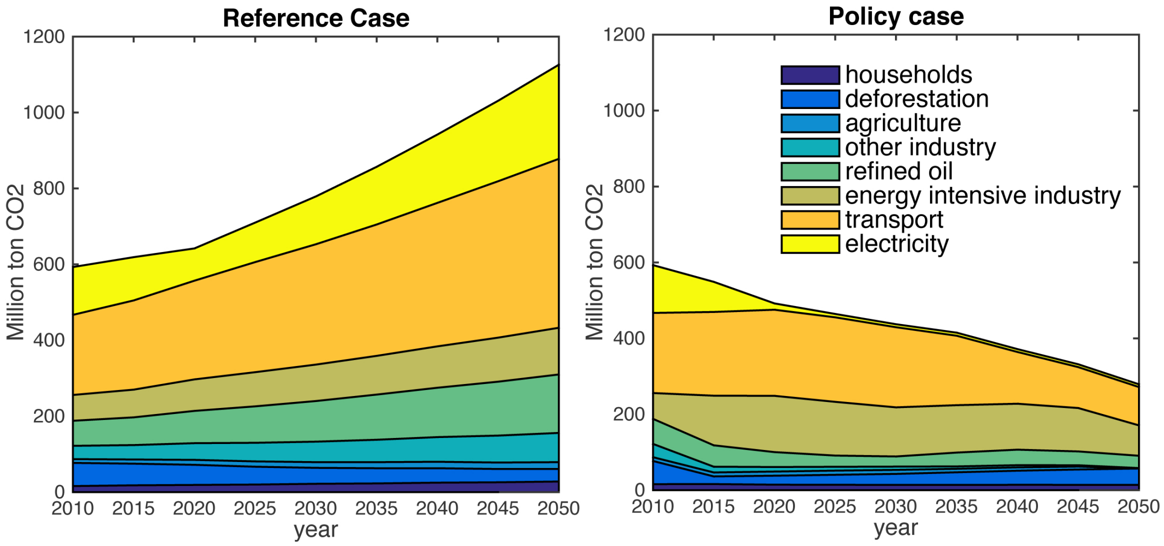

Figure 5-25: Economy-wide emissions projection 2010-2050
Source: Author-modeling results

In the *Climate policy with storage* scenario, storage allows a more efficient integration of renewables into the power sector. Total cost of operating the electric system reduces by 30% compared to the *Climate policy without storage* scenario. The electricity generation mix in 2050 under this mitigation scenario is 74% wind, 10% coal with carbon capture and storage (CCS), 2% from open gas turbines, 7% combined cycles, 4% hydro, 2% nuclear and 1% geothermal. The total capacity needed in the system decreases by 7%, mainly reducing the need for gas technologies. Storage also allows reducing wind curtailment and capacity needs for wind generation.

A more efficient integration of renewables – particularly at this very high penetration level – is important to reduce policy costs. The reduction in costs results in lower electricity prices in the *Climate policy with storage* scenario compared to the *Climate policy without storage* scenario. This change induces other sectors to reduce emissions by switching to electricity more in the *Climate policy with storage* scenario compared to the *Climate policy without storage* scenario. While electricity demand still decreases in the *Climate policy with storage* scenario compared to the reference scenario, it decreases to a lesser extent compared with the *Climate policy with storage* scenario. When the carbon constraint becomes more stringent in 2030, and as it advances to very strict mitigation in 2050, the economy demands more clean electricity because it is a more economic mitigation option than reducing emissions in other sectors. Substitution towards electricity also occurs in the *Climate policy without storage scenario*, but it increases with the availability of storage since storage allows to produce low-carbon electricity more efficiently.

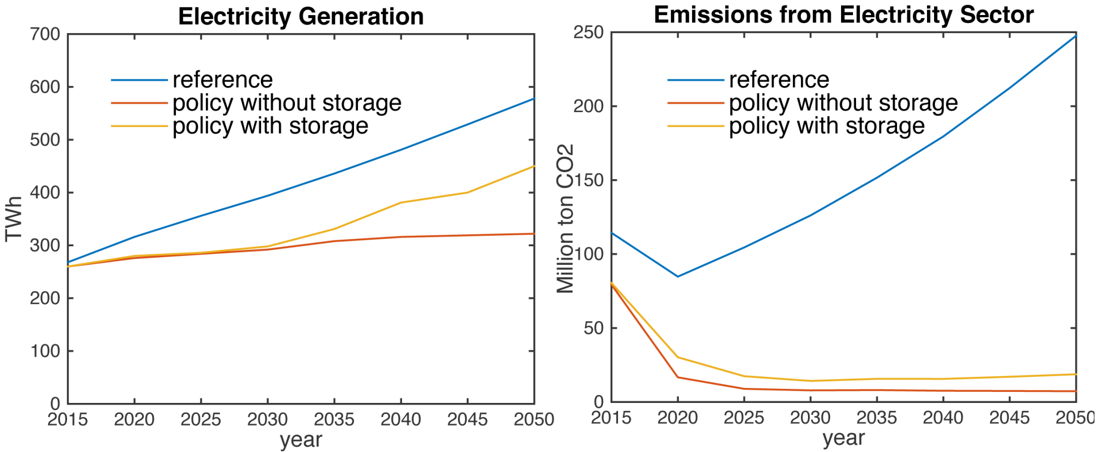

Figure 5-26: Electricity Generation and Emissions 2010-2050
Source: Author-modeling results

As shown in Figure 5-26, with storage, emissions from the electric power sector increase slightly compared to the policy without storage scenario. While the electric power sector is almost fully decarbonized, the reason for this increase is that some gas turbines and the coal with carbon capture technology still emit some CO_2. Because more sectors are using electricity instead of other fossil fuels, total electricity generation increases and therefore the emissions from coal CCS and gas turbines increase.

These dynamics result in a reduction of total policy cost when storage is available in the system. The general equilibrium framework is best suited to provide aggregate measures of economic outcomes. While total GDP loss is a natural parameter used for communicating policy costs, economists usually prefer to use consumption or welfare measures, because they relate to the level of total economic wellbeing of the population in each country, and more clearly reflect the economic impact on their population for any given period [132]. In the EPPA model, "economic welfare" is measured by the change in aggregate consumption as equivalent variation, which reflects the income needed to compensate consumers for welfare losses derived from

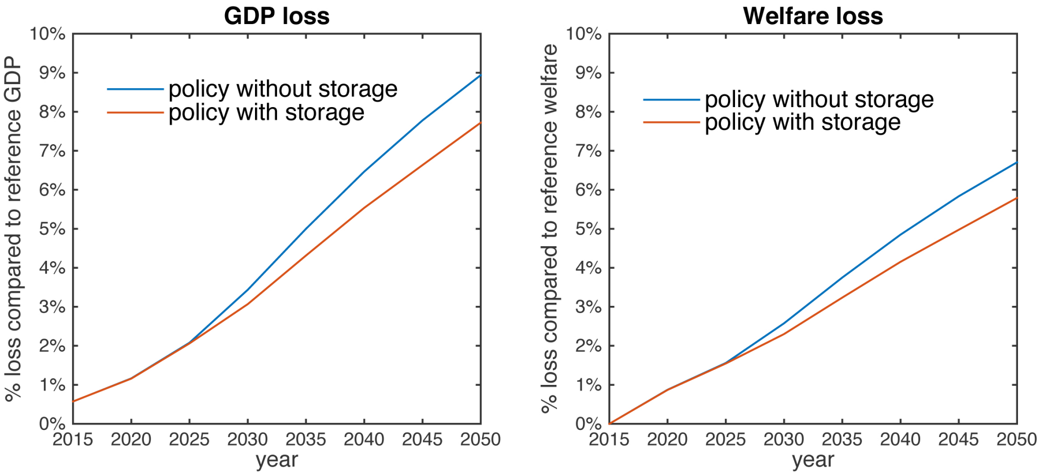

Figure 5-27: Policy Costs 2015-2050
Source: Author-modeling results

policy implementation [136]. Figure 5-27 shows the changes in GDP and the welfare index resulting from the two climate policies modeled compared to the reference case. As shown in the figures, mitigation cost decreases with the availability of storage.

The cost of such a stringent climate policy results in welfare reductions of 6.5% by 2050 compared to the reference case, and 5.8% when storage is available. In terms of GDP, the policy cost without storage by 2050 is about 9% GDP loss compared to the reference case, and 7.8% when compared to the policy with storage. As explained, this results from less expensive mitigation in the electric sector, but also because the lower cost of electricity allows some sectors to move towards electricity more in the *Climate policy with storage* scenario as compared with the *Climate policy without storage* scenario, displacing fossil fuel use in other sectors more economically.

This is in fact a very stringent policy with high costs. Mexico's GDP decreases due to carbon constraints both in the country and also globally. In particular, oil exports from the country reduce as all countries try to shift away from fossil fuels. It is important to clarify that mitigation policy cost refers to the actions to reach emissions reduction targets, i.e. it covers only the mitigation cost component of climate policy and does not capture the benefits of mitigation (nor potential adaptation policy.) Capturing the benefits of mitigation is outside the scope of this dissertation[24]; but I

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[24] Estimating the benefits of climate policy is an important area of research worldwide. It is also a very challenging task, given the complexities of estimating the value of long-term damages of climate

underscore that the risks imposed by climate change certainly call for the analysis of aggressive mitigation policies such as the one modeled in this research that can help countries collectively reach climate stabilization targets.

5.7 Discussion of the value of storage technologies

This analysis is the first to investigate the value of storage using both a detailed electricity sector model coupled with a numerical general equilibrium framework to evaluate climate policy. The proposed hybrid modeling approach and experimental design allows the analysis of both changes in the electric sector driven by storage and economy-wide impacts of climate change policy with and without storage technologies.

As I have discussed in this chapter, the value of electricity storage increases under large-scale penetration of renewable energy. Under an environment of increasing shares of renewables in the power grid, the value of storage could have a present value of over 1500 $/kW in Mexico. Some of the current technologies could provide services at this value; however, most technologies will still have to drastically reduce their cost to compete in the marketplace. The technologies that could provide storage services at this cost – CAES and PHS – have limitations regarding location or scalability, and thus further research to decrease the costs of alternative storage technologies seems necessary.

To explain the value of storage in this chapter, I unpacked the different operational dynamics driving the value of storage and decomposed the value in the different services that storage provides to the system. In the case of Mexico's power system, the value of storage for energy management services results in the highest value component followed by operational reserves provision and capacity margin. The operational flexibility that storage can provide to the system is valuable due to the new challenges of managing fluctuating net demand, which can result in difficult operational conditions as the ones described in Section 5.2. From this analysis, the importance

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change and the underlining uncertainties [178]. For example, it would require an economic assessment of reduced impacts on climate change from extreme weather events, sea level rise, agriculture, etc. For an examination of potential risks of climate change in Mexico see [159].

of the participation of storage in energy and ancillary services markets is clear. The proper remuneration of reserves and capacity provision is critical for storage to be competitive, and to ultimately reach an optimal capacity in the system. Mexico is in the midst of the design of electricity markets as explained in Chapter 2; ensuring market rules that allow this remuneration for storage seems advisable particularly under current policies that aim to scale-up renewable energy and aggressive climate mitigation targets.

My analysis also suggests that under increasing penetration of renewable electricity hourly prices become more volatile; one of the outcomes of storage capacity in the system is to reduce price volatility and the occurrence of negative prices. In theory, allowing for the high price spikes and even negative prices could be necessary to ensure proper remuneration of the technologies that provide services when fluctuations of renewables happen; however, in practice system operators tend to discourage these extreme price spikes resulting in some cases in the so-called missing money problem for other electricity technologies. As shown in this analysis, and due to this practical problem in the operation of power systems, capacity markets, or other reliability instruments such as reliability options, seem necessary, particularly under increasing renewables penetration. Mexico is already planning on launching capacity markets, clean energy markets and clean energy certificates capacity auctions as part as its new market design, which shows the regulators are aware of the need to incentivize reliability with market design.

Last but certainly not least, the analysis of climate policy suggests that the social value of developing these technologies is potentially high, decreasing overall economy-wide costs of policy implementation. As shown by the modeling exercise, under an economy-wide emissions reduction target of 50% by 2050 in Mexico, social welfare is 0.7% higher if we compare the policy case with and without storage.[25] An important policy question is how to incentivize storage cost reductions –and the development of other technologies that could facilitate deployment of clean energy in a climate

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[25] Social welfare is reduced in both policies if compared to the reference case, but the economic availability of storage reduces the overall mitigation costs for the economy.

constrained world– such that the full social value of their availability can be achieved once these policies are implemented.

In the next chapter, I present a sensitivity analysis to the most important technological specifications of storage technologies (rated power and efficiency) to evaluate their impact on the value of storage. In addition, I explore other sensitivities besides storage characteristics that can affect its value, such as the price of natural gas and the availability of hydropower.

Chapter 6

Critical sensitivities to the value of storage

As shown in Chapter 5, the value of storage results from complex system level interactions of the different technologies in the power sector in combination with demand and natural resources dynamics such as wind and hydro inflows. In addition, the value of storage depends on the specific characteristics of the storage technologies themselves. In this chapter, I conduct a sensitivity analysis of the value of storage to some of the most important factors that affect its performance and value in the system.

First, I present the sensitivity to the characteristics of storage technologies. Two particular aspects are given attention: the energy efficiency of a round trip storage cycle and the relationship between storage capacity and power ratio. Second, I discuss the sensitivity of the value of storage to the availability of hydropower. Hydroelectric plants are a built-in source of flexibility in many systems of the world; systems with this resource are already better prepared for renewables integration. Third, I discuss the sensitivity of the value of storage to the price of natural gas. The price of gas is important for the value of storage, since it is often the marginal technology setting energy prices in the system. Also, natural gas technologies provide many of the ancillary services that storage could provide and therefore are in direct competition.

For all the sensitivity analyses, I use the family of scenarios 1a-9a as specified in Table 5.1. I analyze the evolution of the system with a fixed capacity of storage of 10% as percentage of renewable generation. I then compute the present value of storage per GW in 2020 using a discount factor of 6% and assuming the technology operates from 2020-2050. Finally, I compare the present value in each analysis to the one found in Chapter 5 for the same scenario.

6.1 Sensitivity to the efficiency of storage

Today the efficiency of storage technologies varies widely. As discussed in Chapter 3, current storage technologies that can support bulk power management have efficiencies from up to 90% for advanced lead acid batteries and as low as 60% of ZnBr Redox batteries. In the modeling exercise presented in Chapter 5, I used a parameter of 85% efficiency, a representative parameter of current PHS technologies and other technologies in the market such as CAES. The sensitivity analysis considers a lower efficiency parameter of 50%. Figure 6-1 presents the comparison between the value of storage estimated in the reference case and the value of storage with lower efficiency. The present value per GW of storage installed in 2020 decreases by 35% as a result of less efficiency.[1]

Researchers are experimenting with different battery chemistries, or improving technology design to increase the round-trip efficiency (e.g. recent developments of liquid metal batteries or CAES technologies). However, there is a tradeoff between reaching higher efficiencies and cost. This sensitivity analysis shows that efficiency is, as expected, a very important determinant of the value of storage. However, if technologies can reach the cost target (although less efficiently), there could be a market for them.

Finally, it is important to consider that the modeling of efficiency is highly stylized in the RISA model. For many technologies, energy is lost in the process of being stored and discharged, which is what I captured as a round-trip efficiency. I fully

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[1] I consider a GW installed in 2020 with a lifetime of 30 years (2020-2050) for the present value calculation and a discount rate of 6%.

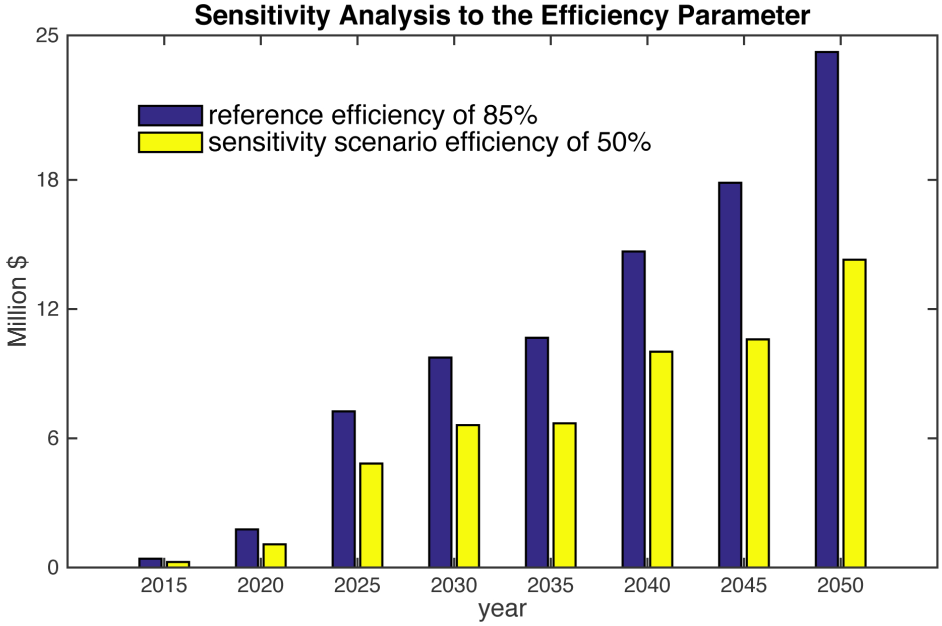

Figure 6-1: Sensitivity to Efficiency Parameter
Source: Author-modeling results

allocate the efficiency loss to the charging process; some model formulations split the losses between charge and discharge times [196]. For some technologies, efficiency is a function of time-in-use and will lose energy when not in use. For this, additional constraints to model the state of the battery in idle condition are necessary. However, I did not include these constraints to avoid binary variables in the model (this allows a faster solution, necessary for the iterations with the EPPA model, and to solve the model at an hourly time-scale). However, it is worth mentioning that considering all the efficiency losses and the technicalities associated with efficiency in the operation of storage could decrease its value. For some technologies, however, the allocation of a round-trip efficiency as specified in the RISA model is a very good approximation of the energy losses in the process, i.e. CAES and PHS.

6.2 Sensitivity to Storage Capacity and Power

Storage technologies have specifications of total capacity (in MWh) and total power (in MW). The ratio between these two specifications determines the total duration in hours that a technology can provide power when fully charged.[2] Costs per MWh

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[2] For example, a pumped hydro facility with 14000 MWh of capacity and power of 1400 MW has a duration of 10 hours.

and MW vary among the different storage technologies (see Table 3.7 on p. 91). As explained in [63, 23], services such as long-duration load shifting require a large volume of storage capacity while other applications used for short-term services require power to be absorbed or injected for only a short period of time.[3] The cost per MWh is more important for the first kind of application, while in the second case the cost per MW could be more relevant. The value of storage, however, is sensitive to the different capacities and power duration relationships of the different technologies providing bulk power management services to support systems and renewables integration.

In the reference case, I specified the capacity and power in the system such that a specific amount of renewable energy could (potentially) be stored in the system (see Table 5.1). I used a duration of 8 hours as the relationship between total installed capacity and power in the system. In the sensitivity analysis, I explore the impact of two different durations holding constant total capacity: one reducing the duration to 4 hours and a second one with an increased duration of 20 hours. This is a range consistent with specifications of different technologies available for bulk power management services.

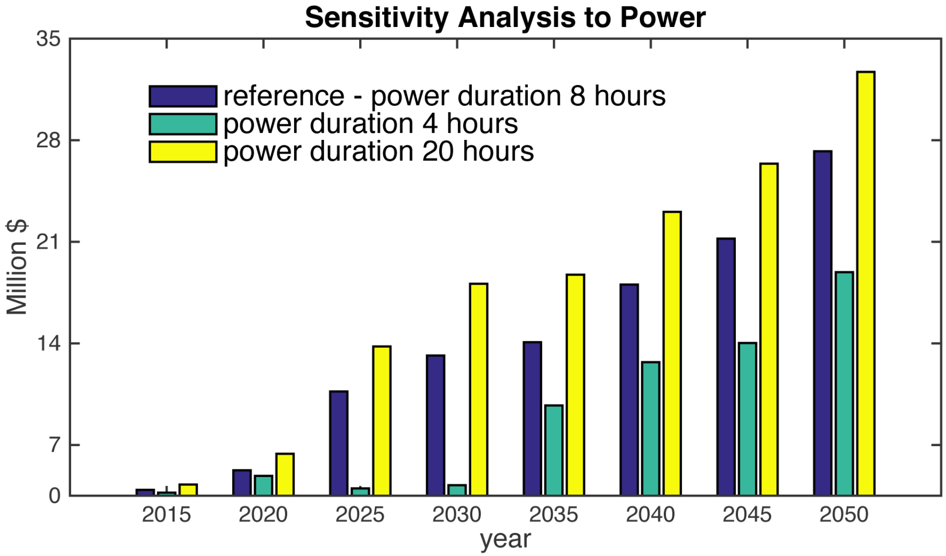

Figure 6-2: Sensitivity to Power
Source: Author-modeling results

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[3] In our modeling exercise, since the RISA model runs on an hourly basis, the very short-term services are not captured in the value of storage.

The analysis shows that the value of storage is sensitive to power as shown in Figure 6-2. Total present value of storage capacity decreases by 75% when power duration is reduced to 4 hours and increases 44% when duration is 20 hours. Regarding the value per kWh, in the reference case the value found was 200 \$/kWh, which decreases to 150 \$/kWh in the lower power duration case, 35% less than the reference case. In the case with higher power, the sensitivity analysis shows a value of 288 \$/kWh. This means that while the cost of some batteries (e.g.ZnBr) could approximate the value per MW, much more research needs to be done for them to reach the target costs per kWh. As shown, the relationships between capacity and power do not extrapolate linearly.

6.3 Hydropower availability

Hydropower facilities with reservoirs are also a form of storage built into the system. In this study, I purposely separated the value of hydropower capacity already in the system, and the value of other technologies that could provide storage services. Current hydropower facilities in Mexico do not have pumped hydro storage, and therefore cannot take electricity from the grid to store energy for later use. However, big hydro dams are an important source of energy storage, since they can store water in the reservoirs, using it when it is more convenient for the system. In fact, the hydro-thermal coordination is an important part both of the system planning and operation. In this section, I explain in more detail the modeling of hydropower and the sensitivity of the value of storage (from other technologies, including potential pump hydro storage) to the system.

6.3.1 Hydropower modeling

Mexico has 11,503 MW of hydroelectric capacity corresponding to 23.1% of total installed capacity [28]. Generation from these facilities depends on natural inflows of water, and provided between 10% and 17% of total generation in the last decade.[4] Of the total hydro capacity, 9,216 MW have regulation capacity, comprising 11 big hydropower plants. The rest are run-off river units without regulation, and therefore these units cannot provide storage services and must be run when water is available. In the model, I consider only the hydro capacity with regulation.[5] Using data from the Federal Commission for Electricity (CFE) of the facilities, as shown in Table 6.1, I grouped the units into their corresponding regions and aggregated their output per region.

In addition to the hydro capacity data, information on the natural inflows and on the equivalent energy that those inflows provide is necessary. I also used data from the CFE for this information. As shown in Figure 6-3 there is a seasonality of the water resource in Mexico, with main inflows coming from June to October, with September being historically the month with most inflows. The months of January to May have much lower inflows. The pattern of energy stored in the reservoirs during the last 5 years is shown in Figure 6-4. The managers of the reservoirs in Mexico consider the historical information of water inflows (60 years), along with different restrictions imposed by the environmental authorities on minimum generation and levels of the dams and minimum generation requirements from the centralized electricity dispatch center (CENACE). I imposed the minimum generation levels requirements in the model, as shown in Table 6.2.

I used the information of the energy stored in the reservoirs to model the reservoirs management in the system. Additional constraints were set in order to ensure that the reservoirs maintain a similar pattern of energy stored by month. In reality, a more complex modeling of the uncertainty of water inflows is necessary; however, I used the expertise of the Mexican system operators (using their historical data on total energy stored in the reservoirs by month) to ensure that the model replicates a reasonable

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[4] Due to the variability of water inflows, generation fluctuates from year to year. During the beginning of the 2000's a dry series of years occurred in Mexico.

[5] I am most interested in modeling hydropower for its ability of facilitating renewables integration and providing energy storing services. The modeling of the other hydro facilities could provide must-run generation in a small amount. Further research can add this technology, in particular, I expect to do that later exploring the role of mini-hydro as part of the renewable energy program of Mexico.

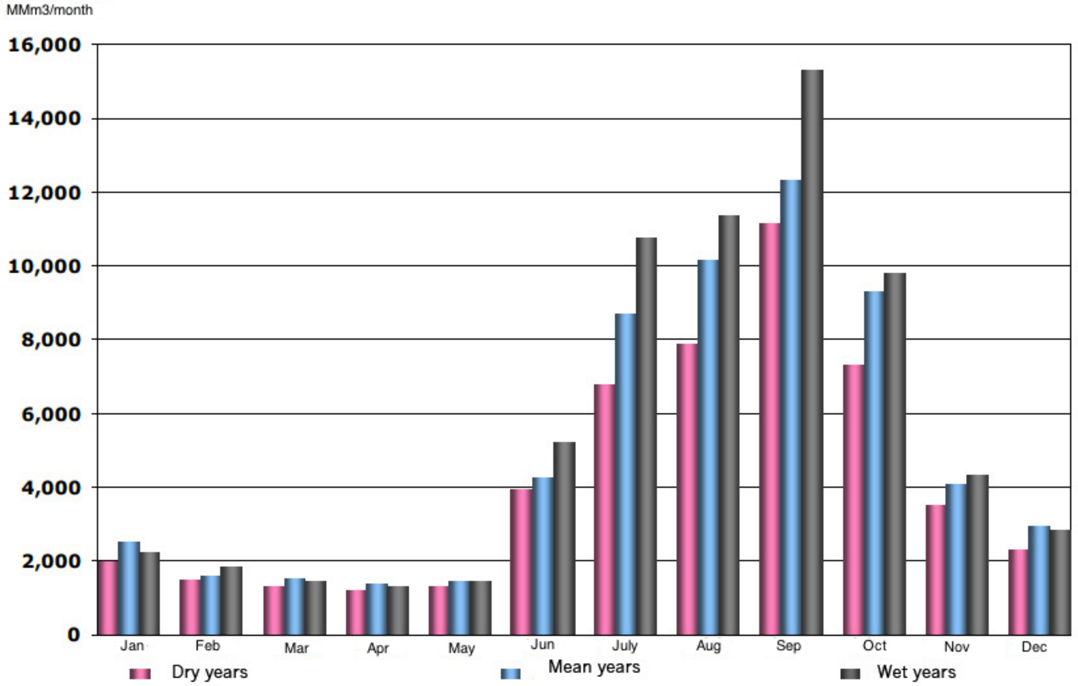

Figure 6-3: Inflows to the Big Hydro Power Facilities of Mexico
(59 years of data 1952-2010)
Source: Federal Commission of Electricity, CFE Mexico [28]

Table 6.1: Hydro Capacity

Unit	Angostura	Chicoasén	Malpaso	Peñitas	Temascal	Zimapán	Caracol	Infiernillo	Villita	El Cajón	Aguamilpa
MW	900	2400	1080	420	354	292	600	1160	320	750	960
GWh	13498	165	2580	11	1012	1007	469	1983	20	1016	919

Source: Federal Commission of Electricity, CFE Mexico [21]

expectation of water inflows and energy stored in the reservoirs. A constraint ensuring that the water level at the beginning of the year is the same as at the end of the year was also imposed; this allows the model to optimize water within the year considering that water must be left in the reservoirs to ensure operations start of the next year.[6]

Modeling hydropower generation and the hydro-thermal coordination problem is a complex modeling task, and by no means does this exercise explore fully the uncertainties and all levels of details of the different units and interactions. It does, however, allow us to capture the main dynamics of the water resources in the system, and explore its interaction with the rest of the system, particularly with the addition of more wind resources that have their own natural resource dynamics.

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[6] One of the reservoirs in Mexico (Angostura system) has inter annual regulation, which was assumed to be taken into consideration in the data of energy stored levels in the reservoirs.

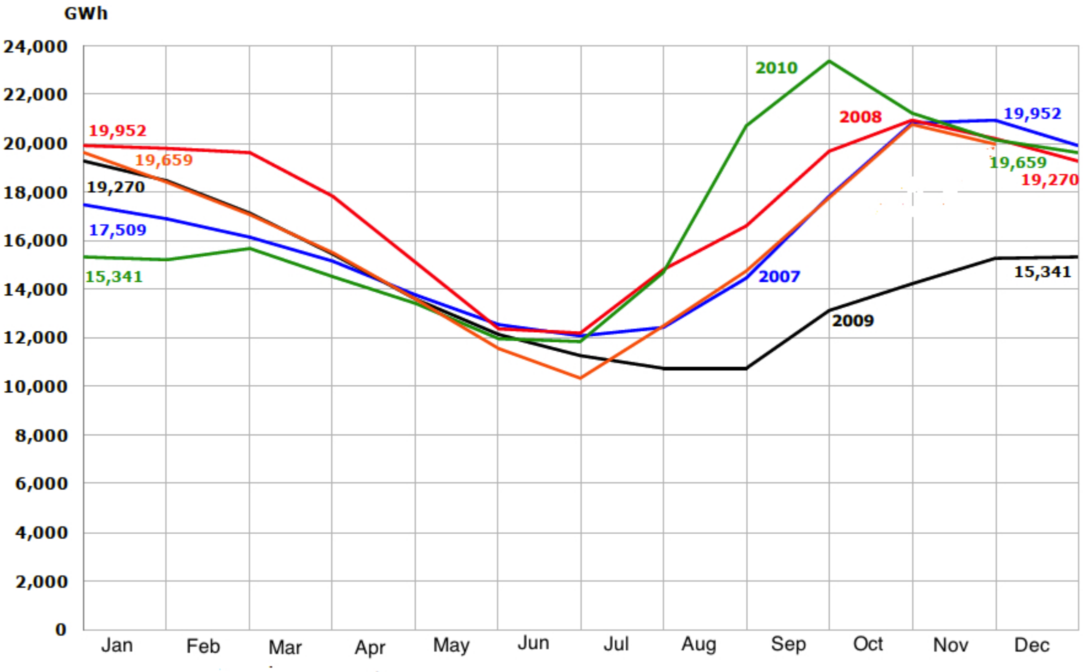

Figure 6-4: Stored Energy in the Big Hydro Power Facilites of Mexico (5 years of data)
Source: Federal Commission of Electricity, CFE Mexico [28]

Table 6.2: Minimum generation limits, GWh

	Angostura	Chicoasén	Malpaso	Peñitas	Temascal	Caracol	Zimapán	Infiernillo	Villa	Aguamilpa
Jan	20	58	159	68	26	16	20	126	54	40
Feb	20	58	144	61	23	14	20	113	48	36
Mar	20	58	159	68	26	16	20	126	54	40
Apr	20	58	154	66	25	15	20	121	52	39
May	20	58	159	68	26	16	20	126	54	40
Jun	20	58	154	66	25	15	20	121	52	39
Jul	20	58	159	68	26	16	20	126	54	40
Aug	20	58	159	68	26	16	20	126	54	40
Sep	20	58	154	66	25	15	20	121	52	39
Oct	20	58	159	68	26	16	20	126	54	40
Nov	20	58	154	66	25	15	20	121	52	39
Dec	20	58	159	68	26	16	20	126	54	40

Source: Federal Commission of Electricity, CFE Mexico [21]

The modeling exercise assumes that the best sites for hydropower development have already been built in the system. In the model, each year about 36,000 GWh of electricity generation comes from hydropower, which is very close to the economically feasible potential reported in [5]. Thus, in the reference case, I do not allow for potential expansion of hydro capacity. However, there is discussion in the country whether more hydro potential could be developed, particularly if fossil fuels use must be reduced. An estimate of the gross theoretical hydro potential of Mexico is 154,726 GWh per year. Costs of new developments above the identified economic potential are necessary to project the potential expansion of these resources. In addition, while some of the constraints on expansion are economic, the construction of big dams have related environmental impacts of disrupting river flows, and thus there is also a debate regarding the net environmental benefits of hydropower. Hydropower development has also some social impacts due to the displacement of communities to construct the dams and the needed infrastructure in some locations. In some cases, due to these environmental and social concerns, countries (like Mexico) have decided not to consider big hydro dams as part of their renewables portfolio standards that are currently subsidized on environmental grounds. In the sensitivity analysis, however, I present an estimate of the impact on the value of storage of developing more hydropower.

6.3.2 Climate change impacts on hydropower

Hydropower is an important source of flexibility in the system. However, it is also dependent on natural resources and thus subject to impacts of climate change. The implications of climate change for planning of hydro resources are significant, particularly in certain geographies of the world that can expect severe droughts or decreases in precipitation. Atypical years, particularly years with lower water availability than the historical low records, could complicate the planning of the system expansion and the operation.

As a first exploration of the direction and potential size of the impact of climate change on water resources in the region where the main hydropower facilities in Mexico are located, I used information from the MIT IGSM model regarding potential precipitation and temperature changes due to climate change.[7] The results of an uncertainty sampling from the IGSM model that considers 400-member ensembles combined with the uncertainty in the regional climate patterns generated from the AR4 climate-model results (total 6800 values) are plotted in Figures 6-5 and 6-6 [156, 148]. As shown in the figures, precipitation in the region is expected to decrease particularly during the summer months when historically more precipitation occurs (high probability of -1 mm/day and some possibility of -3 mm). Temperature is expected to increase (high probability of 2 to 3 degrees Celsius). From this analysis, we can expect decreases in water inflows in the region. A more precise calculation of water availability requires careful modeling of the resulting run-off in the different water basins, an area of future research . For now, I used information from Mexico's water atlas for the Southern Water Regions[8] where for the months of June, July, and August records an average of 24 mm per day inflows, and considered water inflows could decrease by more than 15%.

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[7] I selected a domain with west bounding: $105^\circ\ 22'$; east bounding: $91^\circ\ 16'$; north bounding: 22°; south bounding: 15°. Dr. Adam Schlosser, research scientist at the MIT Joint Program on the Science and Policy of Global Change, was kind enough to run the model for that domain and provide information for this sensitivity analysis.

[8] I consider regions: South Pacific, Gulf, and South Frontier

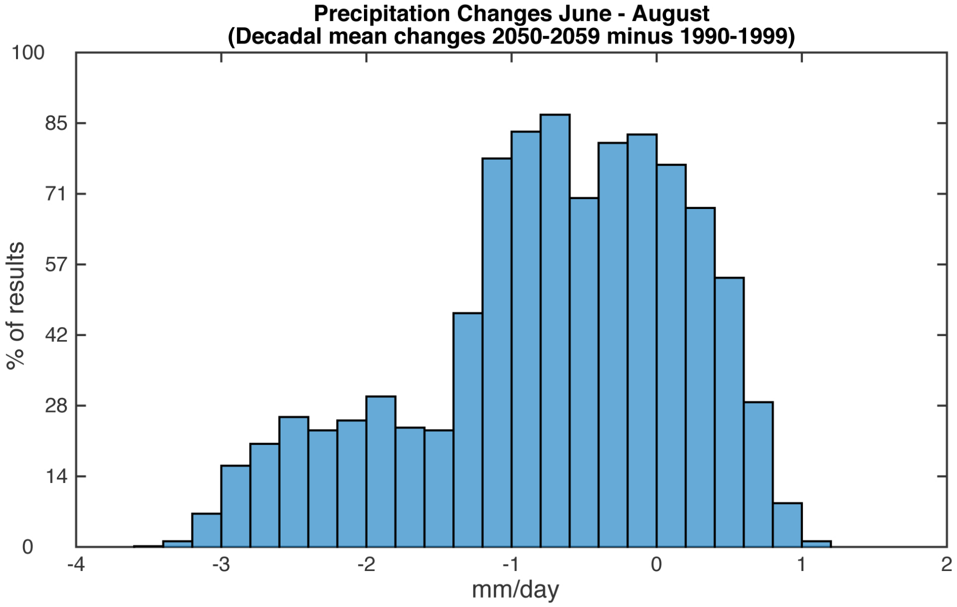

Figure 6-5: Precipitation Changes in Mexico's Region
with Big Hydropower Facilities (summer season)
Source: Schlosser, MIT IGSM model results for this study

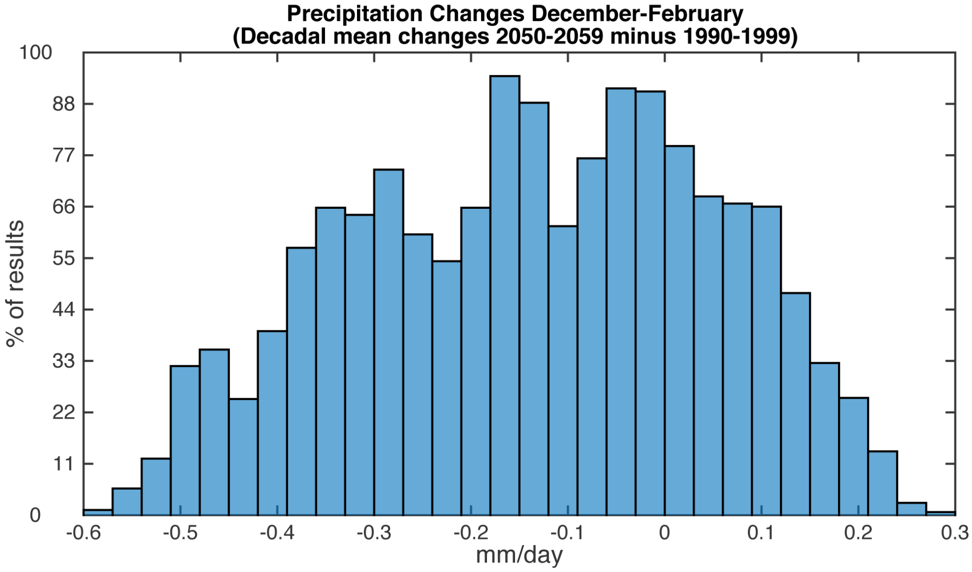

Figure 6-6: Precipitation Changes in Mexico's Region
with Big Hydropower Facilities (winter season)
Source: Schlosser, MIT IGSM model results for this study.

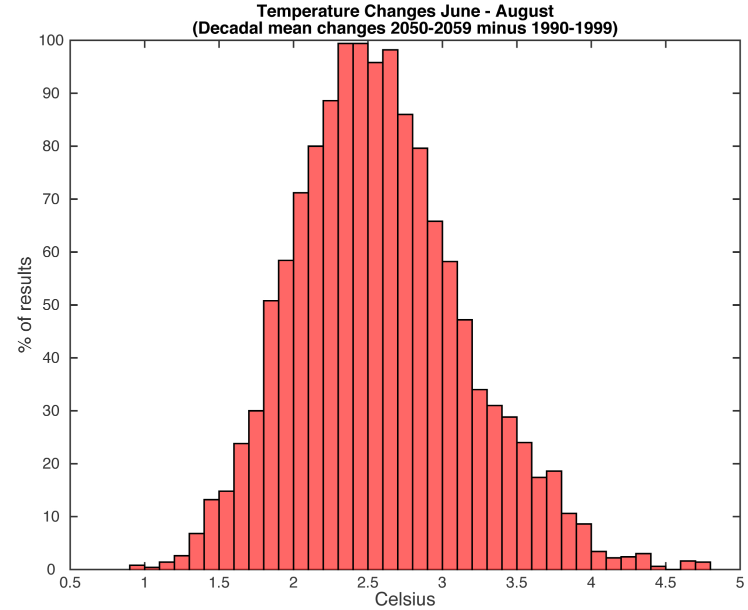

Figure 6-7: Temperature Changes in Mexico's Region
with Big Hydropower Facilities (summer season)
Source: Schlosser, MIT IGSM model results for this dissertation.

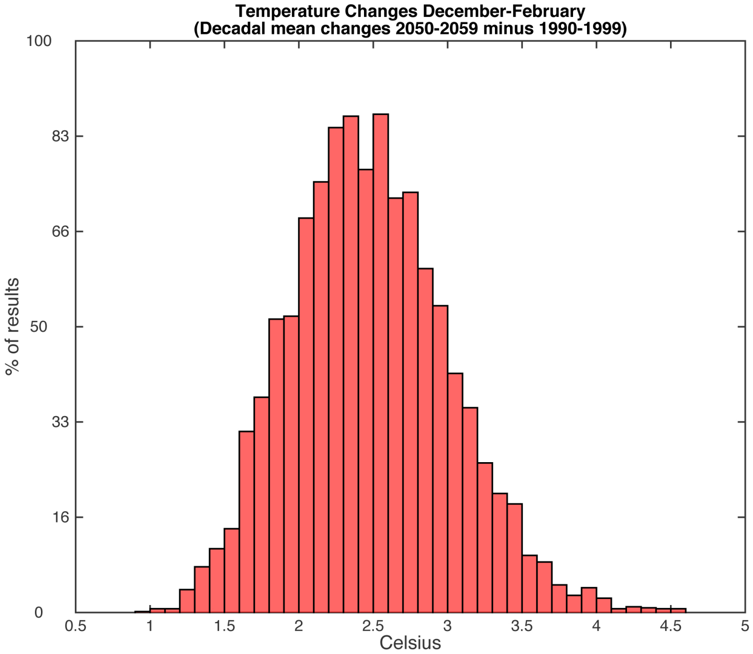

Figure 6-8: Temperature Changes in Mexico's Region
with Big Hydropower Facilities (winter season)
Source: Schlosser, MIT IGSM model results for this dissertation.

6.3.3 Results of sensitivity analysis

After explaining the modeling setting, and some of the issues surrounding the sensitivity to hydropower, I explore the value of storage considering 3 sensitivity scenarios:

- No availability of hydropower.
- Decrease of 50% of hydro inflows due to climate change.
- Doubled hydropower capacity, compared to the year of 2014.

The first exercise is somewhat theoretical, but allows us to explore the lower bound of the problem of hydropower availability in what it concerns to the value of other storage technologies. The second scenario considers the information presented on potential climate change in Mexico, and shocks the model decreasing total water inflows by 50%.[9] The third scenario assumes that some of the theoretical potential of hydropower could be developed economically. I do not model the capacity expansion of hydropower in this sensitivity analysis, I simply double the available capacity in the system and explore what could be the impact on other storage technologies. Figure 6-9 shows the results from the sensitivity analysis.

The results suggest that hydropower and storage are indeed interrelated. With less hydropower the value of storage coming from other technologies increases; with more hydropower the value of storage from other technologies decreases. If no hydropower were available, the value of other storage technologies could be 18% higher, conversely if hydropower capacity doubles, the value of other storage technologies drops by 21%. The sensitivity to less water inflows on the value of storage was low, about 6% increase in its value. This suggests that the available water is used in the hours of highest value and that storage is still able to cover some more hours of high value .

Many have studied the possibility of using current hydro capacity – or expanding current hydro capacity – to deal with intermittency. Jaramillo et al discuss the possibility that wind power can be complemented by hydropower, offsetting intermittency

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[9] As explained, more modeling to estimate a value of water inflows is necessary, for now the combined effect of precipitation and temperature increase is assumed to have extremes as high as 50% decreases in water for hydropower use.

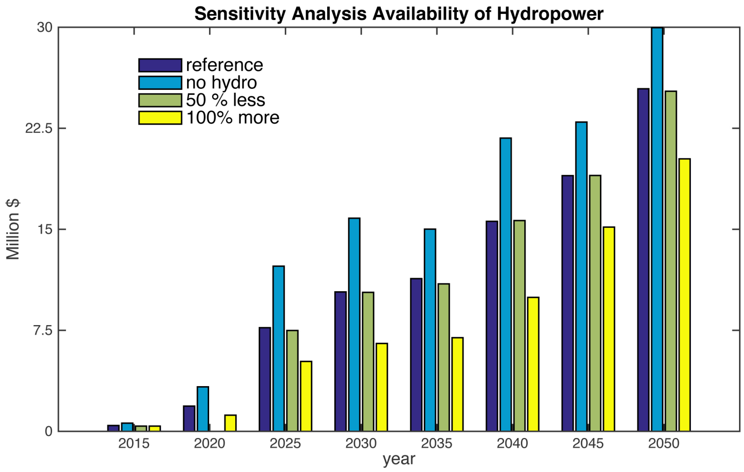

Figure 6-9: Sensitivity to Hydropower
Source: Author-modeling results

of wind.[98] The study analyses the interaction between a potential wind farm in La Venta, the best wind site in Mexico, and a hydropower unit located in Oaxaca.[10] Both sites have good natural characteristics for both resources. Ding et al. proposed an stochastic optimization model for the operation of PHS and wind [41]. These two examples provide good illustrations of different approaches, one using very detailed information at the local level, but focusing only on two facilities. The other detailing the stochastic process of two technologies, but abstracting the systems level interaction. I believe my study, while abstracting from the local units details, and simplifying the uncertainties, provides a different perspective capturing the higher level system interactions in an expanding system under large-scale penetration of renewables.

Finally, I want to remark that while Mexico's system has a small share of hydropower, there are many other systems in the world that are hydro dominated. The economics of renewable energy are different in such systems, since hydro can help balancing the system and provide the flexibility required to follow fluctuations of net load. Systems like the Scandinavians, the Brazilian, and others in Latin America are hydro dominated and the addition of other storage technologies could be much less valuable in such systems. Conversely, the impacts of climate change in these systems on the value of storage could be higher (and of course on total power supply).

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[10] In Juarez, Marques del Valle

6.4 Storage value under different scenarios for the price of natural gas

As shown in Chapter 5, natural gas technologies are expected to play an important role in the expansion of the electric power sector. The interaction between storage and natural gas technologies is an important one. First, natural gas is setting market prices as a marginal technology, and thus determines the hourly prices for energy during many hours of the year. If natural gas price is higher, larger differences between peak and valley hours could be expected. Second, natural gas capacity provides reserves and capacity margin to the system, and thus it also competes with storage in the ancillary services market and for potential reliability incentives. One question that arises is what could be the potential impact on the value of storage if the price of natural gas diverges from our current reference projection in the EPPA model.

Figure 6-10 shows the natural gas price projection of the reference case of the EPPA model, and compares it to the projections (made in 2013) of the Ministry of Energy (SENER) used in the planning of the electric system in Mexico. As shown in the figure, the natural gas price projected by the EPPA model approximates SENER's projections for the medium price scenario and is in between the medium and high price scenario.

Exploring the sensitivity to the price of natural gas is important, since currently many uncertainties surround the price of this fuel. There are many factors affecting the price of natural gas, both domestically and internationally. Natural gas markets are rapidly transforming in North America (Mexico's natural gas price follows closely prices in the US) as a result of the advancement of hydrofracking technologies that have made vast resources economically available and lowered current natural gas prices in the region (natural gas price is higher in other regions of the world.) Among the uncertainties affecting the possible price trajectories are the potential for higher integration of regional gas markets in the world, the extent to which climate regulations will take place inducing substitution from coal to gas, the cost of developing new

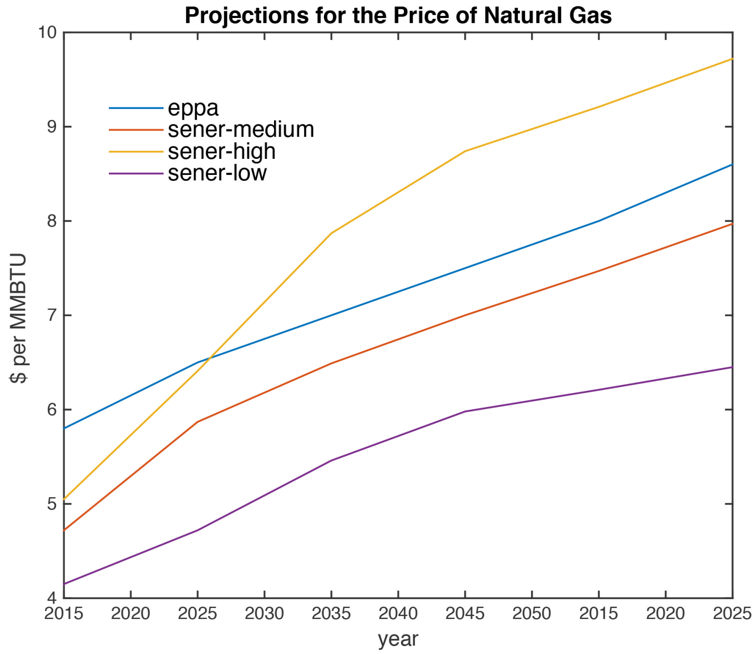

Figure 6-10: Natural gas price projections
Source: Author-modeling results & SENER [27]

resources, and the extent to which new environmental requirements to internalize the environmental impact of shale resources extraction could increase its cost [120]. In the sensitivity analysis, I model two different scenarios one where the price of natural gas is 50% higher and one where it is 50% lower. In this sensitivity analysis, I modified the price of natural gas from the reference case solution only in the electricity model, using the reference trajectories of the EPPA model for all other prices and electricity demand. In this way, the analysis explores the impact of changes in the price of natural gas controlling for all other variables.[11]

Figure 6-11 shows the sensitivity to higher and lower natural gas prices. In 2050, the value of storage is 2.2 times higher when the prices of natural gas are 50% higher; in contrast, in the same year, the value of storage drops by 50% compared to the reference case. This analysis shows that indeed the value of storage highly depends

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[11] With the EPPA model, one can investigate different pathways for the price of natural gas associated with the different dynamics of natural gas markets, such as greater resource availability, the possibility of higher integration of global natural gas markets, and the impact of new regulations, a work presented by [133]. Here my objective is to present the impacts of changes on the price of natural gas on the value of storage holding everything else constant.

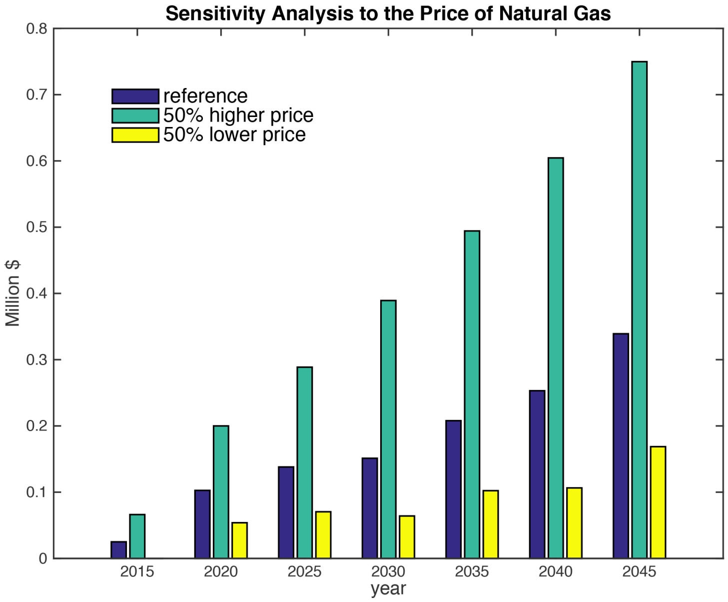

Figure 6-11: Sensitivity to the Price of Natural Gas
Source: Author-modeling results

on the price of natural gas in this electricity system. The present value per GW installed in 2020 is 120% higher when the natural gas prices are 50% higher, and the value decreases 56% when the prices of natural gas are 50% lower.

6.5 Summary of sensitivities to the value of storage

In this chapter, the main factors that influence the value of storage were tested to explore the sensitivity of the value of storage. For all the sensitivities, I consider 10% of storage capacity as a percentage of total renewables generation. I estimated the remuneration of storage technologies for the period 2020-2050, and computed the present value per GW installed in 2020 using a discount factor of 6%. I found that among the sensitivities explored in this chapter, the price of natural gas resulted in the most important factor affecting the value of storage. The present value per GW is 120% higher when the natural gas prices are 50% higher, and decreases by 56% when the prices of natural gas are 50% lower. In second place, the sensitivity to the specification of power resulted in an increase of 44% when power duration is 20 hours and decreases by 75% when power duration is reduced to 4 hours, as compared to the reference specification of 8 hours, holding the same capacity by year. In third place, when we test the relationship of the value with the presence of hydropower, we find that decreasing to zero hydropower availability would increase by 49% the present value of storage per GW and a doubling of current hydro capacity would decrease the value of storage by 33%. In fourth place, decreasing the efficiency of storage from 85% to 50% decreases the present value per GW installed by 35%. Finally, decreasing water inflows in 50%, decreases only 6% the value of storage. Table 6.3 summarizes this chapter's results.

Table 6.3: Sensitivity Analysis Summary

Parameter	**Sensitivity Analysis**	**Increased Value**	**Decreased Value**
Efficiency	decrease from 85% to 50%		35%
Power duration	decrease from 8 to 4 hours	75%	
Power duration	increase from 8 to 20 hours		44%
Hydropower capacity	decrease to zero	49%	
Hydropower capacity	increase 100%		33%
Hydropower inflows	decrease 50%		6%
Price of natural gas	increase 50%	120%	
Price of natural gas	decrease 50%		56%

Chapter 7

Conclusions

Capitalism is by nature a form or method of economic change and not only never is but never can be stationary...The fundamental impulse that sets and keeps the capitalist engine in motion comes from the new consumers' goods, the new methods of production or transportation, the new markets, the new forms of industrial organization that capitalist enterprise creates ... that incessantly revolutionize the economic structure from within, incessantly destroying the old one, incessantly creating a new one. This process of creative destruction is the essential fact about capitalism.

Joseph Schumpeter

Capitalism, Socialism and Democracy

In this dissertation, I have explored the value of electricity storage under increasing renewables penetration. This last chapter concludes the investigation, elaborates on the policy implications of the findings, and identifies key critical areas of future research. Let me start by stepping back and reflecting on why we need to know the value of storage, why it is necessary to understand our power systems' capacity to deal with the stochasticity of renewable energy supply, and the economic implications of the integration of renewables, as we design solutions to reduce the climate risk.

We need to transform the energy system, we need to do it timely, and the challenge ahead is enormous. Traditionally, the power sector has been a slow-moving system, but the size and timing of emissions reduction imply a total disruption for the sector. Much of the climate change mitigation action depends on finding effective technologies to decarbonize the power sector, and to a great extent the political impasse on reaching international agreements for emissions reductions has a fundamental underpinning on the macroeconomic consequences of deep decarbonization. The motivation of this study is to inform society of one possible technology that can facilitate systems transition to clean energy. More broadly, however, it aims to develop tools that can expand our thinking and understanding of critical interactions between the power sector and the economy, and the role of new technologies in facilitating the integration of low-carbon electricity.

As I show in this study, the value of storage technologies increases as the system integrates more renewables; however, current storage technologies, even under scenarios of very large-scale penetration of renewable energy, still need to drastically reduce costs to reach the value target found in this dissertation. As of today, no single electricity technology can provide low-carbon electricity on the scale and cost that society needs. It is on the development of new technologies and markets, on the innovation required to decrease technology cost, that the solution of the climate issue resides. New technologies will transform our current power sector, they will "destroy it" in a Schumpetarian sort of transformation, and new institutional arrangements will emerge. It is in this broader context that I think about storage, renewables, and other important technologies that can facilitate decarbonization.

Change is fundamental to the advancement of human well-being (not only to capitalism), to paraphrase Schumpeter. The world is changing and the need for energy has never been greater. Shedding light on the real social value of different technologies to provide energy in a sustainable way is critical to craft adequate energy and climate policy. We need to create economic value without carbon and the fundamental driver for innovation is the need for human development, the need to protect societies' well-being under multiple drivers of global change. The capacity of society for "creative destruction", the growing awareness of the climate problem around the world, and the impending need to power the world providing increasing standards of living for millions while protecting the planet, makes me confident that innovation is on its way.

7.1 Key findings

Under an environment of increasing shares of renewables in the power grid, the value of storage increases sharply. By 2050, with a 50% renewables penetration, the present value per MW installed found in this dissertation is 1500 \$/MW and 200 \$/MWh.[1] Only two of the current technologies could provide services at these values– CAES and PHS – however, they have limitations regarding location and scalability. All other technologies will still have to drastically reduce their cost to compete in the marketplace, even considering the large-scale penetration of renewable energy modeled in this study. Therefore, further research to decrease the costs of alternative storage technologies seems necessary.

My estimates for the value of storage in 2050 for the Mexican system are higher than the ones previously reported in the literature for different systems around the world, as compiled by [202], and discussed in the literature review chapter. Most previous studies have evaluated systems with low or no penetration of renewable energy. The vast majority of previous studies have focused on estimating the value of storage with the price-taking-approach. For example, my estimate for the value of storage in 2050, of 200 \$/kW, is an order of magnitude higher that the one estimated by Sioshansi et al using an enhanced price-taking method[2] for the PJM system [175]. Sioshansi's value is the highest reported in the family of studies using the price-taking approach. My estimate is also higher than most available studies using system-level models, which vary widely among themselves. Many of this kind of studies find values of less than 50 \$/kW in current systems. Some studies using production costs models find higher values, for example, Denholm et al.'s analysis of a part of the WECC interconnect, finds a value between 40-90 \$/kW. Only one study finds values higher than the ones estimated in this dissertation. Strbac et al reports a range from 180-520 \$/kW studying the UK system with increased deployment of wind.

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[1] The present value is estimated for 1 MW of storage capacity in 2020, operating from 2020-2050 under increasing renewables penetration, at a 6% discount rate.

[2] Sioshansi et al used a price-taking method and feedback functions to approximate the impact of greater availability of storage in prices. This methodology represents and improvement over the traditional price-taking approach.

The operational flexibility that storage can provide to the system is valuable due to the new challenges of managing fluctuating net demand, which can result in difficult operational conditions. I unfolded the different operational dynamics driving the value of storage, analyzed different situations where storage supports operations in the system dispatch, and decomposed the value in the different services that storage provides to the system. In the case of Mexico's power system, the value of storage for energy management services resulted in the highest value component followed by operational reserves provision and capacity payments. In 2050, with a 50% renewables penetration as share of electricity generation, and 10% of storage capacity as a share of total renewable generation, 58% of the value of storage comes from the energy market, 22% from the ancillary services market, and 18% from capacity payments.

It should be noted that, for the capacity payment, I required storage to have a minimum charge, which is the base for this payment. In reality, this creates an inefficiency in the operational regime of storage, and thus different approaches to design mechanisms for reliability payments to storage are necessary. For example, storage could participate in reliability options, or capacity markets, and its remuneration could be associated with their participation under those mechanisms.

I found that the presence of storage changes both investments and operational decisions. In particular, under a renewable portfolio standard requiring higher shares of renewables, the presence of storage decreases the operation of gas turbines. Open gas turbines generate 80% less compared to the scenario without storage, and combined cycle units 18%. Although less generation from open gas turbines is needed, additional capacity is built, to provide reserves to the system. In a scenario when wind capacity is optimized (in contrast with a specific mandated target), storage allows the integration of more wind, and also reduces the need for natural gas combined cycle units and increases the need for open gas turbine units for reserves provision. These results suggest that mechanisms that ensure investments in natural gas turbines providing reserves (but mostly not participating in the energy market) should be considered as renewables penetrate into the system.

My analysis also suggests that, under increasing penetration of renewable electricity, hourly prices become more volatile; one of the outcomes of storage capacity in the system is to reduce price volatility and the occurrence of negative prices. The implications of higher price volatility in electricity markets go beyond the analysis of storage; it affects decisions at different levels from system operators' grid management to generators' long-term investments. System operators are normally concerned with very high price spikes, however, those hours of high prices are needed to remunerate some technologies providing power for few hours of the year. When the operators decide to prevent price spikes (by actions outside the market such as shedding loads or decreasing power voltage) peak units are unable to recover their full investment costs – the so-called missing money problem occurs – and long-term investment in this capacity is disincentivized. In this dissertation I do not capture the value of storage of preventing such disruptions, since I model the optimal dispatch of the system. However, in Chapter 5, I discussed the impacts of storage on prices. Thus, an additional benefit of storage is decreasing price volatility that could (potentially) be problematic for the system.[3]

As shown in our modeling exercise, the value of storage under economy-wide emissions reduction policy plays an important role as it allows more mitigation to occur through substitution towards clean electricity. In the particular case of Mexico, simulating a 50% emissions reduction by 2050, the model demonstrated that storage could decrease total welfare losses by 0.7% when compared to the case without storage. Therefore an important policy question is how to incentivize storage cost reductions –and the development of other technologies that could facilitate deployment of clean energy in a climate constrained world– such that the full social value of their availability can be achieved once these policies are implemented.

The general equilibrium analysis also shows that without policies restricting emissions outside the electric sector, most of the emissions reductions achieved by the electric power sector with the renewable portfolio standard are offset due to increases

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[3] Operators can always let prices fluctuate, however, often the political implications of price "spikes" have resulted in interventions that reduce profits for some generators, a problem that could aggravate as renewables enter the system, since more spikes occur due to wind fluctuations. Instruments to enhance system reliability are in place in many regions of the world, and should probably be revisited as renewables scale-up.

of emissions in other sectors, particularly in energy intensive industries. This highlights the importance of designing comprehensive climate policies that cover all sectors of the economy, otherwise the ultimate environmental outcomes can be dissipated due to changes triggered by the policy. In all, the availability of storage reduced 3% of the economy-wide emissions. The general equilibrium analysis also shows that the value of storage under climate policy highly depends on the ability of the economy to switch to electricity as a mitigation option. Thus enhancing the industrial sector and residential consumers' capacity for this substitution will increase the value of storage and decrease the costs of climate change mitigation more generally.

Finally, key factors that influence the value of storage were tested to explore the sensitivity of the value of storage. In a comparable scenario, with increasing penetration of renewable energy from 2015-2050 and 10% of storage capacity as a percentage of total renewables generation, the value of storage sensitivity was explored against changes in the prices of natural gas, the availability of hydropower, the efficiency parameters, and rated power. By comparing the present value of 1 GW installed in 2020 considering a 6% discount rate, we find that the most important factor affecting the value of storage is the price of natural gas, followed by power duration of storage technology given a fixed capacity, hydropower availability, and efficiency.

The value of storage is 120% higher with an increase of 50% in the price of natural gas, and decreases by 56% when the price of natural gas is 50% lower. Holding the same capacity constant each year[4], increasing power duration from 8 to 20 hours resulted in an increase of 44% of the value of storage; conversely when power duration is reduced from 8 to 4 hours, the value of storage decreases by 75%. These duration values represent ranges of the relationship between total capacity of storage and power of different technologies already in the marketplace. Finally, decreasing the efficiency of storage from 85% to 50% decreases the present value per GW installed by 35%. The sensitivity analysis shows that the relationships of the value of storage and the different parameters are mostly non-linear.

A special sensitivity analysis was conducted for hydropower. Hydropower facili-

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[4] Capacity increases over the time horizon, but we evaluate the same capacity with different power

ties with reservoirs are also a form of storage built into the system. In this study, I purposely separated the value of hydropower capacity already in the system, and the value of other technologies that could provide storage services. This represents the situation of systems that have hydropower capacity, but that do not have pumped hydro storage, and therefore cannot take electricity from the grid to store energy for later use. However, big hydro dams are an important source of energy storage. Since hydropower is also variable, the dynamics of water inflows must be taken into consideration and modeled to carefully assess its interaction with other fluctuating renewables and other storage technologies. I modeled the reservoirs management given information on stored energy by month, capacity in the system, and minimum generation constraints. The analysis suggests that the value of storage from other technologies is related to availability of hydropower. If no hydropower is available, the value of other storage technologies could be 18% higher; conversely if hydropower capacity doubles, the value of other storage technologies drops by 21%. Decreasing water inflows by 50%(potentially driven by climate change impacts on water resources) resulted in a low increase of the present value of storage of 6%.

7.2 Modeling contributions

This analysis is the first to investigate the value of storage using both a detailed electricity sector model coupled with a numerical general equilibrium framework to evaluate climate policy. The proposed hybrid modeling approach and experimental design allows the analysis of both changes in the electric sector driven by storage and economy-wide impacts of climate change policy with and without storage technologies.

General equilibrium models are often used to analyze the consequences of policies with a wide range of impacts in different markets in the economy. Climate policy is one area of public policy where the analysis of economy-wide interactions is critical to fully capture policy costs. Without the coupling of the general equilibrium model, we would certainly miss the value of electricity storage to reach economy-wide carbon reductions. Furthermore, without the electricity model, the general equilibrium model would not be able to capture the value of storage at all, since its value is highly dependent on the hourly time dynamics that make attractive charging and discharging, as well as on specific technical constraints in the system, i.e. avoiding shut-downs and wind curtailment. The proposed modeling approach is robust enough to integrate both electricity constraints at the short-time scale needed for the evaluation of policies on renewable energy and the economy-wide interactions of the economy under climate policy.

As mentioned, previous modeling approaches to investigate the value of storage were dominated by the “price-taking” approach. This approach is unable to explore the value of storage under large-scale penetration of renewable energy in future systems. As demonstrated in this dissertation, storage capacity in the system changes both investments and operational decisions, and with them the prices for energy, ancillary services and reserve margin capacity. In addition, studying historical time-series for systems with low or no renewable penetration is not useful to explore the value of storage under increased renewable penetration, since prices will change as renewables enter the system as well. Previous studies were not designed to evaluate the value of storage under renewables integration, and were well designed to investigate potential value of storage under current market conditions. However, as the systems change, greater emphasis should be put on new modeling approaches.

Few studies have used production cost modeling, a useful approach for the question of the value of storage with renewables integration. However, as shown, since investment decisions are also changed with storage, the modeling of investment decisions and the expansion of the system is necessary. The modeling framework developed in this dissertation is able to evaluate the expansion and operation of the system, with a long-term horizon as the economy develops. The modeling framework developed also simulates the hydro-thermal coordination, by incorporating the main constraints to simulate the hydro dispatch. This was necessary to explore the value of storage, since hydropower is in itself a source of storage in the system.

In sum, this dissertation informs the modeling community of the importance of combining bottom-up and top-down approaches when evaluating policies and technologies affecting the electric power sector, particularly policies targeting renewable energy and the role of supporting technologies and infrastructure for clean electricity deployment, such as storage devices. It does so by using two robust models, the MIT EPPA model with enough detail to evaluate energy and climate policy, and a new model built for this dissertation, the RISA model, that incorporates new features necessary to evaluate storage technologies. It combines the two in a computationally efficient way using a block decomposition methodology [18]. This decomposition approach allows to make the key sector of the model more visible and more easily understood by experts focused on electricity and renewable energy policy.

7.3 Policy implications

When designing policy regarding electricity storage, it is important to consider the implications for other generators and for the overall electric system. As I have found in this dissertation, and others have also discussed, the availability of storage capacity changes investment and operational decisions. In particular, today, some systems around the world have started subsidizing storage and/or setting minimum goals for storage deployment. One should carefully review these policies given that most of the technologies costs are high, and if they prove unable to reach the value proposition in the markets where they operate, social welfare will be reduced as a result of these policies, with the additional implication of having an ill-adapted electricity mix dependent on expensive technologies.

Assessing the value of storage in different systems, considering its overall social welfare value (i.e. including carbon policy) is critical to properly design incentives for storage. The remuneration of all possible services with economic value that storage can provide is recommended, including storage capacity provision of reliability services. In some systems around the world, specific targets in GW of storage capacity are being explored or mandated (e.g. California). The traditional question on the value of research and development versus learning by doing arises in these cases [154, 15, 110, 25], and thus, a careful design of these policies is recommended such that it ensures adequate incentives are in place to incentive innovation in storage technologies.

As discussed in this dissertation, part of the welfare value realized under climate policy due to storage availability is realized in different sectors of the economy, consumers and other generators. Therefore, an important policy question on how to incentivize innovation arises. Studies to support the design of policies for research and development and/or deployment of storage – and other technologies supporting renewable integration such as distribution and transmission networks – are much needed. This dissertation, for example, could support the analysis of the value of storage under stringent mitigation action in Mexico, providing estimates of the value for the economy. Many institutional efforts around the world have committed to assist countries in the deployment of renewable energy, both in developing and developed economies.[5] The value of storage (and other technologies) differs among electricity systems and economies around the world. I argue that modeling frameworks, such as the one developed in this dissertation, could prove valuable to assess the macroeconomic implications of the deployment of renewable energy and storage in other systems.

Given the detailed study of Mexico's power sector and economic assessment of climate policy, I also outline some policy implications for the country. I focus on the implications for climate policy with a general overview given the costs estimates found in this study and on policy implications for the electricity sector. An extensive analysis of other sectors in Mexico, and a comparative analysis of Mexico's policy with peer countries in Latin America, can be found in some of my previous work with the MIT EPPA model [129, 31, 191].

7.3.1 Mexico's climate policy

As I write this dissertation, Mexico's climate policy is in the international press discussing Mexico's role as the first developing country that submitted its climate action

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[5] For example, the World Bank has committed to assist countries in doubling the share of the world's energy supplied by renewable sources from 18 percent to 36 percent.

plan to the UN's upcoming Paris negotiations of December 2015 [34, 192, 179, 127].[6] Many speculate that Mexico's commitment could be important in involving other developing countries in climate mitigation. The US White House commented: "Mexico is setting an example for the rest of the world by submitting an INDC[7] that is timely, clear, ambitious, and supported by robust, unconditional policy commitments." As I ponder these policy developments, and reflect on the value of this study for Mexico's climate and energy policy, I find two main ideas that I would like to underline.

First, Mexico has in fact made a remarkable effort in advancing its legal and policy framework to take action on climate change (see Chapter 2). Moving forward with the implementation of policies is nonetheless a challenging task. My study suggests that the role of renewables and storage in Mexico's mitigation policy could be significant, particularly under stringent mitigation scenarios such as the ones envisioned in Mexico's long-term national mitigation strategy. It also highlights the importance of crafting policies that are comprehensive, and take into account the interaction between different markets in the economy. While there are policy benefits (e.g. fuel diversification) from promoting renewables penetration regardless of the emission outcomes, from a climate change policy point of view, it is necessary to evaluate total emissions reductions. Therefore, the program on renewable energy should be part of an overall strategy that reaches national emissions reductions at least cost. Hence, integrated approaches, such as the one put forward in this dissertation, are very much needed in the country to evaluate policy design.

Second, the policy costs for the country are important and international cooperation should be enhanced to lessen the welfare implications of carbon pricing for the country. This study found that GDP growth could decrease by as much as 9% if emissions were reduced 50% by 2050 from 2010 emissions levels, in a context where all countries are implementing similar mitigation actions. However, given the cur-

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[6] The country has committed to decrease unconditionally 25% of its greenhouse gases (GHGs) and short lived climate pollutants (SLCP) emissions below its business as usual baseline for the year 2030. According to the countries submission, the target implies emissions will peak on 2026, and that emissions intensity per unit of GDP must be reduced around 40% from 2013 to 2030.

[7] Intended Nationally Determined Contributions, the official name for countries submissions to the UN on their voluntary emissions reductions goals.

rent state of the climate negotiations, it is unlikely that all countries will move at the same speed. Mexico's current production structure is carbon intensive, a fact that should be considered in the design of policy and in international negotiations. Emissions leakage effects and trade implications should be carefully assessed in that context. Policies and technologies that allow Mexico to reach emissions reductions in a cost-effective way will be critical to prepare the economy for switches to low-carbon technologies in all sectors. Mexico and the US have announced a joint effort on clean electricity and grid modernization, a step in the right direction given the identified need to provide clean electricity in the context of climate mitigation [84]. Negotiations to facilitate faster technology deployment to modernize energy intensive industries in the country would also be necessary, as I have also identified in this study.

Given the difficulties of advancing global environmental agreements on the climate issue, the need to move forward the negotiations justifies voluntary policy moves. It is no surprise, however, that other developing (and developed) countries are not moving forward at the same pace. Mexico is highly vulnerable to climate change impacts, and thus justifies action on these grounds. However, even if all current countries' pledges of emissions reductions were achieved[8], total global emissions would not reach stabilization targets [96]. The failure of a far-reaching climate agreement would therefore imply costs due to damages of climate change and welfare reductions due to mitigation policy. It is necessary that countries like Mexico that have reached domestic political consensus to move forward on mitigation, continue to be able to justify to their citizens the investments in low-carbon technologies. The international community should not only praise Mexico for its real advancement in reaching domestic climate policies and laws; it should also make sure, through technology and policy expertise transfer, that the countries that are moving forward with climate mitigation achieve real emissions reductions and implement accompanying policies for cost containment to reduce potential distributional impacts [147].

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[8] As of April 5, 2015 Switzerland, Norway, the European Union, the US, Russia and Gabon have submitted INDCs, at different levels of action. European countries have pledged a 40% reduction and a US 25%. More submissions are expected before the COP21 in Paris, of particular attention China's and India's INDC.

7.3.2 Mexico's electricity policy

Under the lens of climate policy, the importance of the new regulatory design of Mexico's electricity market acquires a new dimension. New regulatory developments for a more efficient system, that modernizes generation and transmission assets, and ensures environmental performance, will be critical for low-carbon development. From 2015-2018, markets for electricity, capacity and clean energy certificates will be launched, starting with the day-ahead and spot markets by the end of 2015. In addition, auctions for clean energy capacity (October 2015 for contracts in 2018) and for financial transmission rights will be established.

It is not possible to comment yet on the actual form that the mechanisms will take in Mexico, since market rules are still under design. However, I will briefly comment on some implications of this research that can provide elements for the design of these markets and auctions for a better preparedness for renewables and storage integration. It is worth considering these elements from the outset, as the Mexican market is designed, since experience in other regions of the world has shown that the modification of rules to account for storage is difficult once definitions and procedures have been established.

Flexibility pricing. The increased need for flexibility as renewables penetrate in Mexico's system was made evident in this research; and is now a well identified problem of renewable integration worldwide. However, a few systems today have designed market rules that adequately send market price signals for the different flexibility requirements. In some areas where generation of renewables is growing, ramp capability products will be included in electricity markets (i.e. CAISO, MISO). Energy storage is one of the flexibility options, but different technologies can provide flexibility to the system, and the most economical should be deployed first. As renewables scale-up, specific measures to ensure that the power system has enough operational flexibility will be necessary. In some cases, this could entail the adaptation of the existing definitions of operating reserves considering the added variability of the net load with renewables, such that enough capacity is ready to ramp when the system needs it.

Open market access and full compensation of multiple services. As discussed by [14], there are many regulatory issues that could prevent or facilitate storage deployment. One must recognize that special characteristics make storage difficult to regulate and compensate. First, storage assets are multifunction, they can provide services for energy management, ancillary services, and they can also assist transmission and distribution networks. Markets should be open for storage participation, and compensation for cross products and inter-temporal opportunity cost should be considered. Some difficulties arise when storage provides services to the wholesale market and to networks, for instance to support transmission congestion relief. While storage could provide services both in the energy market and by supporting networks operation (part of its capacity could be used for one service and part for the other), many regulatory schemes do not allow the same asset to participate in wholesale markets and cost-of-service remuneration.[9] As shown in this dissertation, the value of storage comes from the different services that it provides, and given current storage technologies costs, compensation for multiple services will be needed for storage to be economical.

Clear regulatory definitions for storage operation. In addition to market participation and services remuneration, different stipulations in market regulations could impact storage operations. For example, in some markets, discussions as to whether storage should be classified as a generator or as a controllable load have taken place, and different classifications can change the economics of storage.[10] As discussed by [143], as the grid becomes more complex with renewables and new technologies scale-up such as storage devices (and new distributed energy resources or electric vehicles) the traditional dichotomy for classifying generators and loads will be obsolete, since

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[9] Bhatnagar presents a review of different cases in the US FERC regarding storage services, and highlights that it is a difficult regulatory problem, on one hand there is a recognition that storage can provide different services, but on the other hand regulators want to avoid rate payers of transmission services paying for assets that will be used to gain profits in wholesale markets.

[10] For example, in ERCOT, storage is classified as a generation asset, and as such, it is given interconnection rights and transmission assets. However, in the same system, due to definitional issues, some of the electricity that is used in the operation of storage (e.g.cooling skids, heat exchangers, and other equipment) is classified as loads, and must pay retail rates instead of wholesale rates, impacting the economics of storage operation [14].

traditional loads points (e.g. residential customers, industries, etc.) will generate, store, discharge, etc. Thus, definitions that focus on how different users contribute to network costs – and avoid tracking of specific electricity uses behind the meter – will be preferable.

Treatment of storage when it is charging. In some systems, storage is only allowed to charge when a regulation down control signal is issued; conversely when regulation up control signal is in place and the device is charging, the operator then could add that amount to storage as a regulation service. Different rules will be important to consider for storage remuneration services.

Flexible intra-day markets. Flexible intraday markets can help the integration of renewable energy by allowing generators and consumers to balance the market closer to real time. It also helps integrating renewables by using more accurate weather forecasts. In addition, increasing the interconnections with neighboring areas has proven useful in Europe, where Flexible Intraday Trading Schemes (FITS) are facilitating the integration of renewables [176]. As I have found in this study, the increased presence of renewables impacts market prices, incrementing the occurrence of price spikes or negative prices. Countries that have scaled-up renewable energy have encountered this phenomenon as renewables integrate. Day-ahead market coupling and closer to real-time market design have proven useful in Europe to limit the potential price impacts of renewable energy. As we have shown, also, storage can help mitigate price volatility.

Resource adequacy mechanisms. Mexico has announced capacity markets as part of the new market design. Designing security of supply and resource adequacy mechanisms is one of the most challenging tasks as renewables scale-up. All the different time-scales of operation and expansion of power systems will be influenced by security of supply mechanisms. Thus, system design should consider the security (very short time-scale requirements to maintain system stability), firmness (short-to-midterm capacity to meet current demand efficiently) and adequacy (long-term system capacity to meet growing demand) as well as the experience accrued in different markets that have introduced capacity markets [150].[11] In addition, careful study of the capacity credit of wind and solar technologies in each of the different regions should be included. Storage remuneration should encompass its contribution to system reliability and adequacy.

7.4 Limitations of the study

The value of storage cannot be extrapolated to other systems. First, the estimate in this study is very dependent on the electricity mix, resources and demand profiles of Mexico. Also, the climate policy cost evaluation is specific to Mexico. Other economies have different structures, with different mitigation options available. The amount of mitigation that is done through substitution to electricity depends on what are other mitigation options in the economy. Despite these caveats, the Mexico case illustrates the main dynamics that one needs to take into account to understand the value of storage in any system, and highlights that under strict climate policy and increasing renewable integration in the power sector, the value of storage increases both for the services it provides to manage intermittency and because by doing so it helps in larger mitigation efforts.

Also, detailed stochastic modeling of storage and renewables dispatch was not conducted. As described in Chapter 4, I used a 20% probability of wind forecast error by hour in the model to consider the probability of wind generation being lower than expected. More detailed modeling of the uncertainty in wind should therefore be incorporated in future studies.

A third limitation is that the details of the network are very stylized in this study. Detailed assessment of the value of storage in a particular electric region requires more modeling of the particularities of the networks and location of storage. The goal of this study was not to provide such detailed modeling, but to capture the

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[11] Battle el al provide an excellent overview and evaluation of the experience with capacity markets. They also discuss design principles for security of supply instruments [150].

main interactions of storage in an electricity sector with expanding renewable energy and the economy. Thus, the value of storage here should be considered as a first order approximation of the value in the system, and more detailed modeling for each location should be conducted for specific applications. In addition, implicitly in the model I considered utility-based storage, and not consumer-based storage.

7.5 Future research areas

7.5.1 Electricity storage options in other sectors of the economy: transportation and cooling demands

Modeling energy storage options in other sectors of the economy other than the electric sector is an interesting future area of research. The transportation sector could provide storage if greater penetration of electric vehicles is expected. Also, thermal storage technologies could be used to meet cooling demands in households. These types of storage uses could also be analyzed in the integrated EPPA-RISA model, and in this way, the value of storage services in these other sectors could be evaluated. In this dissertation, I established the framework of analysis that could be expanded to analyze these interactions. However, several important adaptations will be needed to further disaggregate electricity loads and optimize charging and discharging of electric vehicles and to characterize storage in final energy uses. Research that informs the possible charging and discharging patterns of electric vehicles considering behavioral elements would be valuable to properly characterize storage in the transportation sector.[12] Similarly, information regarding cooling demands and time-of-day use will be needed to properly characterize the potential use of storage by households for this service.

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[12] While an "optimal" dispatch could be simulated, it is important to consider that unlike utility-scale storage, other storage options in the economy are tightly connected to social activities that do not only depend on the price of electricity, e.g. preferences regarding transportation times, etc.

7.5.2 The role of short-term demand response and its interactions with storage value

The advancement of new power electronics and information technologies could facilitate higher short-term demand response in the future, as new mechanisms for time-of-use pricing are implemented. Exploring the interactions of the value of storage and higher short-term demand response is a future area of research. Understanding the interaction between increased short-term demand response, and long-term elasticity of demand would be necessary to fully integrate the analyses of the macro-economic model and the electricity model with short-term demand response.

7.5.3 The value of storage for distributed energy systems

Currently, much discussion in the electricity sector regards the influence of distributed energy systems in the future of the electric grid. Some technologies – in particular solar PV – are changing the landscape of distributed energy systems. Further research on the value of storage for those systems is necessary. While storage might be located at the distribution level, its impacts would expand to all levels of the power system, and thus an important area of research regards the impacts on generation, transmission, within the distribution network, and on retail activities.

7.5.4 Regulatory schemes for electricity storage

Last but not least, more research on adequate regulatory approaches for storage (and renewables) will be needed to truly allow the markets to deliver the value of these technologies for society. Storage operators will optimize the revenue coming from the markets for energy and ancillary services, and therefore, market rules that take careful consideration of the interaction between these markets will be needed. In addition, different mechanisms for reliability should be explored.

7.6 Final remarks

Integrating renewables and storage technologies to the power grid is a daunting task, and it is no minor undertaking to find solutions that are agreeable to advance climate mitigation. But economists and engineers have solved complex endeavors in the past; or at least they have proposed some ways to look at our human and technical systems, so that society as a whole can understand them, and improve them. In fact, there is a visionary engineer whose work underlines most of the regulatory advancements of modern power systems, who understood profoundly the economics and physical complexities of electricity grids, but, most importantly, I think, believed in societies' capacity for transformation, for integration, for capturing economic value by reorganizing the services that most profoundly impact our daily life [158]. Fred Schweppe, like us today, also spent time thinking about the future evolution of the power sector. So let me end, by taking us back to the future, closing with some of his words and vision. Although many more years might still need to pass for this to happen, I find powerful the way he understood the size of changes to come.[13]

Because more devices for customer generation and storage of energy will be in operation by the year 2000, the customer – residential, commercial, or industrial – will be considered a vital part of the electric power systems of the future. New types of central-station generation, storage, transmission, and distribution will be available, and there will be basic changes in the total energy picture as well. Control systems adapt to changing technology and public needs. Capital and fuel costs will continue to rise rapidly, which will justify the expenditure of more money to improve the economics of power systems operation. Other factors that will influence future changes include the following: New types of central-station generation, storage and transmission/distribution systems... More customer generation and/or energy storage, includ-

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[13] I owe inspiration for my final remarks to Ignacio Pérez-Arriaga for always making his students think about the future power system, and for mentioning Schweppe's work envisioning the 2000 power system, during the MIT Energy Conference 2015; and to Erik Dossier, a classmate, whom I met at the same conference, and who entitled his excellent summary of Scheweppe's *Spot pricing of electricity* book "Back to the Future".

ing solar heating, cogeneration, and eventually solar photovoltaics... Demand depends on weather. Introduction of solar, wind generation, .., will greatly increase weather dependence. Environmental considerations of air and thermal pollution will increase and add even more weather dependence. Very sophisticated systems for monitoring the weather and environment will be integrated into future control systems along with models for forecasting weather and environmental impacts... Computing and communication are among the few things left in our society that are decreasing in cost. Furthermore, data-network communications and mini-and microcomputer technology are evolving at a rate that parallels the needs of electric power systems. Future power systems will exploit this technology extensively... The need exists, the technology is available, and the dividends from its use will justify the expense. Already an electric power system is the largest physically interconnected system man has invented.

Fred Scheweppe, July, 1978
Massachusetts Institute of Technology
Power Systems 2000, in Spectrum, IEEE [157]

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