Renewable Energy Optimal Dispatch Modelling incorporating Energy Storage Systems to Deliver Cost-effective Decarbonisation in an Emerging Economy such as Mexico

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“There is a pleasure in the pathless woods,

There is a rapture on the lonely shore,

There is society, where none intrudes,

By the deep Sea, and music in its roar;

I love not Man the less, but Nature more”

Lord Byron

Lay Summary

As countries worldwide set out an ambitious roadmap towards sustainability, the focus has increasingly turned towards the potential of renewable energy sources. This shift, however, is not without its complexities. Renewable sources like wind and solar are crucial but come with the challenge of variable power outputs, which can't always be directly managed, leading to concerns about their true efficiency in reducing GHG emissions in complex systems.

The core of this thesis is the innovative development of a novel optimal dispatch model for the Mexican electricity network. This model represents a significant breakthrough by integrating Battery Energy Storage Systems (BESS) to balance the intermittency of renewable energy sources. The model navigates through the challenges posed by the fluctuating nature of renewable power and aims to ensure that the energy generated is not only sustainable but also contributes effectively to the grid's stability and energy needs having a significant reduction in dispatch costs.

In Mexico, where the energy landscape is rapidly evolving, the incorporation of BESS offers a promising solution to the operational inefficiencies of conventional power plants. By employing a unique methodology of optimization, this thesis provides robust estimates of carbon savings and energy efficiency, demonstrating that renewables, supported by BESS, can indeed achieve a significant reduction in GHG emissions.

A thorough examination of existing literature creates the foundation of this thesis, identifying where previous estimates of carbon footprints and in the dispatch of electricity in complex networks for emerging countries have not been accounted for. The detailed life cycle analysis of renewable energy technologies, tailored to Mexico's context, certifies the importance of assessing full life cycle impacts rather than focusing on operational emissions only.

Furthermore, this work critically examines the real-world data from Mexico's National Grid to present an accurate picture of the emissions displacement of variable renewable power. It shows that when coupled with BESS, these systems are capable of meeting the demand and potentially optimizing the cost of dispatch, validating the effectiveness of Mexico's renewable energy strategy.

This thesis not only contributes to academic knowledge but could also serve as a practical guide for policymakers, industry professionals, and the public who are impacted by renewable energy developments. It aims to enhance the reliability and comparability of future estimates, helping developers to project the environmental benefits of their installations more accurately.

In essence, this research encapsulates a crucial step towards a sustainable energy future for Mexico, proving that the strategic integration of BESS within the electricity network can fulfill the dual objectives of environmental responsibility, and energy security through cost of dispatch.

Abstract

This thesis addresses the challenge of integrating variable renewable energy sources into the Mexican electricity network, focusing on the strategic use of energy storage systems to optimize dispatch cost and reduce carbon emissions. It demonstrates through an optimal dispatch model that strategic placement of these storage solutions can reduce electricity dispatch costs by 2% and lower carbon emissions by approximately 5%. This research develops and applies a model that optimizes the dispatch of electricity, incorporating energy storage technologies at key nodes within Mexico's electricity grid. The model's outcomes suggest that with the appropriate policy and infrastructure adjustments, energy storage can play a key role in enhancing the efficiency and sustainability of the national electricity system.

Furthermore, the thesis employs Life Cycle Assessment (LCA) as a tool to evaluate the carbon intensity of new energy storage technologies, providing a complete understanding of their environmental impacts from production to disposal. This analysis is important for identifying the most sustainable energy storage solutions, specifically analyzing a heat storage device, to apply the learning on how efficient operation of storage devices (heat) can lead to optimal integration of BESS (electrical).

The findings from this research are used to advocate for targeted policy changes in Mexico, aimed at facilitating the development and integration of new energy storage technologies. By highlighting the benefits of cost reduction, decreased carbon emissions and energy security, the thesis clarifies the importance of policy support in overcoming the technical and economic barriers to deploying energy storage systems. The recommendations offered are intended to guide policymakers, industry stakeholders, and researchers in fostering an energy landscape that is both economically viable and environmentally responsible, marking a significant step towards achieving Mexico's sustainability goals.

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This PhD thesis is dedicated to my family. I could not have dreamed of conducting research at one of the most prestigious universities in the world without my parents' immense sacrifices and diligent work. To my brother, who has been a pillar of support during my endeavors abroad. To my late grandmother, who often asked me, “Mijito, why do you travel so far? Don’t go, or else, one day you’ll come back, and I might not be here.” To her, I say, “For this, my dear grandma.” And to everyone who shared encouraging words with me: thank you. And to God.

In 2016, upon matriculating at The University of Edinburgh, I pledged to become the best possible version of myself. While I may not have achieved that yet, and perhaps never will, I have learned that I possess the strength to keep trying.

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Abbreviations

AC (Alternating Current)

ASOLMEX (Asociación Solar Mexicana)

BESS (Battery Energy Storage System)

BMU (Battery Management Unit)

CEL (Clean Energy Certificate)

CCGT (Combined Cycle Gas Turbine)

CEN (Central)

CENACE (Centro Nacional de Control de Energía)

CFE (Comisión Federal de Electricidad)

CO_2 (Carbon Dioxide)

DC (Direct Current)

DG (Distributed Generation)

ESS (Energy Storage Systems)

GHG (Greenhouse Gas)

LCA (Life Cycle Assessment)

LFP (Lithium Iron Phosphate)

MEN (Mexican Electricity Network)

NES (Noreste)

NOR (Noroeste)

NTE (Norte)

OCC (Occidental)

ORI (Oriental)

PCM (Phase Change Material)

PCS (Power Conversion System)

SENER (Secretaría de Energía)

SIBC (Sistema Baja California)

SIBCS (Sistema Baja California Sur)

SIMUL (Sistema Muelege)

SOC (State of Charge)

SOH (State of Health)

Table of Contents

Figures and Tables

Chapter 1

Introduction

1. Introduction

The current energy grid in Mexico faces significant challenges due to the variability and intermittency of renewable energy sources like wind and solar power. These challenges threaten grid stability and increase the dependency on fossil fuels during peak demand periods. This thesis addresses this critical issue by proposing the integration of Battery Energy Storage Systems (BESS) within an optimal dispatch model tailored for Mexico's unique energy landscape. The purpose of this research is to demonstrate how such integration can reduce both the operational costs and carbon emissions of the grid.

How can an optimal dispatch model integrating Battery Energy Storage Systems be developed for the Mexican electricity network to minimize carbon emissions and dispatch costs under realistic operational constraints?

1.1 Thesis Purpose

The landscape of power generation in Mexico stands on the cusp of a transformation, driven by the imperative to reduce carbon emissions and optimize costs within its electricity supply. The pursuit of a sustainable energy future has catalyzed the development of an optimal dispatch model that integrates Battery Energy Storage Systems into the national grid, a model designed to account for the multifaceted demands of modern energy networks. This thesis presents the culmination of research into the efficiency of such a model, exploring its potential to mitigate climate change impacts and reshape Mexico's electricity landscape. This transformation is shaped by a mix of high renewable potential, traditional fossil-based infrastructure, and an evolving but uncertain regulatory framework. In Mexico, the challenge is compounded by regional disparities in renewable resource availability, ageing grid infrastructure, and a regulatory landscape still in flux, necessitating context-specific models rather than applying generic international solutions.

The creation of this model is aligned with the global push towards decarbonization, where Mexico, in conjunction with many other countries, seeks to diminish its greenhouse gas (GHG) emissions in response to international climate accords. With the nation's targets echoing the ambitious goals set by the UK and other leading countries in renewable energy, there is a growing need to explore how Mexico can evolve its grid to accommodate a significant influx of renewable sources without compromising grid stability and economic viability.

The integration of BESS is a new concept in emerging economies' networks. While other storage technologies like pumped hydro or thermal storage are mature and used in specific contexts, BESS is more scalable, modular, and responsive (Holweger et al., 2021), making it particularly suitable for distributed and industrial applications, explored in Chapter 4. BESS offers the ability to store excess energy from intermittent renewable sources and dispatch it during times of peak demand or low generation, while maintaining grid balance and reducing reliance on fossil-fuelled Peaker plants. This thesis delves into how the optimal dispatch model, tailored for the Mexican energy profile and special characteristics, can harness BESS to address the challenges of carbon footprint reduction and dispatch cost optimization. In addition to the technological challenge, the model responds to Mexico's unique energy policy landscape, including its push for energy sovereignty and the limited effectiveness of carbon pricing or grid incentives. This dual context—technological feasibility and national policy alignment—defines the broader relevance of the research.

The model's development was completed by a thorough analysis of existing international examples, but it is uniquely tailored to Mexico's geographical and infrastructural aspects. With a high potential for solar and wind energy, the model had to consider the variability of these sources and the consequent impact on grid operations. It incorporates the latest advancements in BESS technology, modeling their integration into Mexico's grid at various scales, from distributed generation systems (behind the meter) for demand-side management, to nation-wide applications.

By offering a comprehensive analysis of the environmental and economic impacts of BESS within an optimal dispatch model for Mexico, this thesis stands as a significant contribution to this research area. It provides a foundation upon which policymakers, energy providers, and researchers can build to create an energy system that is both ecologically responsible and economically robust. The implications of this work are profound, setting the stage for a future in Mexico where renewable energy, supported by BESS, forms the backbone of the energy infrastructure.

This research emerges at the intersection of global decarbonization goals and Mexico's national priorities for energy reliability, sovereignty, and economic development. Mexico's ambitious climate targets coexist with a grid that remains heavily dependent on natural gas and centralized thermal generation, with limited deployment of advanced flexibility mechanisms like energy storage. The lack of effective carbon pricing and limited regulatory support for storage technologies have created a gap between policy ambition and system capabilities. This thesis addresses that gap by proposing a tailored, data-driven dispatch model that integrates BESS, offering a realistic pathway to decarbonize the grid while improving cost efficiency, operational resilience and sustainability. By grounding the analysis in Mexico's real grid topology and policy context, the research positions itself as both a technical and strategic contribution to the country's energy transition.

1.2 Research Objectives and Scope

The central aim of this research was to explore and quantify the impact of integrating Battery Energy Storage Systems (BESS) into the Mexican electricity network, achieved by the development of a novel optimal dispatch model that accounts for carbon emissions impact and dispatch cost. This study had several critical objectives:

Assessment of Optimal Dispatch Models: To critically examine the state-of-the-art optimal dispatch models that incorporate BESS, particularly within the Mexican context.

Methodology Evaluation and Creation of Novel Tool: To scrutinize the methodologies employed in the calculation of carbon footprints and optimal dispatch models within the sphere of the Mexican electricity network, identifying potential upgrades and developing a modern tool that serves to critically assess different case studies.

Life Cycle Impact Quantification: To conduct a life cycle assessment of comparable technologies to understand the impacts of BESS integration in Mexico.

Impact on Conventional Generation: To investigate how the incorporation of variable-output renewables alongside BESS influences the operational efficiency and resultant GHG emissions of conventional carbon intensive power plants within the Mexican energy matrix.

By setting forth these objectives, the research directly addresses several of the most pressing barriers to effective energy transition in Mexico. The assessment of dispatch models is essential because no publicly available model currently captures the operational constraints and emissions trade-offs unique to the Mexican grid. Evaluating methodologies and developing a novel tool is critical for supporting decision-makers with reliable, contextualized analytics. The life cycle assessment objective ensures that technologies promoted through dispatch modelling are environmentally friendly across their full lifespan, not just operationally. Finally, studying the impact on conventional generation fills a knowledge gap on how storage affects traditional thermal plants, which still dominate Mexico’s energy mix. Together, these objectives support a justifiable, multi-layered framework aligned with national decarbonization goals, energy sovereignty strategies, and the global shift toward flexible, resilient grids. The end goal was to offer a robust framework that could inform policy decisions and stimulate further academic research into the effective deployment of BESS for a sustainable and economically efficient energy future in Mexico.

1.3 Contribution to Knowledge

The core contribution of this thesis to knowledge is the development and validation of the first comprehensive and Open-source optimal dispatch model tailored to the Mexican electricity network, integrating Battery Energy Storage Systems (BESS) to analyze the complexities of carbon emission impacts and dispatch cost efficiency.

This model is a novel achievement, providing a powerful analytical tool that accounts for the unique characteristics of Mexico's energy infrastructure, renewable energy potential, and operational challenges. It is distinguished by its capability to inform about the operational dynamics of BESS within a grid system strongly interested in renewable energy sources, such as solar and wind power.

The thesis provides a novel insight into the complex interaction between variable renewable energy output, BESS performance, and grid stability in a context that is specific for Mexico. While this model is tailored to the Mexican electricity network, its modular structure would allow for adaptation to other emerging economies facing similar integration challenges with renewables and storage. The methodology and structure can be replicated using region-specific parameters such as grid topology, generation mix, and market rules. This model includes considerations of Mexico’s specific solar and wind resource availability, and the impact of these variables on energy storage and transmission. The optimal dispatch model, thus, serves not only as academic research, but could also act as a practical instrument for Mexico's energy sector stakeholders.

Furthermore, the research explains the previously unquantified effects of carbon emissions attributable to electricity dispatch within the Mexican context. The model's rigorous approach to quantifying these impacts sets a new standard for the evaluation of renewable energy infrastructure within the country.

Additionally, the thesis critically addresses the efficiency of Mexico’s conventional power plants in the presence of variable-output renewables. It quantifies the extent to which BESS can mitigate the potential increase in GHG emissions due to the intermittency of renewable sources, offering a strategic perspective on how Mexico can meet its ambitious carbon reduction targets.

By applying this model to actual historical data and real energy infrastructure from the Mexican National Grid, the thesis transcends theoretical projections, offering practical insights. The optimization analysis simultaneously minimizes total variable dispatch cost and carbon emissions, subject to technical constraints such as generator capacity, BESS operation, power flow limits, and nodal demand. The inclusion of BESS introduces temporal flexibility, allowing stored energy to be shifted across hours, which affects dispatch schedules and reduces reliance on peaking fossil plants in periods of peak demand. This includes providing reliable estimates of total system carbon emissions and detailed evaluations of the effect that the flexibility provided by BESS has upon total cost of dispatch.

This work has laid the foundation for future research endeavors in Mexico and has set a benchmark for the integration of BESS into the national grids, particularly in regions with high fossil fuel reliance or with high penetration of renewables.

1.4 Thesis Outline

This thesis represents a unique comprehensive approach into a better understanding of the domain of energy systems for Mexico, with its core contribution being the development of a novel optimal dispatch model. This model, meticulously outlined in Chapter 3, stands as the first comprehensive study specifically designed for the Mexican electricity network to integrate Battery Energy Storage Systems (BESS), addressing both the challenges of carbon emissions impact and dispatch cost optimization.

Chapter 2 introduces the foundational aspects of optimal dispatch modeling within the Mexican context, examining the current challenges and setting forth the need for innovative solutions provided by BESS.

Chapter 3 describes the detailed methodology to construct optimal dispatch model and delves deeper into the architecture of it, elaborating on the structure, parameters, and decision variables. These set of conditions were all constructed to account for most relevant particularities of the Mexican Electricity Network (MEN) in order to demonstrate through two comprehensive case studies, that the integration of BESS results in a lower total cost of dispatch and carbon emissions.

Chapter 4 advances the discussion by quantifying the economic effects that can be achieved by the incorporation of hybrid BESS PV generation systems into the distributed network, from the perspective of the end-user. Demonstrating the viability of the technology from an economic perspective.

Chapter 5 synthesises the knowledge gained from a detailed Life Cycle Assessment (LCA) study performed on a heat storage device that uses Phase Change Material (PCM) technology to propose a low carbon solution for heating applications. Although PCM systems are different from BESS in their function, the environmental assessment methods and decarbonisation insights from this study offer useful lessons for evaluating storage technologies in general. This chapter highlights the value of applying life cycle thinking to energy systems, which is also reflected in the recommendations regarding how BESS can be integrated into Mexico’s energy future in a sustainable way. Finally, *Chapter 6* concludes the thesis by bringing together the separate elements into a cohesive narrative. This chapter not only summarizes the research findings but also positions the optimal dispatch model as a unique contribution to Mexico's renewable energy initiatives. It articulates the model’s significance as a critical tool for stakeholders, including policymakers, grid operators, and renewable energy developers, ensuring that Mexico's transition towards a sustainable energy future is grounded in robust and innovative research.

Chapter 2

Background of Renewable Energy and BESS in Mexico

2. Background of Renewable Energy and BESS in Mexico

This section introduces the strategic role of energy storage in supporting the transition to renewable energy in Mexico, before narrowing into the specific requirements and methodologies for optimal dispatch modelling explored in later chapters.

2.1 Role of Energy Storage and Dispatch Modelling in Mexico's Renewable Transition

Given the scope of integrating energy storage systems (ESS) into the Mexican electricity network, the importance of such an endeavor is underscored by the global shift towards renewable energy sources (RES) and the pressing need to enhance grid reliability and sustainability. This background analysis draws on a range of representative studies to highlight the critical role of ESS in achieving these goals, focusing on Mexico's unique challenges and opportunities.

Energy storage technologies have been identified as pivotal for stabilizing the grid against the variability and intermittency of renewable energy sources, such as wind and solar power. Recent research shows that integrated energy storage systems (IESS) significantly improve grid reliability, reduce operational costs, and support higher penetration of renewables through load shifting and curtailment reduction. These systems include lithium-ion batteries, pumped hydro and redox flow technologies. A comprehensive academic review highlights that storage is no longer a backup tool, but a central component for flexibility services such as frequency regulation and demand balancing (Areola, Adebiyi & Moloi, 2025). These findings strengthen the rationale for including Battery Energy Storage Systems (BESS) in power system models for countries like Mexico, where grid flexibility remains limited. The integration of renewable energy sources (RES) into power systems poses multiple operational and planning challenges. These include the variability and unpredictability of wind and solar generation, the limited flexibility of traditional grid infrastructure to manage bidirectional energy flows, and the increased need for system balancing and inertia replacement. Additionally, the absence of supportive regulatory frameworks and incentive mechanisms can slow down the deployment of enabling technologies such as energy storage, demand response, or smart grid systems. As Almihat & Munda (2025) highlight, addressing these challenges requires not only technical innovation but also adaptive policy and market structures. Similarly, Eyenubo, Obuseh & Okpare (2025) underline that regulatory uncertainty, financing constraints, and lack of grid modernization are among the most persistent barriers to RES integration, particularly in developing and emerging economies.

Figure 1 - CFE Hydroelectric resources in Mexico as an example of installed capacity. (García, J., 2023)

The technical feasibility and economic viability of deploying various types of ESS across Mexico have been a subject of extensive research. For instance, *van Meervijk, A.J.H.., et al., (2016*) explores the potential of pumped hydro storage systems in supporting renewable energy integration. This could be transferred to Mexico, since they argue that such systems offer a viable solution to the intermittency of renewables, thereby enabling a more stable and reliable electricity supply. This aligns with the broader discourse on the need for flexible and efficient energy storage solutions to leverage Mexico's significant renewable energy potential.

Mexico has considerable technical potential for renewable energy generation, particularly from solar and wind resources. According to the National Renewable Energy Laboratory (NREL, 2021), the country's solar photovoltaic potential is estimated at approximately 24,918 GW, with wind energy potential reaching 3,669 GW. These figures far exceed current installed capacity and highlight the scale of untapped resources available for clean energy deployment. Importantly, the resource availability is geographically diverse—northern and central states such as Sonora, Chihuahua, and Zacatecas exhibit high solar irradiation levels exceeding 5.5 kWh/m²/day, while regions such as Oaxaca and Tamaulipas offer favorable wind conditions. This distribution provides an opportunity for the decentralization of electricity generation and supports the integration of distributed energy resources across various regions of the country.

Unlocking this potential aligns with Mexico's broader decarbonization strategy and long-term energy planning goals. As discussed by NREL (2021), increasing the share of renewable energy in the electricity mix—particularly when supported by flexible technologies such as Battery Energy Storage Systems—can contribute to reducing peak demand pressures, minimizing transmission losses, and improving overall grid efficiency. In addition, targeted policy measures, investment in enabling infrastructure, and regulatory adjustments such as improved interconnection standards and updated compensation mechanisms for distributed generation are necessary to accelerate deployment. Furthermore, the integration of ESS into the Mexican electricity network is not only a technical challenge but also an economic and environmental consideration, conduct a comparative life cycle cost analysis of various electrical energy storage systems, providing insights into the economic considerations that must be factored into the deployment of ESS. Their work highlights the importance of evaluating the cost-effectiveness of energy storage technologies to ensure their sustainable integration into the grid.

The environmental performance of energy storage systems is increasingly evaluated through life cycle assessments, which provide a method to quantify trade-offs between operational efficiency, cost, and environmental impact. A recent study by Yudhistira et al. (2022) compares lithium-ion and lead-acid batteries for stationary storage, emphasizing how material choices and end-of-life management significantly affect total emissions and resource use. Their findings reinforce the need for policy and investment strategies that take into account not just upfront costs but full environmental impact over a system's lifecycle.

In the context of Mexico, Santoyo-Castelazo et al. (2011) conducted one of the few full LCAs of electricity generation for the country, identifying significant benefits from integrating renewable energy with storage. These insights remain relevant for informing sustainable grid planning. Meanwhile, the Energy Regulatory Commission (CRE) published administrative provisions in 2025 aimed at regulating the integration of ESS into the national grid, and recent federal mandates now require that new renewable energy plants include battery storage equivalent to 30% of capacity, with 574 MW targeted by 2028.

These steps are shaping the regulatory environment that will influence how ESS scales in developing markets like Mexico (CRE, 2024).

2.1.1 Challenges of the Mexican Electricity Network

Mexico’s electricity system is a hybrid structure combining centralized fossil-fuel-based generation with a growing share of renewable energy. As of 2022, approximately 65% of electricity was generated from fossil fuels — primarily natural gas — while renewable sources such as wind, solar, hydro, and geothermal accounted for less than one-third of the national energy mix (IEA, 2023). The Comisión Federal de Electricidad (CFE) remains the dominant state-owned utility, responsible for generation, transmission, and distribution, though private participation has increased since the 2013 energy reform.

The country is divided into several control regions managed by the national system operator, CENACE (Centro Nacional de Control de Energía), which oversees grid reliability, dispatch, and market operations. Mexico’s electricity market includes both a long-term auction system and spot market pricing mechanisms. However, in recent years, policy reversals and regulatory uncertainty have reduced investor confidence and delayed renewable project deployment. The shift back toward state-centric control has raised concerns among private developers and international observers regarding competition and transparency (SENER, 2022).

Despite policy uncertainty, Mexico has substantial technical potential for decarbonisation. According to the National Renewable Energy Laboratory (NREL), solar photovoltaic potential alone exceeds 24,000 GW, with wind potential reaching over 3,600 GW. These resources, if effectively integrated, could allow the country to meet both its domestic energy needs and its climate commitments under the Paris Agreement. The government’s long-term planning framework, outlined in the *Programa de Desarrollo del Sistema Eléctrico Nacional*, includes scenarios that emphasize increased deployment of renewable energy supported by storage systems, demand-side management, and grid modernization (SENER, 2022).

In Mexico, the integration of renewable energy is complicated not only by variability, but by the structural mismatch between generation and demand centers. Most wind and solar resources are located in the southeast (Oaxaca) and north (Sonora, Chihuahua), while the largest demand hubs are in the center and west. As shown in the optimal dispatch modelling (see Section 3.2), this spatial dispersion results in transmission bottlenecks, congestion risks, and curtailment events during high-resource hours. Grid expansion is therefore critical but faces both regulatory and financial hurdles, like shown in Figure 2.

Figure 2 - CFE worker maintaining old and inefficient electricity infrastructure in Mexico. (El Universal, R, 2023)

On the economic and financial front, renewable energy integration faces significant hurdles due to high upfront costs and limited financing mechanisms. For Mexico, investment risks are amplified by policy instability and limitations in the local financial system. Moreover, BESS can help avoid capital expenditure on new grid infrastructure, as discussed by Ertugrul (2016) and further discussed in Section 3.4.2 of this thesis. The policy and regulatory landscape in Mexico also presents challenges to renewable energy integration. In the past, studies like *Darghouth, N.R., et al., (2013*) have illustrated how specific policy mechanisms, such as net metering, significantly influence the economic viability of distributed renewable energy systems, like discussed in *Chapter 4*. However, Mexico's regulatory frameworks have historically lacked the clarity and stability required to support renewable energy adoption, creating uncertainty for investors and hindering deployment. Comprehensive policy reforms are essential to provide clear incentives and support for renewable energy adoption within the country.

As described in the 2014 Energy Reform and the Electricity Industry Law, the market was partially opened to private actors. However, changes after 2018 re-centralized planning and procurement under CFE, creating investment uncertainty, but currently under development to create more clarity for the private sector (CRE, 2025). Previous uncertainty reflected in stalled interconnection approvals and shifts in regulatory mechanisms such as net billing, which impact the viability of both utility and distributed energy projects.

Social and cultural factors continue to play a critical role in the acceptance and deployment of renewable energy technologies in Mexico. Velasco-Herrejón and Bauwens (2020) apply a capabilities-based framework to examine how indigenous communities in the Isthmus of Tehuantepec perceive energy justice in wind energy projects. Their findings highlight that distributive, recognitional, and procedural justice are essential components for gaining local community support. Similarly, a recent study on the public acceptability of solar energy in rural Mexico identifies key barriers including a lack of accessible information and widespread institutional mistrust, calling for proactive public engagement strategies to improve project legitimacy (INEGI, 2023).

On the technical front, transmission infrastructure limitations remain a key barrier to integrating large-scale renewable energy. According to the National Renewable Energy Laboratory (NREL), conventional transmission planning methods in Mexico often fail to prioritise zones with high renewable energy potential, leading to system congestion and project delays (NREL, 2021). The Energy Ministry and National Council for Science and Technology (*Figure 3*) have invested substantially to promote technical development in the electricity sector in Mexico.

Figure 3 - CONACYT offices in Mexico City. This research was funded by a joint venture from CONACYT & SENER with the clear objective of promoting qualified individuals to support the energy transition in Mexico.

2.1.2 Benchmark Solutions for a Strategic Approach in Solving Challenges

Addressing the multifaceted challenges of renewable energy integration in Mexico requires a coordinated approach that includes technological innovation, financial mechanisms, policy reforms, and societal engagement. Investments in infrastructure, capacity building, and human resources are vital. By navigating these challenges, Mexico can enhance its energy security, reduce carbon emissions, and advance toward sustainable development goals, leveraging insights from the referenced literature to explore viable solutions and strategies.

The study by (*Atia, R., et al.., 2016*) presents a critical contribution to the field of renewable energy systems, specifically addressing the critical integration of battery energy storage systems within residential microgrids. The paper discusses an exploration of optimization strategies for the sizing and deployment of renewable energy resources coupled with BESS, aiming to enhance the reliability, sustainability, and economic viability of microgrid operations.

The research presents its analysis on a optimization framework that considers both technical and economic variables. This includes the variability of renewable energy generation, the energy demand profiles of residential users, the capacity and discharge characteristics of BESS, and the overarching goal of minimizing operational costs while maximizing energy reliability and sustainability. The methodological approach employs a mixed-integer linear programming (MILP) model, enabling the intricate balancing of generation and storage to meet the specific demands of residential microgrids.

One of the most interesting findings of this work is the demonstration of BESS's role in mitigating the intermittency of renewable energy sources, such as solar photovoltaics and wind turbines. By strategically sizing and deploying BESS, the microgrid can achieve significant improvements in energy reliability, particularly in scenarios of peak demand or low renewable generation. Moreover, the analysis reveals that optimal sizing of BESS not only contributes to grid stability but also to the economic efficiency of the microgrid system by reducing the reliance on grid electricity purchases during peak tariff periods.

The discussion extends to the environmental implications of integrating BESS into microgrids, highlighting the potential reduction in carbon footprint associated with decreased dependence on conventional grid power. This aspect reflects the paper's contribution to the broader objectives of energy transition and sustainability.

While the study focuses on residential microgrids, its findings present relevant implications for Mexico’s national electricity system. As distributed energy systems equipped with BESS become more prevalent, their potential to support the wider grid increases—particularly when interconnected with transmission and distribution infrastructure. Properly integrated, BESS can contribute ancillary services such as frequency regulation, voltage control, peak shaving, and spinning reserve support. These capabilities enhance grid stability, reduce stress during demand peaks, and improve the integration of variable renewable generation at both local and regional levels. Ryan et al. (2021) presents a detailed evaluation of how BESS-equipped microgrids can deliver these grid services, even under constrained operational conditions, reinforcing their value as decentralized but system-relevant assets.

(*Atia, R., et al., 2016*) work clarifies several pathways for future research, particularly in enhancing the model's predictive accuracy and applicability to diverse microgrid configurations. The paper makes a case for the incorporation of more dynamic models that can adapt to real-time data on weather conditions, user behavior, and energy market fluctuations.

From a practical standpoint, the study offers valuable insights for microgrid designers, policymakers, and energy system operators. It provides a robust framework for assessing the viability of BESS integration in residential settings, simplifying the way for more informed decision-making in microgrid development projects.

The works of Atia et al. (2016), Parra et al. (2017), and Khamharnphol et al. (2023) provide indispensable insights into the modelling and optimization of these systems within electrical grids, each highlighting different dimensions of BESS integration. These studies collectively demonstrate the importance of deploying battery energy storage systems (BESS) alongside renewable energy sources to mitigate the intermittency and variability of renewable energy production, which is particularly crucial for developing countries like Mexico that are consciously trying to increase their renewable energy mix. Atia et al. demonstrate the value of demand-side management in residential microgrids; Parra et al. quantify the environmental and economic benefits of BESS integration; and Khamharnphol et al. explore hybrid renewable system configurations under real-world conditions, showcasing cost minimization strategies through storage.

The detailed modelling approach presented by (*Atia, R., et al.., 2016*) through mixed-integer linear programming offers a methodical framework for sizing renewable energy and battery systems in electrical grids. This approach is particularly relevant for developing countries like Mexico, where integrating variable renewables into the national grid requires cost-effective planning tools to address infrastructure gaps and resource constraints. Mexico is an emerging economy where the demand growth has been especially complex to forecast, further demonstrating the criticality of robust modelling techniques.

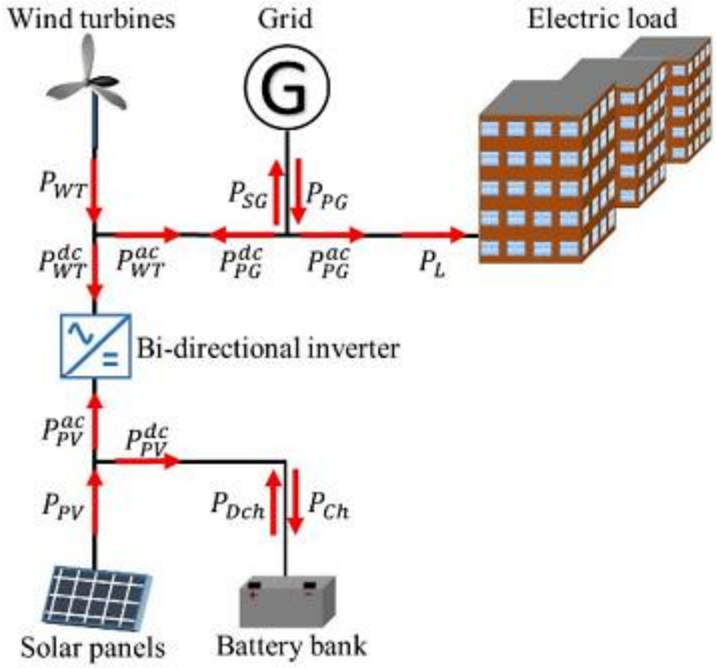


Figure 4 (Atia, R., et al.., 2016) example of a hybrid RE and BESS system.

Figure 4 illustrates a conceptual hybrid system combining solar, wind, and BESS, representative of configurations discussed by Parra et al. (2017), which broaden the discussion by reviewing energy storage technologies within community settings, highlighting the multifaceted challenges and perspectives. When connected to the national grid, hybrid systems like the one illustrated in *Figure 4* can also provide ancillary services such as frequency regulation or peak shaving, supporting grid stability beyond local use. This review emphasizes the need for interdisciplinary approaches to understand and overcome the barriers to energy storage integration, including challenges such as high upfront capital costs, grid interconnection barriers, regulatory uncertainty, and lack of flexible financing schemes. For Mexico, adopting such comprehensive views is crucial for developing effective policies and infrastructure that support the widespread deployment of renewable energy and storage technologies.

Khamharnphol et al. (2023) analyses a 10 MW solar/wind/diesel system integrated with BESS in Thailand, optimizing operations to reduce levelized cost of energy and increase renewable penetration under varying demand conditions. Their approach demonstrates how distributed storage can support both local reliability and broader system planning. Their findings are particularly relevant for Mexico's evolving energy landscape, which is increasingly embracing distributed generation and microgrid solutions to enhance energy access and grid stability in remote and rural areas.

Modelling plays a critical role in this context by providing the tools and frameworks necessary to simulate various scenarios, assess the impacts of different integration strategies. Advanced modelling techniques allow for the evaluation of system performance under a range of conditions, enabling the optimization of system design and operation for improved reliability, cost-effectiveness, and environmental performance.

For Mexico, leveraging these modelling insights cannot only guide the strategic placement of energy storage systems within the electricity network, but also facilitate the transition to a more sustainable and resilient energy infrastructure. By addressing the technical and economic barriers to deploying energy storage and renewable energy systems, Mexico can enhance its grid management capabilities, reduce carbon emissions, and move closer to achieving its sustainability and energy independence goals. In June 2023, shown in Figure 5, Mexico's president Andrés Manuel López Obrador announced the government's acquisition of approximately 8 GW of natural gas and combined-cycle generation assets from Iberdrola. This move was presented as a strategic effort to increase state control over dispatchable capacity and reduce dependence on private generation. It also reflects the urgent need to secure baseload power supply in the absence of widespread utility-scale battery energy storage systems, which remain underdeveloped in Mexico despite growing variable renewable penetration (Iberdrola, 2023).

Figure 5 Mexico's president AMLO (Andrés Manuel López Obrador) signing MOU (Memorandum of Understanding) with Iberdrola's Chairman, Ignacio Galán (Iberdrola, 2023).

The referenced studies highlight the global relevance of advanced modelling in optimizing energy systems and the specific implications for developing countries like Mexico. They make clear the necessity of integrating renewable energy and storage solutions, supported by robust modelling and optimization, to navigate the challenges and capitalize on the opportunities presented by the transition to sustainable energy systems. The novel optimal dispatch model incorporating large scale BESS for Mexico, provides local researchers and decision makers to further study the almost stochastic incorporation of renewable technologies into the generation mix.

To effectively plan and optimize the integration of renewable energy and storage solutions, open-source modelling tools like PyPSA (Python for Power System Analysis) can be instrumental. PyPSA is designed for simulating and optimizing modern power systems, including features such as conventional generators, variable renewable generation, and energy storage units. Its flexibility and transparency make it suitable for assessing various scenarios in energy system planning.

Models like PyPSA offer significant advantages for countries like Mexico, where transparency, adaptability, and cost-efficiency are crucial in energy planning. As an open-source tool, PyPSA allows stakeholders to customize assumptions, data inputs, and optimization scopes, which is particularly valuable in regions with evolving policy frameworks and incomplete datasets. Its modular structure supports integration of high-resolution demand profiles, renewable resource data, and multi-node grid configurations, making it suitable for evaluating scenarios involving large-scale BESS deployment and decentralized generation. However, implementing such models in the Mexican context also presents challenges, including the lack of centralized access to granular network and demand data, limited institutional modelling capacity, and the need for alignment with regulatory and market structures (Brown et al., 2018; Parzen et al., 2022). Adapting PyPSA for Mexico would require collaboration between academic institutions, policymakers, and system operators (e.g., CENACE) to ensure that model outputs are technically robust and policy relevant.

2.1.3 Existing Modelling Tools which Account for Environmental Impacts

In the pursuit of decarbonization, the incorporation of carbon emissions considerations into the optimal dispatch of electricity systems is vital. The studies by Feng et al. (2022), Fan et al. (2023), and Bian et al. (2024) are at the forefront of this effort, contributing robust methodologies that integrate economic efficiency with explicit carbon reduction objectives in energy system operations. Feng et al. (2022) advances the dialogue by integrating carbon emission flow theory into the economic dispatch of coupled electric-gas systems. This allows for a more holistic approach to energy dispatch that actively incentivizes low-carbon generation options.

Their work illustrates how coordinated low-carbon operation across energy vectors can enhance efficiency while respecting emissions limits. Fan et al. (2023) further build on this by incorporating demand-side management and carbon trading mechanisms into the operation of integrated energy systems. This dual integration allows for a more realistic and policy-relevant modeling of decarbonized operations, particularly in environments where carbon markets are emerging or fragmented. Bian et al. (2024) presents a dispatch method for active distribution networks that applies carbon emission flow theory to distribution-level planning. This is a novel approach that supports localized optimization and emissions accountability.

What is particularly valuable about these studies is their multidisciplinary integration of carbon reduction strategies into dispatch optimization — not just as constraints but as central elements of the modeling architecture. They move beyond simplistic carbon caps or cost adders, instead creating models that can dynamically respond to carbon repercussions, policy signals, and operational complexity across time and space. This provides a deeper systems-level view of low-carbon energy planning, one that accounts for interactions between distributed resources, price signals, and operational feasibility.

To expand upon their work, future research could adapt these approaches to Mexico's emerging energy context. Most existing applications are situated in countries with established carbon trading frameworks or integrated market structures. In contrast, Mexico's environment is still evolving, with limited energy storage, nascent carbon pricing, and significant regional diversity in fuel mix. A logical next step would be to explore how these methodologies could be tailored to simulate the effect of shadow carbon pricing or pilot trading schemes on dispatch outcomes under high-renewable penetration scenarios. Furthermore, incorporating location-specific emissions intensities, reflective of CFE's regional generation profiles, could allow for more granular emissions-aware dispatch decisions. These extensions would provide more relevant guidance to the system operator as Mexico seeks to align its energy expansion plans with decarbonization goals.

In the context of countries like Mexico, which are reforming their energy systems to meet both domestic demand and global environmental commitments, these research insights are particularly adequate. They offer a roadmap for incorporating sophisticated energy system models that not only enhance economic competitiveness but also fulfill international and local climate obligations. The dynamic interaction between renewable energy technologies, carbon products, demand response, and energy storage delineated by these studies forms the basis of a robust strategy for efficient decarbonization in the energy sector.

2.1.4 Energy Modelling Trends towards Hybrid and Comprehensive Tools

The future of energy system optimization lies in tools capable of accounting for uncertainty, flexibility, and multiple objectives, especially as renewable penetration increases, and market dynamics evolve. This trend is reflected in growing research that moves beyond traditional least-cost deterministic dispatch to embrace multi-objective models incorporating environmental, economic, and operational priorities. For countries like Mexico, where grid modernization coincides with decarbonization goals and emerging storage solutions, these trends point to the need for modeling frameworks that are both comprehensive and context sensitive. *Chapter 7* of this thesis builds on these insights to propose a Mexico-adapted model integrating energy storage and environmental constraints.

Recent studies by Feng et al. (2022), Fan et al. (2023), and Bian et al. (2024) exemplify this shift. These models adopt hybrid optimization structures that combine classical dispatch logic with carbon emission flow theory, dynamic carbon pricing mechanisms, and demand-side flexibility. Unlike traditional approaches that optimize for cost under fixed system configurations, these models simulate the behavior of distributed energy resources, account for variability in carbon intensity, and incorporate feedback loops from emissions targets or policy instruments like carbon trading. This internalization of environmental costs within the optimization framework marks a conceptual departure from cost-minimization-only paradigms.

Traditional dispatch models, such as those developed by Cai et al. (2009), typically assume a static cost-optimization objective under deterministic supply-demand conditions. These models are computationally efficient and widely used in energy planning, but they often neglect the operational and temporal impacts of renewable variability and carbon emissions. For example, they do not model changes in dispatch because of fluctuating marginal emissions or policy-driven constraints, which can lead to suboptimal outcomes under high-renewables scenarios.

In contrast, hybrid and modern approaches incorporate stochastic treatment of renewable supply, explicitly simulate carbon pricing signals, and model emissions evolution over time. Bian et al. (2024) proposes a dispatch method for active distribution networks that includes regional carbon emission flow tracking, while Fan et al. (2023) integrate demand-side response and carbon trading mechanisms. These models offer a more granular and policy-relevant understanding of energy system behavior under decarbonization pathways.

This evolution in modeling approaches is particularly relevant for developing countries like Mexico, where both technical and institutional constraints shape the feasibility of different policy instruments. However, many of these advanced models have been developed in the context of mature carbon markets or centralized grid control. There remains a gap in the literature on how to adapt them to fragmented regulatory settings or developing economies with limited storage deployment. This research addresses that gap by proposing a dispatch optimization framework that integrates utility-scale battery energy storage and low-carbon constraints tailored to Mexico’s regulatory, technological, and demand-side context.

Figure 6 First inner-city (Mexico City) 18MW PV project with intentions to demonstrate Demand-side management by incorporating BESS and EV chargers to a flexible demand system (Rojas, R. 2024)

Furthermore, by utilizing the principles highlighted in these studies, Mexico can effectively plan and execute energy dispatch strategies that conform to international climate commitments while also catering to national economic and social objectives. *Figure 6* demonstrates current efforts from Mexico City's government to achieve low-cost renewable energy in low resource areas. The integration of carbon emissions modelling ensures that every megawatt-hour of electricity generated or consumed is accounted for in terms of its carbon footprint, leading to more informed and strategic decisions in energy production and consumption.

An optimal dispatch model that explicitly incorporates carbon emissions and BESS significantly advances the energy sector's approach to sustainability and climate change mitigation. By integrating emissions considerations directly into the operational decision-making process, such models ensure that electricity generation aligns with broader environmental objectives. The unique contribution of this methodology lies in its ability to balance economic efficiency with environmental congruence, offering a path toward achieving decarbonization targets without compromising the reliability of the energy supply.

In Mexico, existing models for electricity dispatch primarily focus on optimizing for cost and reliability, often without directly accounting for carbon emissions and/or storage systems (*Fuentes, R., 2012*). Integrating a hybrid model that incorporates carbon emissions into the dispatch process represents a novel contribution to knowledge. It bridges the gap between traditional economic optimization and the urgent need for environmental sustainability in emerging economies.

2.2 Life Cycle Assessment as a Complementary Modelling Tool

Life Cycle Assessment (LCA) is a robust and systematic analytical methodology used to assess the environmental impacts of a product, process, or service throughout its entire life cycle, from raw material extraction (cradle) to end-of-life disposal (grave). This comprehensive approach considers every stage, including raw material extraction, material processing, manufacturing, distribution, use, and disposal or recycling.

The integration of LCA within the optimal dispatch modelling tools enhances the sustainability aspect of energy production and distribution (*Reap, J. et al., 2008)*. It allows for a more comprehensive understanding of the environmental impacts associated with different energy sources and technologies, going beyond the operational emissions to include the full spectrum of environmental burdens. By considering the entire life cycle, energy planners and decision-makers can identify areas where improvements can be made to minimize negative environmental impacts (*Masanet, E. et al., 2013*).

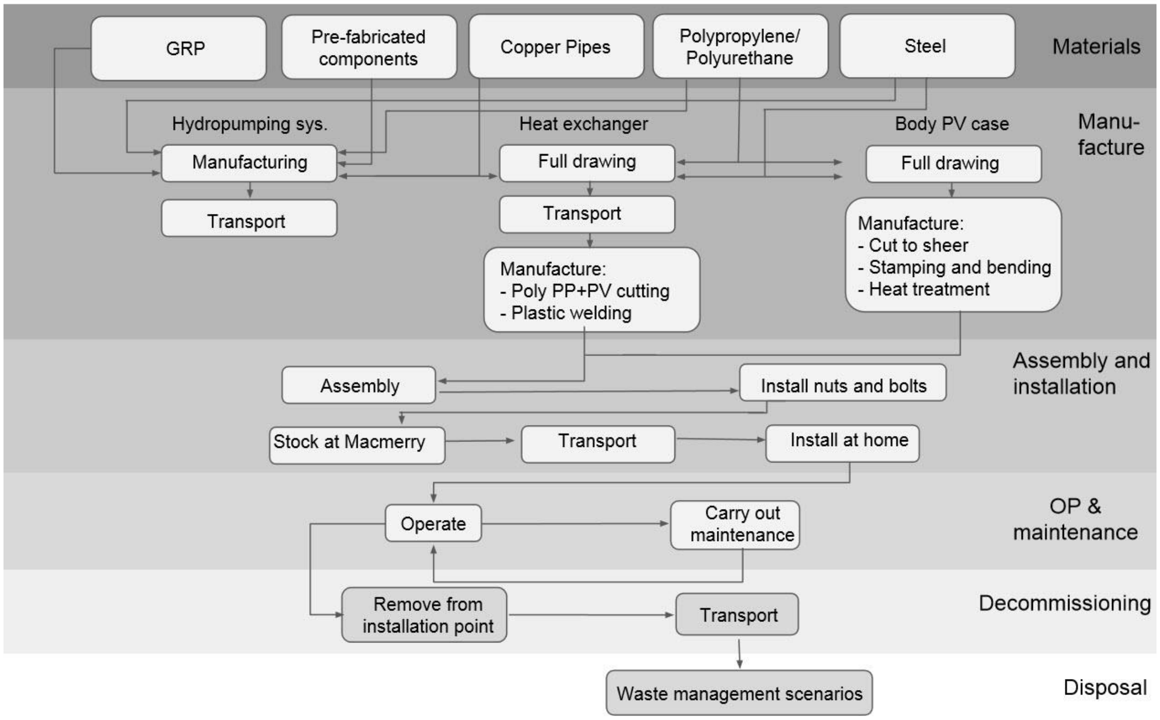


Figure 7 Life Cycle systematic diagram of a Heat Storage device. (Own elaboration)

Figure 7 illustrates a simplified life cycle assessment (LCA) framework for a heat storage device, detailing each stage from raw material extraction and manufacturing to operation, maintenance, and disposal. This visualization emphasizes the importance of considering not just operational emissions, but also upstream and downstream environmental impacts such as material processing, transport, and end-of-life handling. Incorporating this full system view into energy modelling enables planners to identify where emissions or resource use may be concentrated, and which life stages present the greatest opportunities for improvement or trade-off analysis.

One of the significant benefits of incorporating LCA into energy modelling tools is the ability to compare the environmental footprints of various energy systems on a consistent basis. For instance, while the operational emissions from renewable energy sources such as wind or solar might be negligible, the LCA approach reveals the environmental costs associated with the manufacturing, installation, and decommissioning of these systems (*Reap, J. et al., 2008*).

Furthermore, LCA provides a quantitative basis for the evaluation of trade-offs between different environmental impact categories, such as global warming potential, acidification, eutrophication, and ozone depletion. This is especially important in the context of optimal dispatch, where the trade-off between reducing carbon emissions and other environmental impacts must be carefully balanced.

LCA can help in policy-making and strategic planning for long-term energy scenarios. By analyzing the full environmental impacts of different energy sources, policies can be crafted to support those technologies with the most favorable environmental profiles over their entire life cycle. This approach supports the development of a more sustainable and environmentally friendly energy landscape.

LCA also plays a critical role in the advancement of new technologies. By assessing the full life cycle environmental impacts, researchers and developers can identify hotspots of environmental burdens and focus their efforts on mitigating these impacts in the early stages of technology development. This can lead to innovations that are not only efficient in operation but also sustainable throughout their entire life cycle (Bergerson, J. et al., 2019) at a lower cost, due to the stage at which the early development still lies.

2.2.1 Context of Life Cycle Assessment for a BESS System

Conducting a Life Cycle Assessment of a proposed Battery Energy Storage System is crucial to understand its environmental impacts within the Mexican context. An LCA provides a comprehensive picture of the environmental impacts associated with all the stages of a product's life from cradle to grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling).

In Mexico, where the energy sector is undergoing significant transformation, the move toward integrating BESS to optimize grid operations has environmental implications beyond just operational (*Hendrickson, P. T., et al., 2015*) emissions (*Valdez, L, et al., 1997*). By implementing LCA, stakeholders can assess the impacts of manufacturing the batteries, including the extraction of lithium and other minerals, which is particularly relevant given the geographical and geological context of Mexico, known for its rich mining sectors.

Additionally, an LCA can reveal the potential environmental benefits of using BESS for grid services, such as frequency regulation and renewable energy smoothing, compared to traditional energy storage and regulation methods. This is significant in Mexico, as the country aims to reduce its carbon footprint and improve energy sustainability.

Considering the end-of-life phase, an LCA will help understand the implications of battery disposal or recycling, which is a growing concern given the expected increase in battery usage. In Mexico, this is particularly pertinent, as the country is still developing its recycling infrastructure for such advanced technologies.

LCA facilitates a better understanding of the environmental trade-offs and benefits throughout the lifecycle of the BESS (*Velázquez-Martínez, O. et al., 2019*), enabling a more informed and sustainable approach to integrating new technologies into the Mexican energy network.

Chapter 3

Optimal Dispatch Model for the Mexican Electricity Network with BESS Integration

3. Optimal Dispatch Model for the Mexican Electricity Network with BESS Integration

This section will explain the formulation of an optimal dispatch model for the Mexican Electricity Network and present two case studies relevant to the thesis.

3.1 Introduction to Developing Optimal Dispatch Modelling

An optimization modelling approach is designed to find the best possible solution to a problem from a set of available options, governed by predefined constraints and objectives. This approach is critical in power systems for operations like dispatch, where the aim is to determine the most cost-effective and efficient generation mix that can always meet the demand.

The structure of an optimization model typically involves:

- *Objective Function*: This is the heart of the model, which needs to be either maximized or minimized. In the context of dispatch, the objective function often represents the cost of generation, which the model strives to minimize.
- *Variables*: These are the elements that the model will solve for. In dispatch models, variables could include the amount of power generated by each unit, the state of charge of energy storage systems, and the flow of electricity through various network paths.
- *Constraints*: These are the restrictions within which the model must operate. For energy dispatch, constraints could include generation limits, storage capacity, transmission capacities, and demand requirements. They ensure the model's solutions are not only optimal but also feasible and realistic.

- *Parameters*: These are the constants used in the model, such as the efficiency of generation units, fuel costs, or emissions factors. They provide the necessary context for the model's calculations.
- *Algorithms*: These are the methods used to solve the optimization problem. Common algorithms in dispatch include linear programming for systems with linear relationships or mixed-integer programming when the model includes decisions that are discrete (e.g., on/off states of power plants).

By employing such an optimization modelling approach, decision-makers and grid operators, as an example from CENACE, can achieve operational efficiency, ensuring that energy is not only delivered in a cost-effective and environmentally friendly manner but also in alignment with the strategic goals of the energy sector.

3.1.2 Optimization Modelling and Solving Methodology

The optimization modelling approach uses JuMP, an algebraic modelling language embedded in Julia that enables the definition of optimization problems in a symbolic and human-readable form. JuMP allows for the concise formulation of objective functions, constraints, and decision variables, which are automatically compiled into sparse matrix structures compatible with standard solver interfaces. This abstraction bridges mathematical formulation with efficient numerical computation, facilitating the implementation of complex, large-scale dispatch models. This model employs the General Linear Programming Kit (GLPK) as its solver, which is normally used for solving large-scale linear programming, mixed integer programming, and other related problems.

For the optimal dispatch model proposed, temporal and spatial elements are discretized into time periods and network topology, respectively. The time periods are discretized into 24 hourly intervals, capturing the diurnal patterns of demand and generation across Mexico. This resolution offers a tractable model size while still representing key operational dynamics such as efficiencies and storage cycling. While suitable for long-term planning studies, finer resolutions (e.g., 15-minute intervals) may be necessary for existing systems with high renewable penetration or fast-response assets. The network topology is defined by buses and lines, representing the grid's nodes and connections. The formulation uses input parameters, such as generator capacities, variable costs, and carbon emissions, which are essential for modelling the economic and environmental aspects of power dispatch. The parameters' modularity ensures the model's flexibility and adaptability to different scenarios or changes in input data.

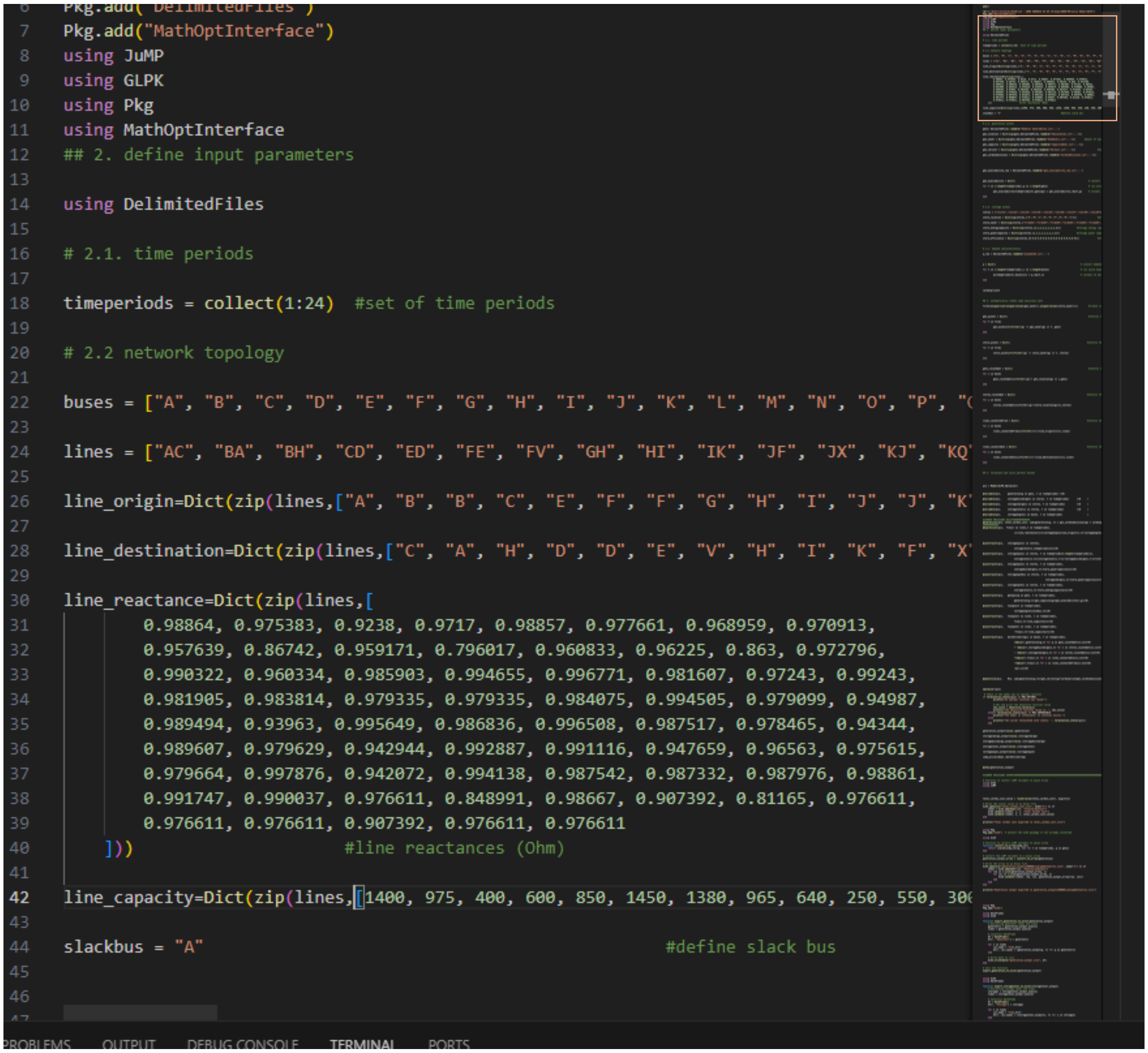
The objective function reflects the goal of minimizing the cost of generation, accounting for both variable costs and carbon emissions, making it pertinent to today's energy markets that are sensitive to both economic and environmental concerns. Using GLPK as a solver ensures computational efficiency for linear programming formulations by leveraging the revised simplex method and a well-maintained open-source ecosystem. Its capabilities are well-suited for academic-scale prototypes and planning models where transparency, replicability, and reliable convergence are critical, making it suitable for large-scale models like national electricity grids, where solution speed and stability are critical. These outputs can support system-level planning and energy policy design by quantifying dispatch costs, emissions, and operational constraints across different scenarios, consistent with current energy system optimisation frameworks (Ringkjøb et al., 2018; Brown et al., 2018).The solving methodology for finding an optimal real solution in the context of optimization modelling, such as in power system dispatch, involves translating the physical system and its operational constraints into a mathematical model (*Carpentier, J., 2015*) (*Mohanan, M. and Go, I, Y., 2020*). The solver employs mathematical programming techniques to navigate through the feasible solution space defined by the constraints in search of the optimal solution. For linear problems, solvers use algorithms like the simplex method or interior point methods (Carpentier, J., 2015). Interior point methods approach the solution from within the feasible region and are particularly effective for large, sparse problems, providing polynomial-time convergence in convex formulations., given that the problem has a convex nature for being a linear-programming optimization problem.

Incorporating renewable energy sources adds another layer of complexity due to their variability and uncertainty. Advanced models may use stochastic programming or scenario-based approaches to account for this, optimizing not just for cost but also for reliability and non-linear environmental impacts. For the purpose of this research, all formulation is non-stochastic.

The output of the solver provides not just the optimal dispatch strategy but also valuable insights into the operation of the system under the given constraints and objectives (*Momoh, A, J., 2000*). It can do so by producing time-resolved dispatch schedules, nodal marginal prices, line loading levels, and storage usage profiles, which reveal where constraints bind, where congestion occurs, and how various constraints or policy choices affect system-wide costs and emissions.

3.1.3 Julia Language for Open-Source methodologies

The Julia programming language is particularly well-suited for optimal dispatch models due to its high performance, similar to more static languages like C or Fortran, while maintaining the simplicity and flexibility of dynamic languages like Python or MATLAB (*Aruba, B., et al., 2014*). This combination is ideal for handling the complex, computationally intensive tasks involved in optimal dispatch, where solving large-scale optimization problems quickly and efficiently is crucial.



```julia
Pkg.add("DelimitedFiles")
Pkg.add("MathOptInterface")
using JuMP
using GLPK
using Pkg
using MathOptInterface
## 2. define input parameters

using DelimitedFiles

# 2.1. time periods

timeperiods = collect(1:24)  #set of time periods

# 2.2 network topology

buses = ["A", "B", "C", "D", "E", "F", "G", "H", "I", "J", "K", "L", "M", "N", "O", "P", "

lines = ["AC", "BA", "BH", "CD", "ED", "FE", "FV", "GH", "HI", "IK", "JF", "JX", "KJ", "KQ

line_origin=Dict(zip(lines,["A", "B", "B", "C", "E", "F", "F", "G", "H", "I", "J", "J", "K

line_destination=Dict(zip(lines,["C", "A", "H", "D", "D", "E", "V", "H", "I", "K", "F", "X

line_reactance=Dict(zip(lines,[
        0.98864, 0.975383, 0.9238, 0.9717, 0.98857, 0.977661, 0.968959, 0.970913,
        0.957639, 0.86742, 0.959171, 0.796017, 0.960833, 0.96225, 0.863, 0.972796,
        0.990322, 0.960334, 0.985903, 0.994655, 0.996771, 0.981607, 0.97243, 0.99243,
        0.981905, 0.983814, 0.979335, 0.979335, 0.984075, 0.994505, 0.979099, 0.94987,
        0.989494, 0.93963, 0.995649, 0.986836, 0.996508, 0.987517, 0.978465, 0.94344,
        0.989607, 0.979629, 0.942944, 0.992887, 0.991116, 0.947659, 0.96563, 0.975615,
        0.979664, 0.997876, 0.942072, 0.994138, 0.987542, 0.987332, 0.987976, 0.98861,
        0.991747, 0.990037, 0.976611, 0.848991, 0.98667, 0.907392, 0.81165, 0.976611,
        0.976611, 0.976611, 0.907392, 0.976611, 0.976611
    ]))                     #line reactances (Ohm)

line_capacity=Dict(zip(lines,[1400, 975, 400, 600, 850, 1450, 1380, 965, 640, 250, 550, 30

slackbus = "A"                                        #define slack bus
```

Figure 8 Example of the interface of the software used for modelling, Visual Studio Code running Julia Programming Language. This example shows how some of the key network topology features were coded. (Own elaboration)

Julia's design (*Figure 8*) specifically supports mathematical and numerical computing, offering a complete set of packages for optimization, such as JuMP for modelling and GLPK for solving linear problems (*Dunning, I., et al., 2017*). These tools are deeply integrated into Julia, enabling simple and efficient model development and execution.

Being open-source, Julia benefits from collaborative development and widespread scrutiny by a global community. This ensures continuous improvement, with features and bug fixes rapidly incorporated. The open-source nature also means that users can customize and extend the language and its libraries to suit specific project needs without licensing constraints or costs. This flexibility and accessibility promotes innovation and allows researchers and practitioners to apply the latest techniques in optimization without additional cost.

Furthermore, the Julia community has a strong focus on high-performance computing, making it a dynamic platform that stays relevant of computational efficiency and capability. This makes Julia programming language an ideal selection for developing and running optimal dispatch model presented in this thesis (*HP, Jl., et al., 2020*).

3.2 Optimal Dispatch Model Structure

In this section, the complexities of integrating energy storage systems within the Mexican electricity network are described, by using an optimal dispatch model to demonstrate the transformative potential of such integration. The Mexican energy sector stands at a pivotal crossroads, driven by increasing demand, the urgent need for decarbonization, and the integration of renewable energy sources. In response, this Doctorate thesis proposes a model to explore strategic placement and operation of BESS across the network. This approach not only seeks to minimize the overall cost and carbon footprint of electricity dispatch but also to enhance grid reliability and flexibility in the face of intermittent renewable outputs.

The Mexican electricity network, characterized by its diverse topology and varied energy resources, presents unique challenges—such as limited grid flexibility in remote regions and aging transmission infrastructure—and opportunities, including abundant solar potential and rising industrial energy demand that aligns with storage applications. The integration of these systems is crucial for addressing the intermittency of renewable energy sources, such as solar and wind power, which are increasingly significant contributors to the national energy mix. By optimizing the dispatch of electricity, incorporating various types of energy storage technologies at key network nodes, this model aims to provide a comprehensive and novel analysis of the economic and environmental benefits of BESS. Previous work has researched high-penetration scenarios for renewable energy, but with limited focus on system-level optimisation of BESS integration in emerging economies (*Castellanos, S. et al., 2018*).

To achieve this, the model considers a set of time periods within a typical day, representing the dynamic nature of electricity demand and generation. The network topology is defined by a set of buses and transmission lines, reflecting the complex interconnections within the Mexican electricity grid (*Fuentes, R., 2012*). Each line's physical characteristics, such as reactance and capacity, are accounted for to ensure accurate simulation of power flows. The model employs a DC Optimal Power Flow formulation, where active power flows are linearly related to voltage angle differences and line reactance. This approximation simplifies the AC power flow equations by assuming flat voltage magnitudes and small angle differences, enabling computationally efficient yet sufficiently accurate dispatch simulations for system-wide studies. Furthermore, the model incorporates a diverse array of generation assets, capturing the wide range of variable and fixed generation costs, as well as carbon emission factors, thereby enabling a detailed assessment of the generation mix's environmental impact.

Central to the model's functionality is the representation of energy storage assets, including their location, energy and power capacities, and efficiency. These parameters are critical for evaluating the role of storage in smoothing out energy supply, providing ancillary services, and enhancing grid stability. By simulating the charging and discharging activities of storage facilities, the model offers insights into the optimal operational strategies that maximize their economic and environmental benefits.

Demand characteristics across the network are also intricately modelled, drawing from historical data to reflect realistic consumption patterns. This allows for the examination of how energy storage can be leveraged to meet demand peaks, mitigate the need for expensive peaking power plants, and reduce reliance on carbon-intensive generation sources (*Sheinbaum, C., et al., 2010*).

The following sections detail the development and application of the optimal dispatch model. The model's mathematical formulation is then presented, employing a mix of linear programming techniques and real-world data to simulate the network's operation. Through this analysis, it is aimed to highlight the potential of energy storage to revolutionize the Mexican electricity sector.

3.2.1 Sets and Indices

In the optimal dispatch model for integrating energy storage systems into the Mexican electricity network, sets and indices serve as foundational elements that structure the complex interactions between various components of the electrical grid, as illustrated in *Figure 8*. These mathematical abstractions are critical in defining the scope, scale, and granularity of the model's analysis, allowing for a precise representation of the network's operational dynamics.

$$T = \{1,2,\dots,24\}: \quad Set\ of\ time\ periods \tag{3.1}$$

$$B = \{A, B, C, \dots, ZZ, AAA\} \quad Set\ of\ buses\ in\ the\ network \tag{3.2}$$

$$L = \{AC, BA, BH, \dots, YYZZ\} \quad Set\ of\ transmission\ lines \tag{3.3}$$

$$G: \quad Set\ of\ generation\ units \tag{3.4}$$

$$S = \{store1, store2, \dots, store9\} \quad Set\ of\ BESS\ facilities \tag{3.5}$$

The set of time periods captures the temporal dimension of the electricity network's operation, typically segmented into hourly intervals over a 24-hour cycle. This segmentation reflects the fluctuating nature of electricity demand and generation capacity throughout the day, accounting for peak and off-peak periods. It is crucial for modelling the variability in energy production from renewable sources and the corresponding need for storage and dispatch to ensure a constant and reliable power supply.

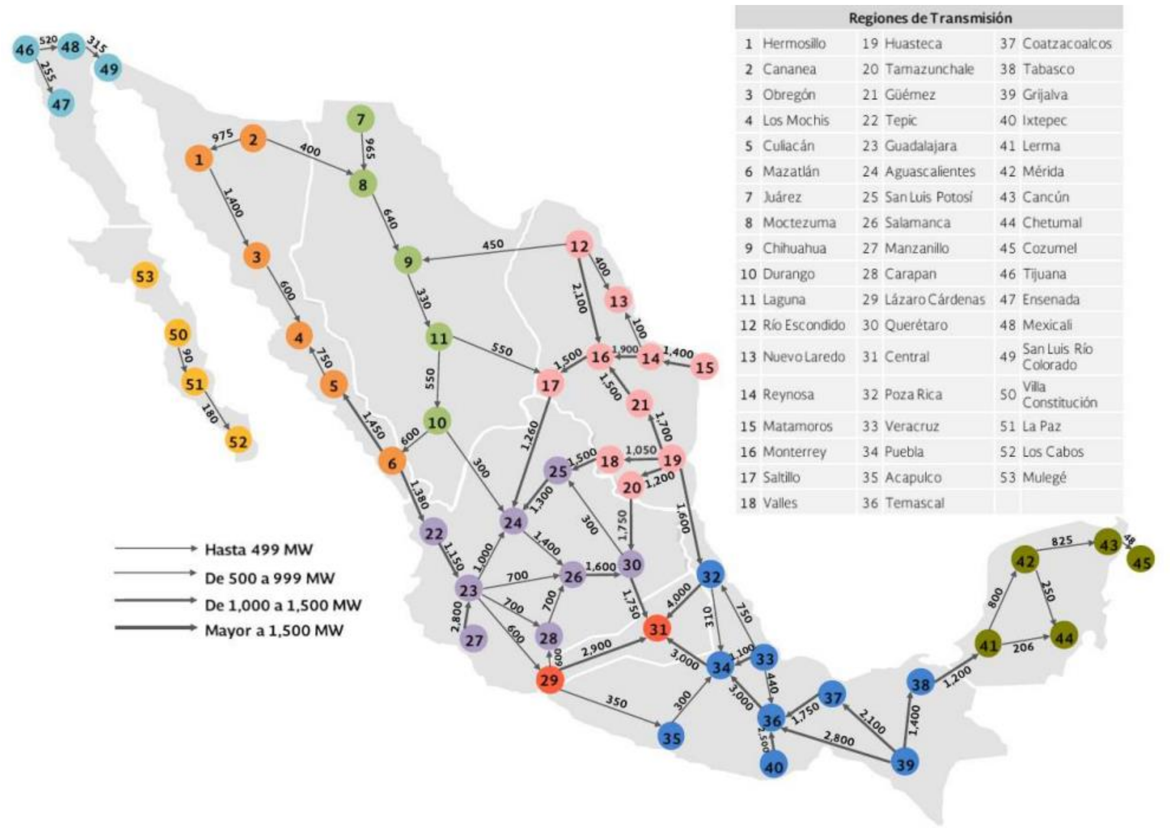
The set of buses represents the nodes within the electricity network, each acting as a point of connection for generation assets, storage facilities, and loads. Buses are pivotal in modelling the spatial aspects of the electricity grid, facilitating the analysis of power flows across different regions and the identification of strategic locations for deploying energy storage systems to optimize network efficiency and reliability.

Node	Code	Name	Control Region
1	A	Hermosillo	Noroeste
2	B	Cananea	Noroeste
3	C	Obregón	Noroeste
4	D	Los Mochis	Noroeste
5	E	Culiacán	Noroeste
6	F	Mazatlán	Noroeste
7	G	Juárez	Norte
8	H	Moctezuma	Norte
9	I	Chihuahua	Norte
10	J	Durango	Norte
11	K	Laguna	Norte
12	L	Río Escondido	Noreste
13	M	Nuevo Laredo	Noreste
14	N	Reynosa	Noreste
15	O	Matamoros	Noreste
16	P	Monterrey	Noreste
17	Q	Saltillo	Noreste
18	R	Valles	Noreste
19	S	Huasteca	Noreste
20	T	Tamazunchale	Noreste
21	U	Güémez	Noreste
22	V	Tepic	Occidental
23	W	Guadalajara	Occidental
24	X	Aguascalientes	Occidental
25	Y	SLP	Occidental
26	Z	Salamanca	Occidental
27	AA	Manzanillo	Occidental
28	BB	Carapan	Occidental
29	CC	Lázaro Cardenas	Central
30	DD	Querétaro	Occidental
31	EE	Central	Central
32	FF	Poza Rica	Oriental
33	GG	Veracruz	Oriental
34	HH	Puebla	Oriental
35	II	Acapulco	Oriental
36	JJ	Temascal	Oriental
37	KK	Coatzacoalcos	Oriental
38	LL	Tabasco	Oriental
39	MM	Grijalva	Oriental

40	NN	Ixtepec	Oriental
41	OO	Lerma	Peninsular
42	PP	Mérida	Peninsular
43	QQ	Cancún	Peninsular
44	RR	Chetumal	Peninsular
45	SS	Cozumel	Peninsular
46	TT	Tijuana	Baja California
47	UU	Ensenada	Baja California
48	VV	Mexicali	Baja California
49	WW	San Luis Rio Colorado	Baja California
50	XX	Villa Constitucion	Baja California Sur
51	YY	La Paz	Baja California Sur
52	ZZ	Los Cabos	Baja California Sur
53	AAA	Mulegé	Mulege

Table 1 List of the 53 Nodes (and individual codes assigned) in the system modelled for each of the MEN Control Regions. (Own elaboration)

This set defines the electrical pathways that connect different buses, allowing for the transmission of electricity across the network. Each line is characterized by specific physical properties, such as reactance and capacity, which influence the flow of power. Understanding these constraints is essential for accurately simulating grid operations and identifying potential congestion or opportunities for infrastructure improvements.



Regiones de Transmisión					
1	Hermosillo	19	Huasteca	37	Coatzacoalcos
2	Cananea	20	Tamazunchale	38	Tabasco
3	Obregón	21	Güémez	39	Grijalva
4	Los Mochis	22	Tepic	40	Ixtepec
5	Culiacán	23	Guadalajara	41	Lerma
6	Mazatlán	24	Aguascalientes	42	Mérida
7	Juárez	25	San Luis Potosí	43	Cancún
8	Moctezuma	26	Salamanca	44	Chetumal
9	Chihuahua	27	Manzanillo	45	Cozumel
10	Durango	28	Carapan	46	Tijuana
11	Laguna	29	Lázaro Cárdenas	47	Ensenada
12	Río Escondido	30	Querétaro	48	Mexicali
13	Nuevo Laredo	31	Central	49	San Luis Río Colorado
14	Reynosa	32	Poza Rica	50	Villa Constitución
15	Matamoros	33	Veracruz	51	La Paz
16	Monterrey	34	Puebla	52	Los Cabos
17	Saltillo	35	Acapulco	53	Mulegé
18	Valles	36	Temascal		

Figure 9 Main Transmission line Network Topology for Mexico and Line Capacity characteristics. (PRODESEN, 2022)

Figure 9 provides a visual representation of Mexico's electricity transmission network, showing the capacity and inter-regional connectivity of 53 major nodes as defined by PRODESEN. In this model, all 53 buses are explicitly included as part of the dispatch topology, each mapped to regional demand and generation data. Arrow markers denote directional flow assumptions and conceptual connections, particularly in regions where transmission corridors are simplified for clarity. The figure shows transmission lines by their capacity, color-coded to indicate lines with capacities up to 499 MW, those ranging from 500 to 999 MW, lines between 1,000 to 1,500 MW, and lines exceeding 1,500 MW. Such detailed articulation is necessary for constructing an optimal electricity dispatch model that is not only operationally correct but also considers regional energy demands and transmission limitations.

A crucial part of the analysis is the need to ensure that transmission lines, particularly those of higher capacities, are effectively utilized to distribute electricity generated from both conventional and renewable sources. *Figure 9* shows the strategic placement of high-capacity lines which serve as the main arteries of the grid, crucial for transmitting large volumes of power from generation hubs to demand centers. The optimal dispatch model must, therefore, account for these high-capacity transmission paths, ensuring that the grid's structural integrity is maintained while minimizing transmission losses and avoiding potential congestion of the grid.

Moreover, *Figure 9* shows the importance of regional balance in electricity distribution. The spatial distribution of the nodes and their interconnections via transmission lines across Mexico's transmission/control regions suggests a varied landscape of energy production and consumption. An optimal dispatch model should utilize this regional data to align generation with local demand profiles, adapt to regional generation capabilities—such as solar potential in high-solar resource areas or wind farms in high-wind regions—and contribute to the impact of local policy variations or other environmental considerations.

Figure 10 Control Regions numbered and named across the MEN.(SENER, 2023)

Figures 9 and 10, also serve as a foundation for assessing the potential for renewable energy and BESS integration. Nodes with lower-capacity lines may indicate regions where the grid could benefit from distributed generation sources to enhance local reliability and resilience (*ASOLMEX, 2022*). In contrast, nodes with higher-capacity lines may represent areas where there is potential for large-scale renewable energy projects that can contribute significantly to national energy production without necessitating substantial grid upgrades.

Incorporating carbon emissions modelling into this framework is vital for achieving Mexico's carbon reduction objectives. By analyzing the capacity and utilization of transmission lines, as shown in *Figure 9*, an optimal dispatch model can identify opportunities for reducing carbon emissions through strategic placement of BESS and demand-side management assets, as discussed in *Chapter 4*. This model will prioritize dispatch from cleaner energy sources while considering the real-time status and constraints of the transmission network.

Note that these CO2 emissions represent the operational emissions of each specific technology. They do not consider the full life cycle emissions of constructing, maintaining and decommissioning, which can be significant for low-carbon technologies like BESS. *Chapter 5* discusses how life cycle carbon emissions (and other environmental impacts) are calculated, and further work could extend the energy systems model to include these embodied impacts.

There are, however, intrinsic challenges and potential areas for further research highlighted by the current set-up of the model. For instance, the current set-up does not explicitly denote the seasonal variability in renewable energy generation, which is critical for detailed carbon emissions modelling, further discussed in *Chapter 6*. There is also an absence of real-time data flow, which would be essential for a dynamic optimal dispatch model that responds to instantaneous grid conditions. The model presented in this thesis can be extended to accommodate for those particularities.

By detailing the characteristics of these assets, including their location, capacity, and operational costs, the model can optimize their usage to meet demand efficiently and sustainably.

Line	From	Node	To	Node	From	Link	To	Capacity (MW)	Reactance (Ohms)
1	1	A	3	C	Hermosillo	-	Obregón	1400	0.01136
2	2	B	1	A	Cananea	-	Hermosillo	975	0.024617
3	2	B	8	H	Cananea	-	Moctezuma	400	0.0762
4	3	C	4	D	Obregón	-	Los Mochis	600	0.0283
5	5	E	4	D	Culiacán	-	Los Mochis	850	0.01143
6	6	F	5	E	Mazatlán	-	Culiacán	1450	0.022339
7	6	F	22	V	Mazatlán	-	Tepic	1380	0.031041
8	7	G	8	H	Juárez	-	Moctezuma	965	0.029087
9	8	H	9	I	Moctezuma	-	Chihuahua	640	0.042361
10	9	I	11	K	Chihuahua	-	Laguna	250	0.13258
11	10	J	6	F	Durango	-	Mazatlán	550	0.040829
12	10	J	24	X	Durango	-	Aguascalientes	300	0.203983
13	11	K	10	J	Laguna	-	Durango	550	0.039167
14	11	K	17	Q	Laguna	-	Saltillo	550	0.03775
15	12	L	9	I	Río	-	Chihuahua	500	0.137
16	12	L	13	M	Río	-	Nuevo Laredo	400	0.027204
17	12	L	16	P	Río	-	Monterrey	2100	0.009678
18	14	N	13	M	Reynosa	-	Nuevo Laredo	140	0.039666
19	14	N	16	P	Reynosa	-	Monterrey	1900	0.014097
20	15	O	14	N	Matamoros	-	Reynosa	1400	0.005345
21	16	P	17	Q	Monterrey	-	Saltillo	1500	0.003229
22	17	Q	24	X	Saltillo	-	Aguascalientes	1500	0.018393
23	18	R	25	Y	Valles	-	SLP	1500	0.02757
24	19	S	18	R	Huasteca	-	Valles	1050	0.00757
25	19	S	20	T	Huasteca	-	Tamazunchale	1200	0.018095
26	19	S	21	U	Huasteca	-	Güémez	1700	0.016186
27	19	S	32	FF	Huasteca	-	Poza Rica	1650	0.020665
28	20	T	30	DD	Tamazunchale	-	Querétaro	1750	0.020665
29	21	U	16	P	Güémez	-	Monterrey	1500	0.015925
30	22	V	23	W	Tepic	-	Guadalajara	1150	0.005495
31	23	W	24	X	Guadalajara	-	Aguascalientes	1000	0.020901
32	23	W	26	Z	Guadalajara	-	Salamanca	700	0.05013
33	23	W	28	BB	Guadalajara	-	Carapan	700	0.010506
34	23	W	29	CC	Guadalajara	-	Lázaro	600	0.06037
35	24	X	26	Z	Aguascalientes	-	Salamanca	1400	0.004351
36	25	Y	24	X	SLP	-	Aguascalientes	1300	0.013164
37	26	Z	30	DD	Salamanca	-	Querétaro	1600	0.003492
38	27	AA	23	W	Manzanillo	-	Guadalajara	2800	0.012483
39	28	BB	26	Z	Carapan	-	Salamanca	700	0.021535
40	29	CC	28	BB	L.Cárdenas	-	Carapan	600	0.05656
41	29	CC	31	EE	L.Cárdenas	-	Central	2900	0.010393
42	29	CC	35	II	L.Cárdenas	-	Acapulco	350	0.020371
43	30	DD	25	Y	Querétaro	-	SLP	300	0.057056

44	30	DD	31	EE	Querétaro	-	Central	1750	0.007113
45	32	FF	31	EE	Poza Rica	-	Central	4000	0.008884
46	32	FF	34	HH	Poza Rica	-	Puebla	310	0.052341
47	33	GG	32	FF	Veracruz	-	Poza Rica	750	0.03437
48	33	GG	34	HH	Veracruz	-	Puebla	1100	0.024385
49	33	GG	36	JJ	Veracruz	-	Temascal	440	0.020336
50	34	HH	31	EE	Puebla	-	Central	3000	0.002124
51	35	II	34	HH	Acapulco	-	Puebla	300	0.057928
52	36	JJ	34	HH	Temascal	-	Puebla	3000	0.005862
53	37	KK	36	JJ	Coatzacoalcos	-	Temascal	1750	0.012458
54	38	LL	41	OO	Tabasco	-	Lerma	1200	0.012668
55	39	MM	36	JJ	Grijalva	-	Temascal	2800	0.012024
56	39	MM	37	KK	Grijalva	-	Coatzacoalcos	2100	0.01139
57	39	MM	38	LL	Grijalva	-	Tabasco	1450	0.008253
58	40	NN	36	JJ	Ixtepec	-	Temascal	2500	0.009963
59	41	OO	42	PP	Lerma	-	Mérida	800	0.023389
60	41	OO	44	RR	Lerma	-	Chetumal	206	0.151009
61	42	PP	43	QQ	Mérida	-	Cancún	825	0.01333
62	42	PP	44	RR	Mérida	-	Chetumal	250	0.092608
63	43	QQ	45	SS	Cancún	-	Cozumel	48	0.18835
64	48	VV	49	WW	Mexicali	-	San Luis Colorado	315	0.023389
65	46	TT	48	VV	Tijuana	-	Mexicali	520	0.023389
66	46	TT	47	UU	Tijuana	-	Ensenada	255	0.023389
67	53	AAA	53	AAA	Mulege	-	Mulegé	500	0.092608
68	50	XX	51	YY	Villa Const	-	La Paz	90	0.023389
69	51	YY	52	ZZ	La Paz	-	Los Cabos	180	0.023389

Table 2 Transmission line infrastructure for the MEN built for modelling purposes with real data from SENER. It includes power flow directions, name of transmission links, capacity and reactance. (SENER, 2023)

Building the virtual infrastructure for an optimal dispatch model into Mexico's complex electricity network is indispensable for fostering the balance between electricity generation and consumption, underscored by the imperatives of efficiency, reliability, and environmental responsibility. *Table 2* outlines the geographical distribution and electrical specifications of grid nodes and transmission lines, which serves as a foundational pillar for the development of a model tailored to reduce the complexities of operational efficiency and sustainability within the grid.

In addition to the main national grid, Mexico operates several isolated systems, notably in Baja California and Baja California Sur. These regions are not connected to the central national grid but operate independently, relying on local generation and, in the case of Baja

California, international interconnections. The Baja California system is synchronised with the Western Electricity Coordinating Council (WECC) in the United States, enabling electricity imports from California and enhancing reliability during peak demand periods or supply shortfalls. This cross-border interconnection is critical given the region's high population density and growing industrial demand, and it exemplifies the strategic importance of regional grid cooperation in areas where integration with the national grid is technically or economically unfeasible (NREL, 2021).

Each transmission source or sink has been tagged with a unique identifier and associated with specific geographic places, signifying critical junctures such as substations or power generation sites. The precise representation of these nodes offers a transparent framework for separating the flow of electricity across the network, enabling a clear understanding of potential congestion points or sectors necessitating infrastructural enhancements to accommodate escalating demands.

The details provided in *Table 2* about the capacity and resistance of transmission lines show how much electricity the grid can handle and the limitations it faces. The capacity of these lines is crucial because they demonstrate how much electricity can be transmitted without causing problems or risking outages, helping to make the grid stronger. On the other hand, resistance affects how efficiently electricity can be transmitted, which has both cost and environmental effects. Understanding these factors is key to creating a plan that reduces energy loss and improves how the grid works.

This detailed look at the grid's structure and performance is very important for planning ahead, especially when thinking about making the grid more capable or updating outdated parts. By identifying where the grid is close to its limit or where it's not working adequately because of high resistance, we can invest wisely to greatly improve how the grid operates. As we use more renewable energy in Mexico, which can variate in how much power it produces, having a grid that can handle these peaks and low points and still work efficiently is critical.

Modelling based on the particularities of *Table 2* is essential for creating a plan that considers Mexico's specific grid needs.

3.2.2 Parameters

In the optimal dispatch model designed for enhancing the efficiency and sustainability of the Mexican electricity network, parameters play a crucial role in encapsulating the real-world characteristics and constraints of the system. These parameters include the variable costs of generation units, carbon emissions rates, capacities of generation units, availability of generation units, demand at each bus, line capacities, reactance, and carbon emissions. Through their precise definition, these parameters allow the model to accurately reflect the operational realities of the Mexican electricity sector and guide the strategic deployment of energy storage systems.

$X_l: Reactance\ of\ line\ l\ \in\ L\ (Ohms)$ *(3.6)*

$C_l: Capacity\ of\ line\ l\ \in\ L\ (MW)$ *(3.7)*

$V_g: Variable\ cost\ of\ generation\ unit\ g\ \in\ G\ (\$/MWh)$ *(3.8)*

$E_g: carbon\ emissions\ rate\ of\ generation\ unit\ g\ \in\ G\ (ton/MWh)$ *(3.9)*

$P_g: Capacity\ of\ generation\ unit\ g\ \in\ G\ (MW)$ *(3.10)*

$A_{gt}: Availability\ of\ generation\ unit\ g\ \in\ G\ at\ time\ t\ \in\ T$ *(3.11)*

$D_{bt}: Demand\ at\ bus\ b\ \in\ B\ at\ time\ t\ \in\ T\ (MW)$ *(3.12)*

$CP_s: Power\ capacity\ of\ storage\ s\ \in\ S\ (MW)$ *(3.13)*

$CE_s: Energy\ capacity\ of\ storage\ s\ \in\ S\ (MWh)$ *(3.14)*

$\mu_s: Roundtrip\ efficiency\ of\ storage\ s\ \in\ S$ *(3.15)*

$\pi: Carbon\ price\ (\$/ton)$ *(3.16)*

The variable costs and carbon emissions rates of generation units are pivotal in determining the economic and environmental impacts of electricity generation. For instance, a combined cycle gas turbine might have a variable cost of approximately \$30-\$32/MWh and emit 0.4 tons of CO2 per MWh (*IEA, 2023*) (*NREL, 2023*). In contrast, solar PV, with virtually zero variable cost and minimal carbon emissions once operational, represents a drastically different profile. By incorporating these parameters, the model can prioritize the dispatch of cleaner and more cost-effective resources.

The generation capacity and availability parameters reflect the physical and operational limits of power plants. However, its availability varies based on solar irradiance patterns, necessitating sophisticated modelling to optimize its integration alongside other resources and storage solutions.

Demand and line capacities are critical for ensuring reliability in the electricity supply. Mexico City, for example, experiences peak demands significantly higher than other regions, requiring careful management of transmission lines with capacities that might range up to 1,000 MW or more. Accurately modelling these parameters ensures that the system can meet demand at all times without overloading network components.

Line reactance affects the efficiency of power transmission. Lower reactance values, common in short, high-capacity lines, facilitate better power flow but require substantial investment (*Alomoush, I, M, 2004*) (*Amin, H, D., 2020*). The parameter for the price of carbon emissions, currently under discussion in Mexican energy policy circles, could be set at a level that reflects international carbon pricing trends, say $20/ton (*IEA, 2023*) (*NREL, 2023*), to simulate future regulatory scenarios, but will be inactive for the purposes of these case studies. Operational carbon emissions are incorporated directly into the model's objective function, which simultaneously minimizes both the total generation cost and the emissions produced by each generating unit, based on their emission rates. This ensures that the dispatch decisions account for environmental impact as part of the core optimisation process

By integrating these parameters into the optimal dispatch model, the analysis not only captures the operational aspects of the Mexican electricity network but also aligns with the strategic vision for the country's energy future. Through this detailed parametric representation, the model offers insights into achieving a balance between economic efficiency, environmental sustainability, and system reliability, providing a valuable tool for policymakers and energy planners. The demand profiles for each control region are shown in *Figure 14*. Demand characteristics, profiles and Max Demand for all 53 buses can be viewed in *Appendix 2*.

3.2.3 Decision Variables

Decision variables are the backbone of the optimal dispatch model, serving as the primary tools through which the model can manipulate the system to achieve its objectives. These variables, including electricity generation from units, charging and discharging of storage facilities, energy levels in storage, and voltage angles at buses, provide a framework for operational flexibility and strategic planning within the electricity network.

They enable the model to simulate a wide range of operational strategies, from adjusting generation outputs to manage peak demand periods effectively, to optimizing the use of storage systems for balancing supply and demand over time. By quantifying these actions within the model, decision variables allow for a detailed examination of how different configurations of the network's assets can meet both current and future energy needs, while also adhering to cost and environmental constraints. *Figure 11,* is an example of this, the Puerto Peñasco solar plant (*García, J., 2023*), with a planned total capacity (In three phases) of about 900 MW PV and 90MWh BESS, demonstrating the potential for solar energy in Mexico.

Figure 11 Example of the first phase of Puerto Peñasco PV project (120 MW PV + 24MWh BESS). (García, J., 2023)

The decision variables modelled are the following:

$Gen_{gt}: Electricity\ generation\ from\ unit\ g\ \in\ G\ at\ time\ t\ \in\ T\ (MW)$ *(3.17)*

$Charge_{st}: Charging\ power\ into\ storage\ s\ \in\ S\ at\ time\ t\ \in\ T\ (MW)$ *(3.18)*

$Discharge_{st}: Discharging\ power\ from\ storage\ s\ \in\ S\ at\ time\ t\ \in\ T\ (MW)$ *(3.19)*

$Level_{st}: Energy\ level\ of\ storage\ s\ \in\ S\ at\ time\ t\ \in\ T\ (MWh)$ *(3.20)*

$\theta_{bt}: Voltage\ angle\ at\ bus\ b\ \in\ B\ at\ time\ t\ \in\ T\ (rad)$ *(3.21)*

$Flow_{lt}: Power\ flow\ on\ line\ l\ \in\ L\ at\ time\ t\ \in\ T\ (MW)$ *(3.22)*

The energy level of each storage unit evolves over time based on the difference between charging and discharging power, adjusted by roundtrip efficiency. Specifically, the energy level at time ttt is equal to the previous energy level plus the energy charged (scaled by efficiency) minus the energy discharged.

The analysis of decision variables can yield critical insights into the operational dynamics and strategic opportunities within the Mexican electricity network. For instance, by examining the patterns of generators across different time periods, stakeholders can identify the potential for cost savings through the increased use of low-marginal-cost renewable energy sources. Similarly, the charging and discharging profiles of energy storage can reveal how storage can be leveraged to mitigate the variability of renewable generation, avoid the necessity for peak-power generation plants, ensuring a more stable and reliable supply of electricity.

Furthermore, the data on level of stored energy can inform investment decisions regarding the sizing and placement of new storage facilities, ensuring they are optimally located to serve as buffers against demand spikes or renewable intermittency. The analysis of voltage angles across the network can highlight potential transmission constraints or inefficiencies (*Barreto-Mederico, C., et al., 2009*), guiding infrastructure upgrades or the reconfiguration of network operations to enhance overall system performance. These insights are invaluable for guiding Mexico towards a more sustainable, efficient, and resilient energy future, highlighting the critical role of decision variables in transforming abstract models into actionable strategies.

This is done by analysing the relative differences in voltage angles between connected buses: large angle differences across a line typically indicate high power flows and possible congestion. When such differences persist or approach system-defined thresholds, they can reveal overloaded lines or sections of the grid operating near their transfer capacity. These insights can support reconfiguration or reinforcement planning

3.2.4 Objective function and Constraints

The objective function in an optimal dispatch model plays a critical role in guiding the decision-making process toward achieving a specific goal. In the context of integrating energy storage systems into the electricity network, the primary objective often revolves around minimizing the total cost of electricity generation while considering environmental impacts. This involves not only the direct operational costs associated with running various types of power plants but also the costs related to carbon emissions, reflecting a broader commitment to sustainability.

The rationale behind focusing on cost minimization is the following: electricity generation and transmission need to be economically viable to ensure that power remains affordable for consumers and that the energy sector can sustain its operations without undue financial strain. By including variable costs of generation units and the intensity of carbon emissions, the objective function captures both the economic and environmental dimensions of electricity production. This dual focus helps to balance the financial aspects of energy production with the urgent need to reduce greenhouse gas emissions, aligning with global and national sustainability targets.

The inclusion of carbon pricing in the objective function underscores the growing recognition of the environmental costs of conventional energy generation. It incentivizes the shift toward cleaner energy sources by making the environmental impact a tangible factor in the economic calculations. This approach encourages the adoption of renewable energy technologies and the efficient use of energy storage systems to mitigate the variability of renewable sources.

Objective function:

Minimize the total cost of generation and carbon emissions:

$$Min \sum_{g \in G} \sum_{t \in T} Gen_{gt} \cdot \left(V_{gt} + \pi \cdot E_g\right) \tag{3.23}$$

Where,

$Gen_{gt} = Electricity\ Generation\ by\ unit\ g\ at\ time\ t\ (MW)$

$V_{gt}\ = Variable\ Generation\ cost\ of\ unit\ g\ (\$/MWh)$

$E_g = Emissions\ factor\ or\ unit\ g\ (ton/MWh)$

$\pi = Carbon\ price\ (\$/ton)$

Subject to*:*

Generation constraint,

$$Gen_{gt}\ \leq\ P_g\ \cdot\ A_{gt}\ ,\ \forall\ g\ \in\ G, t\ \in\ T \tag{3.24}$$

Where,

$P_g\ = Capacity\ of\ generator\ g$

$A_{gt} = Availability\ of\ generator\ g\ at\ time\ t$

Storage operation constraints,

$$Level_{st,t}\ =\ 0\ ,\ \forall\ s\ \in\ S\quad t = 1 \tag{3.25}$$

$$Level_{st,t}\ =\ Level_{s,\ t-1} - Discharge_{s,\ t-1}\ + Charge_{s,\ t-1}\ \cdot \mu_s\ ,\ \forall\ s\ \in\ S,\ t\ \in\ T \setminus \{1\} \tag{3.26}$$

$$Charge_{st}\ , Discharge_{st}\ \leq\ CP_s\ ,\ \forall\ s\ \in\ S, t\ \in\ T \tag{3.27}$$

$$Level_{st}\ \leq\ CE_s\ ,\ \forall\ s\ \in\ S,\ t\ \in\ T \tag{3.28}$$

Where,

$\mu_s = Roundtrip\ efficiency\ of\ storage\ unit\ s\ (\%)$

$CP_s\ = Power\ capacity\ of\ storage\ unit\ s\ (MW)$

$CE_s\ = Energy\ capacity\ of\ storage\ unit\ s\ (MWh)$

Transmission constraints,

$$Flow_{lt}\ =\ \leq\ \frac{1}{X_l}(\theta_{origin(l),t}\ -\ \theta_{destination(l),t})\ ,\ \forall\ l\ \in\ L,\ t\ \in\ T \tag{3.29}$$

$$-\,C_l\ \leq\ Flow_{lt}\ \leq\ C_l\ \ ,\ \forall\ l\ \in\ L, t\ \in\ T \tag{3.30}$$

Where,

$X_l = Reactance\ of\ line\ l\ (Ohms)$

$C_l\ = Capacity\ of\ line\ l\ (MW)$

Market clearing constraints,

$$\sum_{g \in G_b} Gen_{gt} + \sum_{s \in S_b} Discharge_{st} - \sum_{s \in S_b} Charge_{st} + \sum_{l \in L_{to\,(b)}} Charge_{st}\, Flow_{lt} - \sum_{l \in L_{from\,(b)}} Charge_{st}\, Flow_{lt} = D_{bt}, \quad \forall\, b \in B, t \in T \tag{3.31}$$

Slack bus constraint,

$$\theta_{slack,t} = 0\,,\ \forall\ t \in T \tag{3.32}$$

The generation capacity constraint (*Eq. 3.24*) ensures that the output from any given generation unit does not exceed its maximum capacity. This constraint is vital for maintaining the physical and safety limits of generation equipment. Overloading a generator beyond its design capacity can lead to equipment failure, safety hazards, and unexpected outages, compromising the reliability of the electricity supply. Therefore, this constraint is essential for modelling realistic operational scenarios that align with the technical capabilities of generation assets. It reflects the inherent limitations of power plants, dictated by engineering specifications and operational conditions, ensuring that the dispatch strategy remains within feasible bounds.

The storage operation constraints (*Eq. 3.25, 3.26, 3.27, and 3.28*) governs the behaviour of energy storage systems within the network, detailing how energy can be charged into, held within, and discharged from storage assets. These constraints are crucial for accurately representing the physical characteristics and operational limits of storage technologies. They ensure that the energy content of a storage system does not exceed its capacity, that charging and discharging activities do not surpass the power ratings, and that the state of charge is correctly updated to reflect energy inflows and outflows, adjusted for efficiency losses with values for round trip efficiency during each cycle. By capturing these dynamics, the storage operation constraints enable the model to utilize storage assets effectively, enhancing grid stability and facilitating the integration of intermittent renewable energy sources.

Transmission constraints (*Eq. 3.29 and 3.30*) model the physical limits of the power grid's transmission lines, ensuring that the flow of electricity does not exceed the capacity of these lines. This is critical for preventing line overloads that can cause blackouts or damage to the infrastructure. These constraints consider the line reactance, which affects the efficiency of power transmission and the distribution of flows across the network. By accurately representing these limitations, the transmission constraints help to optimize the routing of electricity, promoting efficient use of the transmission network and supporting the reliable delivery of power. In this model, the power flow constraint assumes unidirectional flow per line, meaning that electricity can only flow in one defined direction at any time step. This simplifies the routing logic and ensures physical feasibility by preventing simultaneous reverse flows on the same line. It also allows the model to identify which corridors are being actively used and which are underutilized, improving the realism of congestion and dispatch analysis.

The market clearing constraint (*Eq. 3.31*) is fundamental to ensuring that, at every moment, the amount of electricity generated matches the demand across the network. This balance is crucial for the stability and reliability of the power system, as any significant discrepancy between supply and demand can lead to power outages or damage to the infrastructure. The market clearing constraint achieves this balance by requiring that, for each location in the network and at each point in time, the total electricity supplied—whether from generation units or discharging storage systems—minus any electricity stored equals the demand.

This constraint embodies the core principle of power system operations: that electricity is a unique commodity that must be produced and consumed simultaneously. It also reflects the physical realities of power flow in an electrical grid, where electricity can be transmitted over long distances, but losses and constraints on transmission lines must be considered. By ensuring that generation meets demand while accounting for the flow of electricity across the network, the market clearing constraint provides a framework for operational decisions that maintain system integrity.

The need for this constraint (market clearing) arises from the complex dynamics of electricity markets and the technical characteristics of power systems. It ensures that the model's solutions are not only economically optimized but also technically feasible, considering the limitations and capabilities of the generation fleet, storage assets, and the transmission network. This holistic approach ensures that the model accurately reflects the operational challenges and opportunities within the electricity system, facilitating strategic planning and decision-making.

Voltage angle constraints are used to model the phase differences in voltage across the network, which are essential for calculating power flows in an alternating current (AC) system (*Barreto-Mederico, C., et al., 2009*). These constraints ensure the model accurately represents the physical laws governing electricity flows, such as Kirchhoff's voltage law (*Bushnell, J., et al., 2019*). The voltage angles at different buses are critical for determining the direction and magnitude of power flows across transmission lines. By including these constraints, the model can simulate realistic grid conditions, optimizing power flows while maintaining system stability and adhering to operational limits.

Power flow equations, which describe the relationship between the generation, flow, and consumption of electrical power within a network, are inherently nonlinear and complex. These equations require a reference point to establish voltage magnitude and phase angle values across the network. The slack bus provides this reference by arbitrarily fixing its voltage magnitude and phase angle, usually to 1.0 per unit and 0 degrees, respectively (*Bushnell, J., et al., 2019*). This establishes a baseline against which the voltages at all other buses in the system can be measured and calculated. Without a slack bus, the system of equations derived from Kirchhoff's laws would be indeterminate, lacking a unique solution, as there would be more unknowns than equations.

From a physical perspective, the slack bus represents the net balance of power within the system. It accounts for losses in transmission lines and discrepancies between forecasted and actual demand or generation. In a real power system, these losses and discrepancies mean that the total generated power must slightly exceed the total consumed power to maintain system stability. The slack bus effectively "absorbs" or "supplies" this difference, acting as a source or sink of additional power to ensure that the power generation equals the load demand plus losses. This makes the model not just solvable but also reflective of real operational conditions (*Liu, Z., 2015*) (*Taylor, C., 1993*).

Together, these constraints form a comprehensive framework that ensures the model's solutions are not only economically optimized but also technically feasible and safe. They reflect the multifaceted nature of electricity systems, encompassing generation dynamics, storage capabilities, transmission limitations, and the fundamental principles of electrical engineering. By adhering to these constraints, the model can propose strategies that optimize the use of resources, enhance grid reliability, and facilitate the transition towards cleaner energy sources.

The integrated approach allows for a complex analysis of the electricity system, highlighting opportunities for improvements in efficiency, sustainability, and resilience. It supports informed decision-making by providing insights into the potential impacts of different operational strategies, policy measures, and technological advancements. This holistic understanding is crucial for addressing the challenges of modern electricity systems.

The validity of the optimal dispatch model is established through the integration of real-world data, consistent technical assumptions, and alignment with the operational behaviour of the Mexican electricity system. Input parameters such as generator capacities, fuel costs, emissions intensities, and transmission constraints are derived from publicly available datasets (e.g., SENER, CENACE), ensuring that the model reflects physical and operational realities. Moreover, the model's output—particularly dispatch schedules and system-wide costs—shows close agreement with observed generation patterns for January 2023, reinforcing its practical applicability. The system's responsiveness to BESS integration, with corresponding shifts in cost and emissions, further supports the internal consistency and reliability of the formulation.

3.3 Case Study: Renewable Energy Current Penetration

Days are selected based on their ability to capture critical operational conditions in the electricity system. These include: (1) a peak demand day in winter, (2) a typical weekday with average load, (3) a weekend or low-demand day, and (4) a day with high renewable generation but low fossil dispatch. This approach is consistent with established methods for selecting representative days to reflect variability in load and renewable supply (Poncelet et al., 2016). For this study, 30 January 2023 was chosen as it represents a high-demand winter weekday, confirmed by national grid load data and renewable output profiles. This approach ensures that the model accounts for seasonal variations—such as changes in temperature affecting cooling and heating demands, and fluctuations in solar and wind energy production. It also allows for the evaluation of system resilience and reliability under different scenarios, including peak demand periods and minimal renewable generation days. For optimal dispatch models, especially those incorporating Battery Energy Storage Systems and renewable energy sources in a context like Mexico, this approach facilitates a comprehensive understanding of how different seasons affect energy storage requirements and renewable generation capacity. However, along with comparison to other representative days throughout the year, 30th January 2023 has been selected as the basis for all data harvesting and the presentation of the main results. This methodological rigor enhances the accuracy of dispatch models, facilitating more informed decision-making for grid operation and planning. A comparison of daily demands for the same period of year is shown in *Appendix D*.

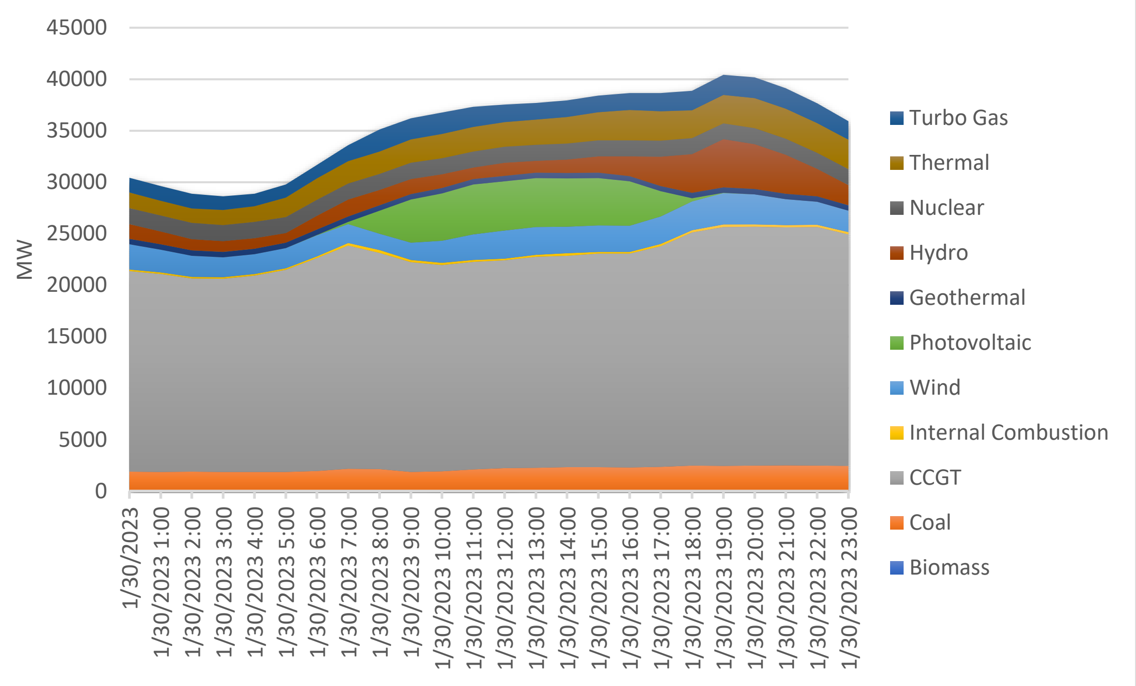


Figure 12 Real Generation technology mix for the Mexican Electricity Network for the 30th of January 2023. (Own elaboration, data from SENER)

The generation mix of Mexico on January 30th, 2023, as shown in *Figure 12*, illustrates a diversified portfolio of energy sources. Notably, renewable energy penetration, including hydro, wind, geothermal, and photovoltaic, is evident, albeit with room for expansion. The role of Battery Energy Storage Systems could be pivotal in this context. BESS can optimize renewable energy penetration by mitigating intermittency and facilitating load balancing. By storing excess generation during peak renewable output and discharging during low production periods, BESS enhances grid stability and ensures a more consistent utilization of renewable sources. This storage capability is particularly significant for photovoltaic and wind sources (available 6am to 6pm and 24-hours respectively), as demonstrated in *Figure 12*, which are subject to diurnal and stochastic variability. Integrating BESS into the dispatch model would enable a higher penetration of renewables, by acting as a buffer against intermittency.

In this model, hydropower is treated as a dispatchable generation resource, but without explicit modelling of reservoir dynamics or water inflow constraints. While many hydro units do offer storage-like flexibility, the absence of detailed hydro storage modelling here means BESS is isolated as the sole flexible energy storage mechanism for analysing temporal balancing effects.

While this study focuses on a 24-hour dispatch horizon to examine short-term BESS operational behaviour, such as daily charge–discharge cycles and peak-shaving, it does not capture seasonal or long-duration storage dynamics. This limited horizon is chosen for tractability and to reflect the real-time operational role of BESS, but future work could extend this to multi-day or seasonal simulations.

Control Region	**Biomass**	**Coal**	**Gas**	**Geothermal**	**Hydro**	**Nuclear**	**Oil**	**Solar**	**Thermal**	**Wind**	**Total**
Baja California			2922	600			482.7	150		10	4165.1
Baja California Sur							216.6				216.6
Central	8.6	2778			1557						4344
Mulege				10				4			14
Noreste	102.3	2600	8864		408.9		1080	818		22	13895.2
Noroeste	30.6		735		820.2		2052				3637.8
Norte	6.4		3021		163		936				4126.4
Occidental	108.1		2814	225	3130		2550	3.8	420		9251.2
Oriental	334.2		4361	68.6	6363	1510	2217		2160	1553	18567.4
Peninsular	12.4		2957				1988			1.5	4959
Total	**602.6**	**5378**	**25674**	**903.6**	**12443**	**1510**	**11522**	**976**	**2580**	**1587**	**63176.7**

Table 3 Installed Capacity by technology matrix for each of the Control Regions in the MEN in MW. (Own elaboration, data SENER)

In reviewing the energy infrastructure across Mexico's regions, there's a clear variation in the types of energy sources each region is equipped to handle. *Table 3*, shows the data on installed energy capacity—how much power could potentially be produced if all facilities were running at full capacity—paints a picture of regional energy strategies and potential areas for growth.

Baja California has a strong foundation in Gas with an installed capacity of 2922 MW. This is supported by Thermal and Oil capacities of 482.7 MW and 150 MW, respectively. The absence of renewable energy installations like Biomass, Coal, Geothermal, Hydro, Nuclear, and Solar suggests this region is heavily reliant on fossil fuels and could benefit from diversifying into cleaner energy sources.

Baja California Sur, on the other hand, is all-in on oil-based thermal generation, with an installed capacity of 216.6 MW. The lack of variety in energy sources here could indicate a smaller, less complex energy market, or perhaps a region that's just beginning to develop its energy infrastructure. Baja California Sur is not connected to the rest of Mexico's national grid, operating instead as an isolated system. This limits its ability to import power and increases the importance of local capacity and storage

The Central region shows a balance, leaning heavily on Coal (2778 MW) and Thermal (1557 MW) energies, making up a total capacity of 4344 MW. The very small Biomass capacity of 8.6 MW hints that renewable energy is still in its early stages here.

Mulege's energy profile is quite limited, with a small Gas capacity of 10 MW and an even smaller Solar capacity of 4 MW, summing up to a total of 14 MW. CFE data shows Mulegé's typical demand remains below 10 MW, consistent with the installed capacity profile and supporting the interpretation of limited industrial load and early-stage energy development.

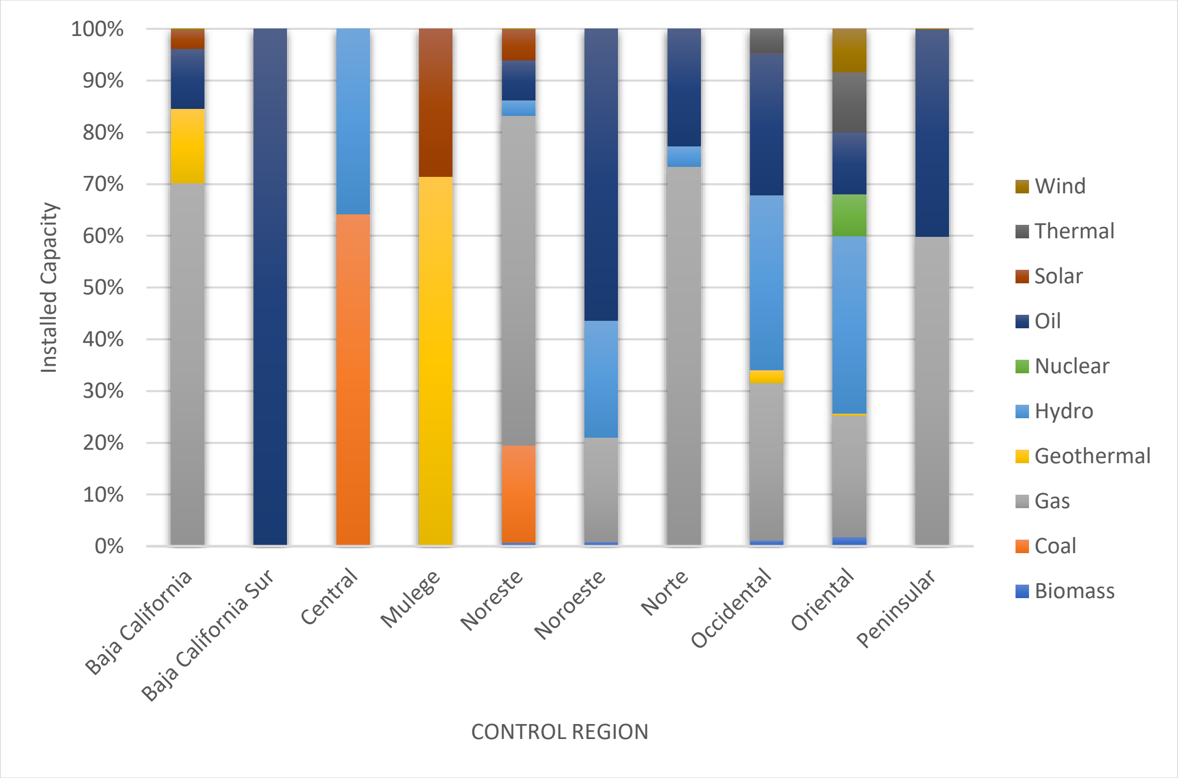


Figure 13 Percentage representation of the Installed Capacity per Control Region in the MEN. (Own elaboration, data SENER)

The Noreste region has a more varied energy mix, with a strong focus on Gas (8864 MW) and Coal (2778 MW). An additional 408.9 MW is classified as generic Thermal capacity, representing legacy or mixed-fuel plants. The existence of Nuclear and Oil capacities at 1080 MW and 818 MW, plus small Solar at 22 MW, bring its total capacity to 13895.2 MW. This shows a region with a well-rounded energy setup, capable of producing energy from multiple sources.

Noroeste's energy capacity is defined by a notable Hydro capacity of 820.2 MW and a Gas capacity of 735 MW, with a smaller Biomass contribution of 30.6 MW. Together, these total 3637.8 MW, suggesting a region that takes advantage of its water resources and also has a fair amount of gas power.

In Norte, Gas is the main player again, with an installed capacity of 3021 MW. Hydro adds 163 MW, and a small Biomass capacity of 6.4 MW brings the region's total to 4126.4 MW. Here, the preference for Gas is evident, with little investment in other types of energy. Norte is a highly industrialized zone in Mexico with the need for a reliable 24-hour stable generation.

Occidental has a diverse energy profile, led by Geothermal at 3130 MW. Gas and Coal also make significant contributions, and the presence of some Nuclear and Oil, along with Solar capacity, add up to a total capacity of 9251.2 MW. This region seems to have tapped into its geothermal resources well, along with a mix of other energy types.

Oriental is the most diverse of all, with a large Hydro capacity of 6363 MW. Gas and Solar also contribute significantly, and there are smaller amounts from Biomass, Nuclear, Thermal, and Wind, resulting in a total capacity of 18567.4 MW. This region has a wide-ranging energy portfolio, with a strong focus on renewables.

The Peninsular region mainly relies on Gas (2957 MW) and Hydro (1988 MW), with a little bit of Biomass and Wind, totaling 4959 MW. This shows a focus on gas and hydroelectric power, with some room for growth in other areas.

Overall, Mexico's total installed energy capacity is 63176.7 MW. Gas (CCGT) leads the way with 25674 MW, followed by Hydro and Coal. Renewable energies like Solar, Wind, and Biomass are less represented but offer room for growth. This snapshot of Mexico's energy potential suggests a country that's still leaning on traditional energy sources but has the foundations to expand into renewables for a more balanced energy future.

3.3.1 Generation profiles for the Mexican Electricity Network

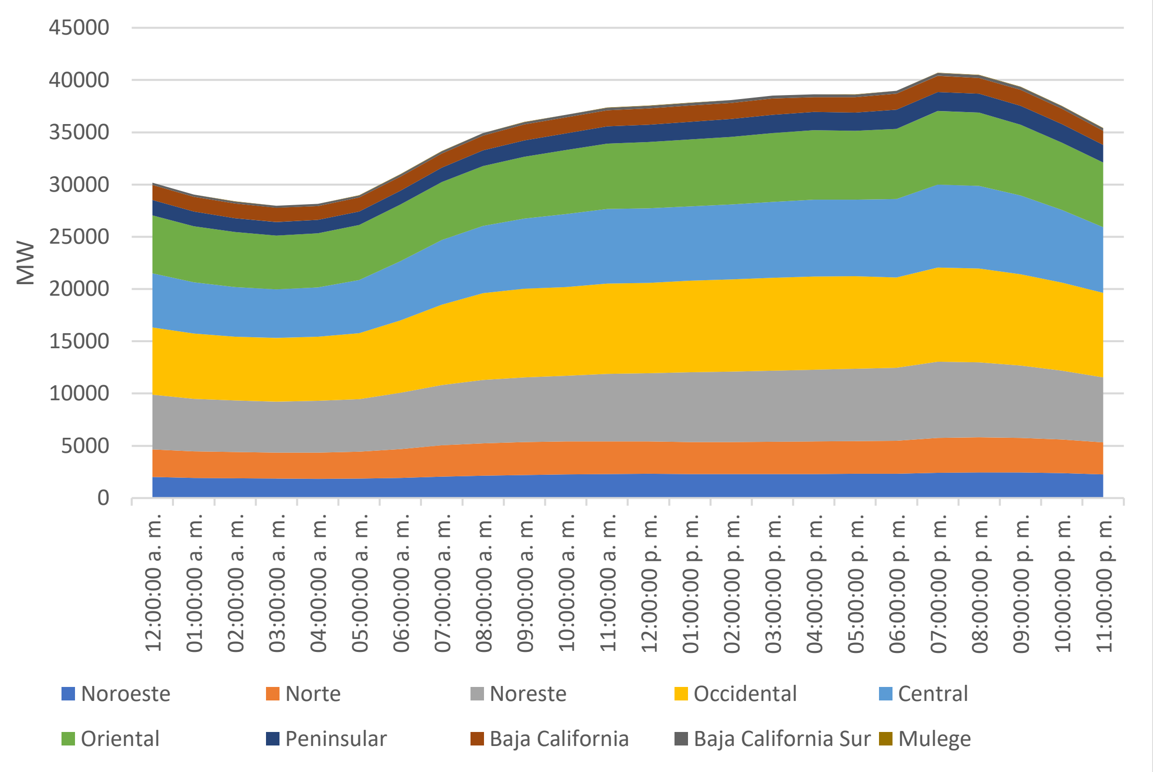


Figure 14 Real Demand Profile for the 30th January 2023 for the different Control Regions in Mexico. (Own elaboration, data SENER)

Figure 14 illustrates the aggregated electricity demand profile for the national electricity network in Mexico over a 24-hour period. The demand is segmented by regional distribution, including Noroeste (Northwest), Norte (North), Noreste (Northeast), Occidental (Western), Central, Oriental (Eastern), Peninsular, Baja California, Baja California Sur, and Mulege. Each region contributes to the total load, reflected by the stacked area plot, providing a visual representation of both regional demand behavior and the overall national electricity consumption.

A discernible feature of the demand profile is the characteristic diurnal pattern, with a trough observed during the early hours (12:00 AM - 5:00 AM) and a peak during the late afternoon to early evening (6:00 PM - 9:00 PM). This pattern is consistent with typical human activity cycles, where economic and domestic activities reduce significantly overnight and increase during the day, reaching a climax in the evening when commercial activity coincides with high residential consumption. In Mexico, there is not a considerable affectation to the profile by thermal requirements. Heating is not common, and AC systems are only used in summertime by a small fraction of the population in the North region (INEGI, 2020).

The profile indicates that the Central region maintains the highest demand throughout the day, which could be attributed to its population density and industrial activity. As the economic heartland of Mexico, the Central region likely hosts a concentration of industrial facilities and a high residential population, both of which contribute to its dominant energy consumption (Pina et al., 2012).

The Peninsular region shows a relatively flat demand profile, suggesting a balance between day and night activities or a lack of heavy industry that would otherwise create a more pronounced peak. This could be indicative of a tourism-focused economy, which tends to have a less variable load compared to industrial regions.

In contrast, regions such as Baja California and Baja California Sur exhibit notable variability. The demand in Baja California Sur, for instance, appears to be significantly lower than in other regions, which may be due to its smaller population and lower industrial activity. However, the profile for Mulege within Baja California Sur indicates an even lower demand, possibly pointing to a very small or energy-efficient community.

The Occidental and Noroeste regions present a secondary peak around 11:00 AM, which might suggest a substantial presence of commercial or industrial operations that begin their main activities in the late morning. Additionally, this could be reflection of regional seasonal touristic activities, like in Coastal cities.

The Oriental region shows a steady increase in demand from the early morning until the evening peak, followed by a gradual decrease. This could be representative of a region with a balance of residential, commercial, and light industrial activities, with energy consumption increasing steadily as all sectors ramp up their activities throughout the day.

The demand profile of the Norte and Noroeste regions shares similarities, with a less pronounced evening peak compared to the Central region. This could be reflective of a smaller population size or a mix of activities that do not coincide with creating a sharp peak in demand.

The aggregated demand for electricity in Mexico's national network displays the complex interplay of various regional dynamics. The Central region’s prominence in the demand profile dictates the importance of focusing energy efficiency and management efforts in this area to mitigate peak demand pressures. Moreover, the specific regional demand characteristics suggest that tailored energy policies are required to address the unique needs and consumption patterns of each area.

3.3.2 Physical Construction of the Nodal System and Real Location of the Generators

Analyzing the spatial distribution of power generation assets across a geographical region is fundamental to understanding the dynamics of energy dispatch, grid congestion, and other technical aspects of power system operation. The map show in *Figure 15* shows the location of generators with a capacity greater than 1 MW across Mexico, categorized into various regions such as Noroeste (Northwest), Occidental (Western), Peninsular (Peninsula), Baja California, Noreste (Northeast), Oriental (Eastern), Baja California Sur, Norte (North), and Central.

Mexico's vast and varied geography leads to diverse energy needs and generation profiles across the country. Regions with a high density of generation assets, such as the Central region, likely have a robust industrial and residential demand for electricity. High generation capacity in close proximity to load centers can result in lower transmission losses and improved system efficiency. However, it can also lead to a localized surplus of generation, potentially underutilizing plants during off-peak hours or when renewable generation (such as solar during midday) peaks. Construction *Table 4* and *Table 5* demonstrate the matrices built to relate the geolocation of the Nodes with the real geolocation of each of the 253 generation assets contemplated. All generation assets above 1MW of installed capacity in Mexico were used to construct the optimal dispatch model.

Conversely, regions with fewer generation assets, particularly renewable energy facilities, may rely more heavily on energy imports from other regions. This dependency can influence dispatch tendencies, with grid operators potentially favoring local generation to mitigate transmission constraints and reduce reliance on inter-regional power flows.

Node	Code	Name	Control Region	Latitude	Longitude
1	A	Hermosillo	Noroeste	29.07297	-110.955919
2	B	Cananea	Noroeste	30.99018	-110.300499
3	C	Obregón	Noroeste	27.48277	-109.930367
4	D	Los Mochis	Noroeste	25.79047	-108.985886
5	E	Culiacán	Noroeste	24.80907	-107.394012
6	F	Mazatlán	Noroeste	23.24941	-106.411142
7	G	Juárez	Norte	31.69036	-106.424548
8	H	Moctezuma	Norte	29.80718	-109.674833
9	I	Chihuahua	Norte	28.633	-106.0691
10	J	Durango	Norte	24.02772	-104.653176
…					
…					
…					
53	AAA	Mulegé	Mulege	26.88242	-111.982232

Table 4 Node & Code construction matrix based on real location of each Node. Complete table shown in Appendix B.

(Own elaboration, data SENER)

Gen Node	Generator	Type	Control Region	Capacity	Name	Ext Code	Latitude	Longitude
32	**Gen1**	Oil	Oriental	2100	Adolfo LÃ³pez Mateos	MEX0001766	21.0151	-97.3334
22	**Gen2**	Hydro	Occidental	960	Aguamilpa solid	MEX0001856	21.8395	-104.804
31	**Gen3**	Hydro	Central	7	Alameda	MEX0006565	18.8452	-99.4619
22	**Gen4**	Hydro	Occidental	750	AlfredoElÃas	MEX0001859	21.1979	-104.105
19	**Gen5**	Oil	Noreste	500	Altamira	MEX0001776	22.4351	-98.0081
19	**Gen6**	Gas	Noreste	495	Altamira II	MEX0001794	22.4978	-97.9017
19	**Gen7**	Gas	Noreste	1036	Altamira III y IV	MEX0001774	22.4939	-97.9014
19	**Gen8**	Gas	Noreste	1121	Altamira V	MEX0001773	22.4997	-97.9053
12	**Gen9**	Gas	Noreste	180.3	Altos Hornos de	MEX0001834	28.4658	-100.7
	Gen…							
	Gen…							
37	**Gen251**	Hydro	Oriental	420	Ã•ngel Albino Corzo (PeÃ±itas)	MEX0001862	17.4463	-93.4628

Table 5 251 Generators & Node construction matrix based on real geolocation of each generator. Full table shown in Appendix C. (Own elaboration, data SENER)

The physical placement of generators affects the flow of electricity through transmission lines. In areas where generation capacity significantly exceeds local demand, such as might be seen in regions with a high concentration of renewable energy sources, the excess power must be transmitted to other regions. If the transmission infrastructure is not adequately developed to handle these power flows, it can lead to congestion. Congestion not only increases the operational complexity but also necessitates the use of congestion management strategies, which can include re-dispatching of generation units and utilization of storage solutions to alleviate overloaded lines.

The geographic dispersion of renewable assets, particularly wind and solar, can be seen in regions such as Baja California and the Peninsular area. These generators are subject to variability due to their dependence on weather conditions. For instance, solar generators exhibit a diurnal pattern with no output at night, while wind generation can be unpredictable. This variability can lead to challenges in maintaining a stable and balanced grid, particularly if the renewable generation capacity forms a significant portion of the regional energy mix.

The spatial distribution of generators relative to load centers is also a determinant of transmission losses. In regions where generation is far from consumption centers, the energy losses over transmission lines can be considerable, reducing overall system efficiency. Moreover, long-distance transmission can necessitate higher capital and maintenance costs for the infrastructure required to sustain reliable power delivery. While this study focuses on transmission losses across high-voltage infrastructure, it is important to note that distribution-level losses can also significantly impact overall system efficiency. However, these are outside the scope of this model, which is based on aggregated nodal demand at the transmission level.

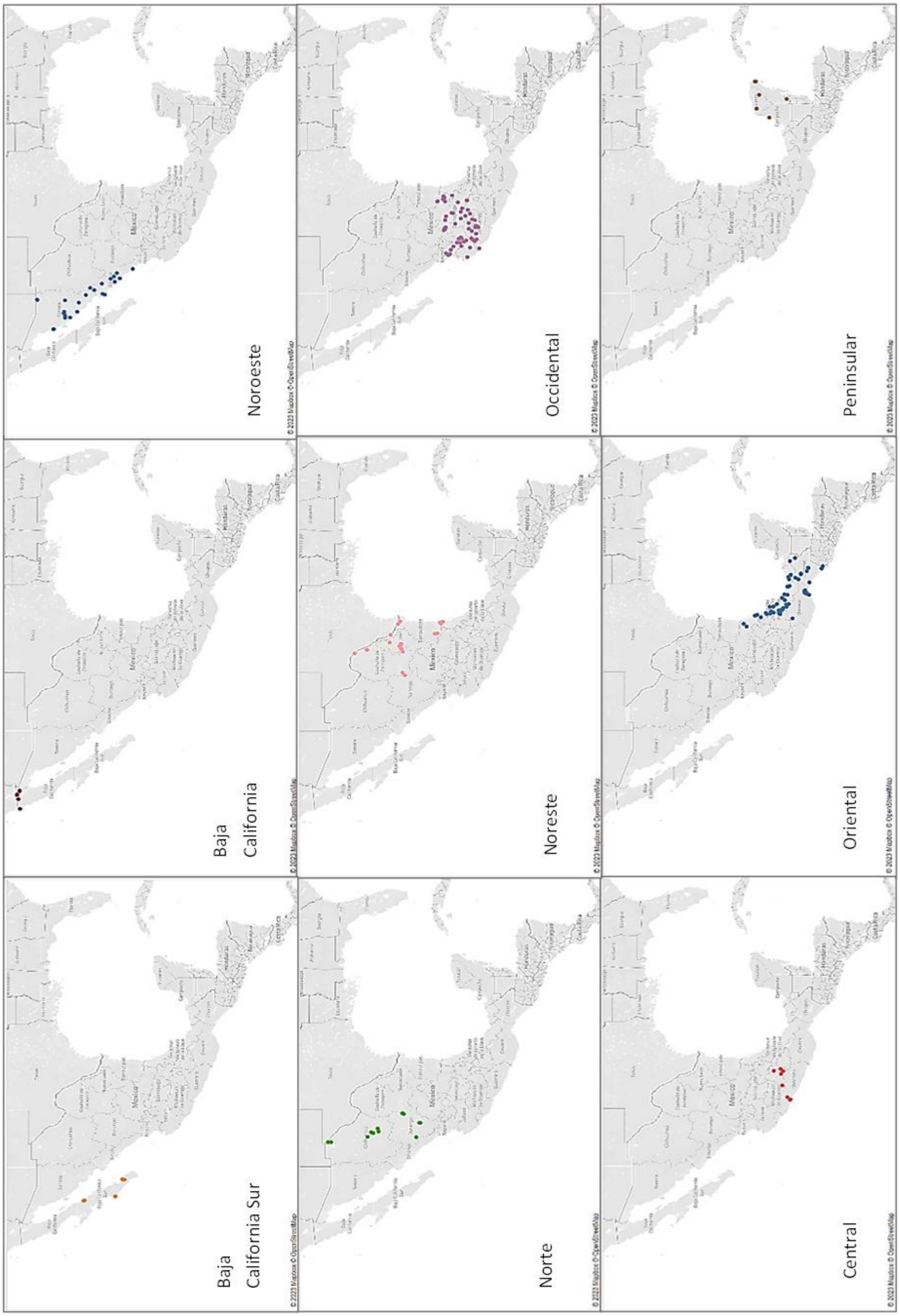


Figure 15 Real Geolocation for the 251 generators modelled for the Mexican Electricity Network. (Own creation, data SENER)

The environmental impact of generator locations is also notable. Regions that rely on fossil fuel-based generators may experience higher levels of local air pollution and greenhouse gas emissions. Conversely, regions with a higher proportion of clean energy generators contribute to Mexico's overall reduction in carbon footprint and alignment with international environmental commitments.

The Mexican government and energy sector stakeholders can use the spatial distribution of generation assets to inform strategic planning and policymaking. For instance, understanding the regional disparities in generation capacity can help prioritize infrastructure investments, such as transmission upgrades or the construction of new renewable energy facilities in regions with high demand but low local generation capacity.

The specific locations of generators across Mexico have profound implications for the country's energy dispatch tendencies, grid congestion, and technical aspects. Regional disparities in generation capacity necessitate a careful balancing act to ensure efficient, stable, and environmentally sustainable power delivery. Grid operators must account for the spatial distribution of these assets in their operational strategies, while policymakers must consider them when planning for the country's energy future.

3.3.3 Simulated 24 (hours) by 251 (generators) Generation Matrix

In the context of power systems, with no exeption for the Mexican national electricity network, the alignment between generated and demanded energy is a critical determinant of grid stability and efficiency. *Figure 16* is a comparison between the real generation data, the modelled generation (with a solving time of 2-3 hours), and the demand profile serves as a pragmatic approach to validate the optimal dispatch model that was used to simulate the generation profile.

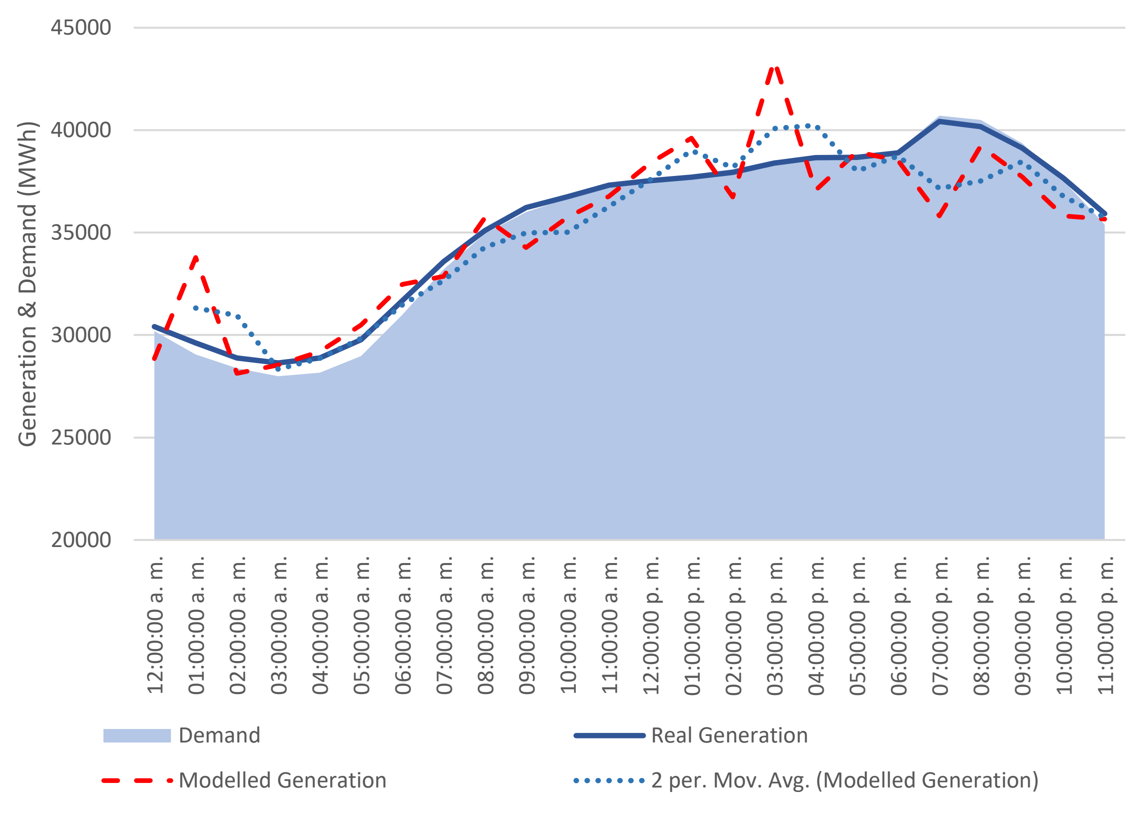


Figure 16 Comparison of Real Demand, Real Generation and Modelled Generation profiles for the 31st January 2023. NOTE: Y-Axis has been shortened for better observation of the deviated values. (Own elaboration, data SENER)

The modelled generation, depicted as a dashed line, is an outcome of an optimal dispatch model that has been constrained at a nodal level rather than on a system-wide scale. This distinction is fundamental in understanding the observed variances between the modelled and real generation profiles. In this run presented in *Figure 16*, the nodal demand constraints were relaxed by ±20%, allowing the modelled generation to deviate from exact hourly demand at each node. This margin represents the assumed operational flexibility provided by BESS, simulating how a 20% local storage buffer could absorb or supply power to help meet load without requiring exact real-time matching. This approach enables the identification of nodes where BESS would be most valuable in balancing generation and demand. The real generation data, represented by the dotted line with markers, and further smoothed by a two-period moving average, indicates the actual operational response of generation units to the demand profile, which is illustrated by the shaded area in the graph.

A simple analysis of *Figure 16* reveals that the modelled generation generally mirrors the trend of the demand profile, suggesting an overall effective grasp of the system's load patterns by the optimal dispatch model. Particularly during off-peak hours, from midnight to early morning, the modelled generation closely follows the actual generation, indicating the model's effectiveness in capturing the baseload generation requirements. However, as the demand rises, certain discrepancies become apparent.

Operational ramp rates or the inertia of the thermal generation units and the lack of integration of real-time operational constraints, such as start-up times and minimum load levels of conventional power plants can be explored as potential future work to expand this optimal dispatch model.

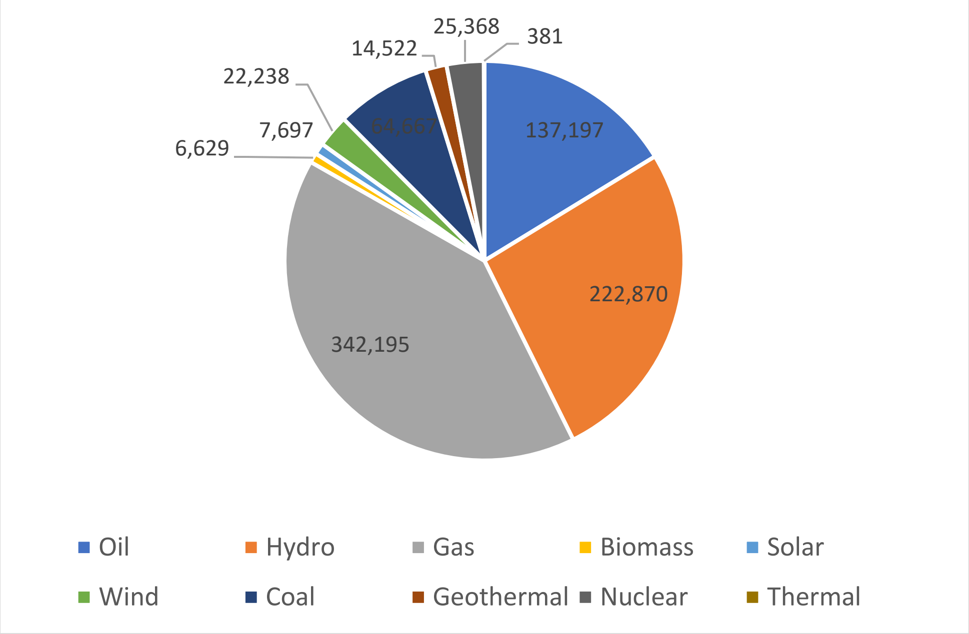


Figure 17 Total Modelled Generation by the mix of Technologies for the 31st January 2023. (Own elaboration, result modellation)

Technology	Modelled Generation (MWh)	Power Capacity (MW)	Installed Capacity (MW)	Available Capacity (MW)	Capacity Usage (%)
Oil	137197	5717	11522	9218	62%
Hydro	222870	9286	12443	9954	93%
Gas	342195	14258	25674	20539	69%
Biomass	6629	276	603	482	57%
Solar	7697	321	976	321	100%
Wind	22238	927	1587	927	100%
Coal	64667	2694	5378	4302	63%
Geothermal	14522	605	903	722	84%
Nuclear	25368	1057	1510	1208	88%
Thermal	381	16	2580	2064	1%

Table 6 Flexible Total Modelled Generation by the mix of Technologies for the 31st January 2023. (Own elaboration, modelled)

The model found a real solution (total cost of dispatch and carbon emissions will be presented in *Section 3.3.5*) by maxing out on renewable sources with low variable costs and low carbon intensity (as shown in *Table 6*). It also maximizes the use of Hydro resource, which doesn't reach 100% of Capacity Usage given the modelled limitations and the real installed infrastructure. In some periods, the use of a large hydro plant is unfeasible given the real demand characteristics, although this could be enhanced by Pumped-Hydro storage systems, which are outside of the scope of this research. This is primarily due to mismatches between hydro generation potential and demand patterns: at certain hours, hydro units cannot be dispatched at full capacity without violating nodal or transmission constraints. Additionally, since the model does not account for water inflows or storage dynamics, it cannot shift hydro output flexibly over time. This limits its dispatch during periods where other resources or grid limits are more optimal. In order to ensure the model meets the demand at each time period, not only at a system scale but also at a nodal scale, the flexibility of generation constrains were eliminated and the results of the new simulation are shown in *Table 7*:

Technology	Modelled Generation (MWh)	Power Capacity (MW)	Installed Capacity	Available Capacity	Capacity Usage (%)
Oil	138637	5777	11522	9218	63%
Hydro	222870	9286	12443	9954	93%
Gas	351737	14656	25674	20539	71%
Biomass	6629	276	603	482	57%
Solar	7697	321	976	321	100%
Wind	22238	927	1587	927	100%
Coal	53684	2237	5378	4302	52%
Geothermal	14522	605	903	722	84%
Nuclear	25368	1057	1510	1208	88%
Thermal	381	16	2580	2064	1%

Table 7 Inflexible Total Modelled Generation by the mix of Technologies for the 31st January 2023. (Own elaboration, modelled)

The model effectively reaches optimality by adequately selecting the shutting down of Coal fired generation plants (decrease in capacity usage from 63% to 52%), given its high carbon intensive process, and ramping up the production of the cheapest technology available:

CCGT plants (increase in 2%). The optimized and balanced system results are shown in *Figure 18*:

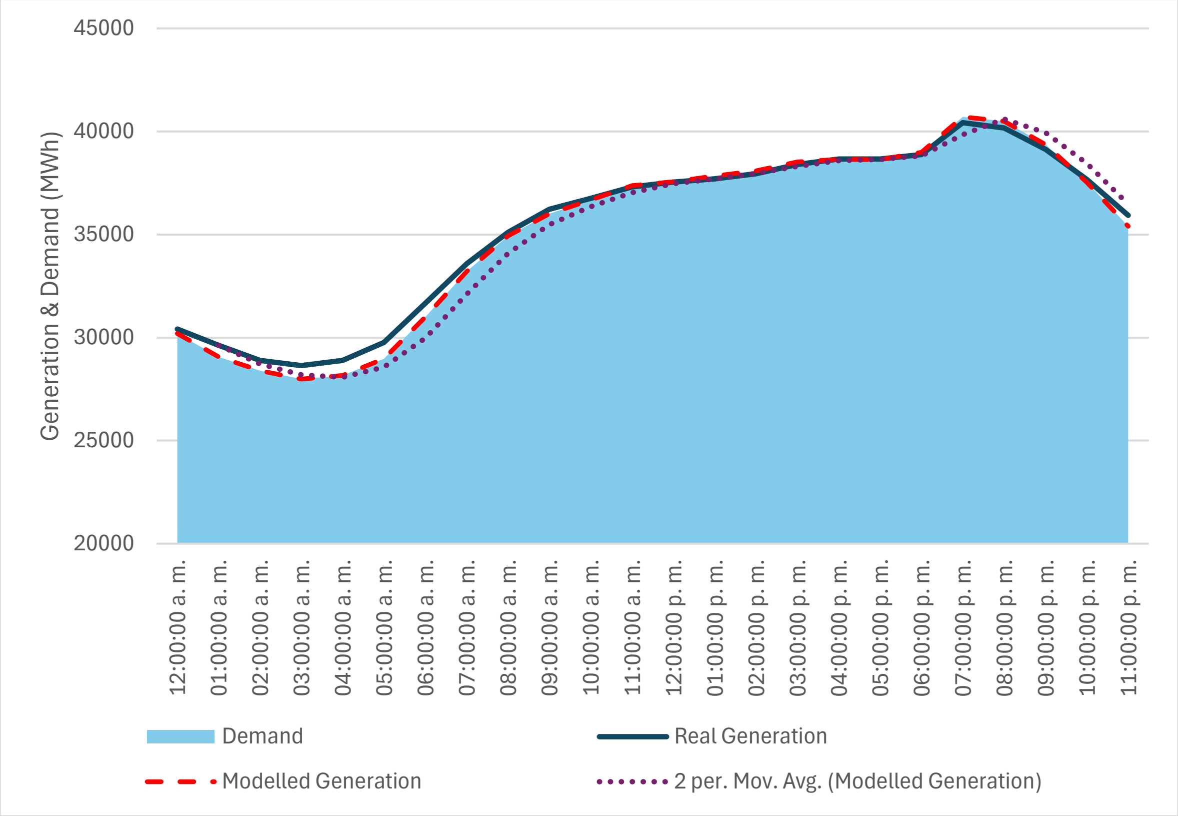


Figure 18 Comparison of Real Demand, Real Generation and Modelled Generation profiles for the 31st January 2023 without Nodal flexibility. NOTE: Y-Axis has been shortened for better observation of the deviated values. (Own elaboration, modelled)

In the early hours of the day, real generation exceeds modelled generation due to system-level operational practices such as generator minimum output levels, spinning reserves, and potential over-commitment of baseload units during off-peak periods (CFE, 2022). These operational constraints are not explicitly modelled in the simulation, which seeks an ideal dispatch based solely on cost minimisation and load balance at the nodal level.

3.3.4 Reliability of Modelled Parameters and Significance

The significance of proving the accuracy of such models is multifold in the context of power system operation and planning. Firstly, an accurate model is essential for the economic dispatch of generation units. By ensuring that the generation matches the demand at the lowest possible cost, system operators can optimize fuel consumption, minimize operational costs, and consequently, reduce electricity prices for consumers.

Secondly, accurate modelling is critical for maintaining system reliability. The grid operates on a delicate balance where the supplied power must constantly match the demand to prevent frequency deviations that could lead to system instability or failure (*Agüero, R, J., 2012*). A model that accurately reflects generation capabilities ensures that system operators can reliably plan for generation scheduling, maintenance, and contingency operations.

Furthermore, as Mexico progresses towards integrating more renewable energy sources, the variability and uncertainty inherent in sources such as wind and solar necessitate precise models to manage the balance of supply and demand effectively. Models that can predict the intermittency of renewables and incorporate them into the generation schedule are indispensable for ensuring grid resilience and reducing reliance on fossil fuels (*Castellanos, S., et al., 2018*).

The optimal dispatch model's predictive accuracy is also critical for infrastructure investment decisions. Accurate demand and generation modelling inform policymakers and investors about where and when to build new generation capacity, transmission lines, or energy storage systems (*Fattahi, A., et al., 2020*).

In addition to guiding operational decisions, the model's precision is crucial for strategic planning, particularly in the face of changing energy policies, evolving market dynamics, and the transition towards sustainable energy sources (*Lopion, P., et al., 2018*). Accurate models enable policymakers to craft more informed, forward-looking policies that can navigate the complexities of the energy transition, ensuring that the Mexican national electricity network can meet future energy needs sustainably and efficiently.

3.3.5 Case Study: Optimizing for Cost and Carbon Emissions

The optimization of energy generation not only requires a delicate balance between meeting the demand and minimizing costs but also necessitates a profound consideration of the environmental impact. *Table 8* details the Levelized Cost of Electricity (LCOE), variable costs, and emissions for different energy technologies, which are the foundational parameters for optimizing power generation in terms of economic and environmental outcomes.

Oil, characterized by its high LCOE of USD 125/MWh and significant emission profile at 875 kg CO_2 eq./MWh, represents a costly and environmentally impactful choice for power generation. Despite its high variable cost of USD 50/MWh, oil remains a critical part of the energy mix, primarily due to its availability and established infrastructure (*NREL, 2023*) (*IRENA, 2023*).

In stark contrast, hydro and wind power offer a compelling mix of low LCOE, at USD 45/MWh, and minimal emissions, nearly negligible at 1 kg CO_2 eq./MWh. Their low variable costs, USD 7.50/MWh for hydro and USD 7.60/MWh for wind, underscore their economic advantage once the infrastructure is in place. These technologies are cornerstones in the transition towards a sustainable energy portfolio (*NREL, 2023*) (*IRENA, 2023*).

Natural gas, with an LCOE of USD 55/MWh and variable cost of USD 32/MWh, stands as a bridge technology in the energy transition. Emitting 475 kg CO_2 eq./MWh, it offers a cleaner alternative to coal and oil, although still a significant contributor to greenhouse gas emissions (*NREL, 2023*) (*IRENA, 2023*).

Technology	LCOE USD/MWh	Variable USD/MWh	Emissions Kg CO_2 eq./MWh
Oil	125.00	50.00	875.00
Hydro	45.00	7.50	1.00
Gas	55.00	32.00	475.00
Biomass	100.00	40.00	8.00
Solar	35.00	6.00	1.00
Wind	45.00	7.60	1.00
Coal	75.00	28.00	1000.00
Geothermal	55.00	16.00	75.00
Nuclear	85.00	26.00	1.00
Thermal	82.00	50.00	80.00

Table 8 Referenced LCOE, Variable Cost and Emissions intensity for each of the technologies modelled. Own elaboration from (NREL, 2023) (IRENA, 2023)

Biomass, solar, and geothermal technologies showcase their potential in a low-carbon future with relatively low emission profiles and competitive LCOE values. Biomass, despite its higher LCOE of USD 100/MWh, offers a sustainable waste-to-energy pathway with emissions at 8 kg CO_2 eq./MWh. Solar power emerges as the most cost-effective with the lowest LCOE at USD 35/MWh and variable cost of USD 6/MWh, paralleled by its negligible emissions, making it an increasingly favored choice (*NREL, 2023*) (*IRENA, 2023*).

Coal, with an LCOE of USD 75/MWh and emissions peaking at 1000 kg CO_2 eq./MWh, remains the most carbon-intensive option. The economic feasibility is offset by its environmental cost, highlighting the global trend towards its phase-out. Geothermal and nuclear, both with an LCOE of USD 55/MWh, present low-emission profiles of 75 and 1 kg CO_2 eq./MWh, respectively. Their higher upfront costs are balanced by low variable costs and virtually zero emissions, making them strategic choices for baseload power generation (*NREL, 2023*) (*IRENA, 2023*).

Thermal generation shows an LCOE of USD 82/MWh and moderate emissions of 80 kg CO_2 eq./MWh (*NREL, 2023*) (*IRENA, 2023*).

In the optimization process with the relaxed nodal constraints, these variables serve as inputs to determine the most cost-effective and environmentally sustainable energy mix. The interplay between economic factors and emissions is crucial, especially in the context of Mexico, where the energy transition must consider not only the global imperatives but also the unique socio-economic and geographical characteristics of the country. The accurate modelling and optimization against these parameters are fundamental to devising a generation strategy that aligns with both national interests and international commitments to combat climate change. The results of the flexible constraints modelling for Cost and CO_2 emissions is shown below in *Table 9*.

Total Variable Cost of Dispatch	$	22,683,616	USD	$ 385,621,470	MXN
Total CO_2 of Dispatch		348,707,632	kg CO_2 eq	348,708	Ton CO_2 eq

Table 9 Total Variable Cost of Dispatch and Total CO_2 emissions from dispatch as a result of the optimal solution found. Relaxed constraints at a nodal level. (Own elaboration, modelled)

However, after the constraints were closed again to ensure optimality at a nodal and system level, the results show significant variations. The optimized results are shown below in *Table 10*:

Total Variable Cost of Dispatch	$	22,753,465	USD	$ 386,808,908	MXN
Total CO_2 of Dispatch		343,517,722	kg CO_2 eq	343,518	Ton CO_2 eq

Table 10 Total Variable Cost of Dispatch and Total CO_2 emissions from dispatch as a result of the optimal solution found. Optimal solution at a nodal and system level. (Own elaboration, modelled)

As explained in *Section 3.3.3* the main deviations come from the incorporation of Gas into the mix and reducing Coal generation. Gas is slightly more expensive than Coal, hence the increase in total dispatch cost. However, there is a significant decrease in carbon emissions due to the less intensive technology that was incorporated. These two generation mixes were chosen to explore trade-offs between cost and emissions: the first prioritizes traditional high-emission baseload sources (such as Coal), while the second simulates a transition scenario with increased Gas usage to assess environmental benefits and economic feasibility

The total variable cost of dispatch and the total carbon emissions resulting from the modelled operation of a power system are key performance indicators that reflect the economic and environmental dimensions of electricity production. In the case of the Mexican modelled power system, the model has found a total variable cost of dispatch at $22,753,465 USD ($386,808,908 MXN), with total CO_2 emissions quantified at 343,518 metric tons CO_2 eq. These findings are some of the key findings of this Research thesis and represent the pivotal intersection of energy policy, environmental impact, and economic implications for the Mexican context.

In economic terms, the variable cost of dispatch is a critical factor in the operational cost of electricity. It includes the cost of fuel, variable operation, and maintenance costs. These costs directly influence the marginal cost of electricity (*Castellanos, S., et al., 2018*) and, subsequently, the market price in deregulated markets or the cost-recovery pricing in regulated ones. In the Mexican context, the energy sector has been undergoing a gradual liberalization, which implies that variable costs have become an increasingly significant determinant of electricity prices (*Rosellón, J., 2007*). The optimization model's capacity to minimize these costs while meeting demand is essential for ensuring competitive pricing in the national market and affordability for the Mexican population and industry.

When converted to the local currency, the model's finding of $386,808,908 MXN in variable costs has implications for national energy budgeting and financial planning. It provides a clear indicator for cost management and offers a benchmark for evaluating operational efficiency against other national systems and historical data within Mexico. By comparing the model's output with historical dispatch data and emissions benchmarks, planners can assess how close current operations are to optimal cost and emissions targets. This helps identify inefficiencies or opportunities for structural improvement in fuel use, generation mix, regional balancing or system upgrades.

The environmental impact, measured in total CO_2 emissions, is equally important. The value of 343,518 metric tons of CO_2 eq. puts the environmental footprint of the 24-hour power dispatch into perspective. To contextualize this, the average passenger vehicle emits about 4.6 metric tons of CO_2 annually (*SENER, 2023*). The total emissions from the Mexican power dispatch are equivalent to the yearly emissions from approximately 75,801 passenger vehicles (*SENER, 2023*). This is a substantial environmental impact, reflecting the need for ongoing efforts to decarbonize the energy sector in line with Mexico's commitments under the Paris Agreement (*UNFCCC, 2015*) and its own national climate action plans (*SENER, 2023*).

The importance of this model, being the first of its kind, is multifaceted. Firstly, it is a substantial contribution to the field of energy economics and environmental management in Mexico. It provides a tool for quantitatively assessing the trade-offs between economic and environmental objectives in the power dispatch process. The model's ability to minimize costs while considering carbon emissions is a testament to its robustness and its potential as a decision-support system for policymakers and energy planners. The model's nodal resolution allows for detailed nodal analysis of the effects of incorporating storage into the MEN.

The model represents a significant advancement in applying optimization techniques to complex systems like national power grids, specifically for the Mexican infrastructure. By incorporating various generation technologies with their respective costs and emissions, the model reflects the real-world complexity of power systems management. It captures the nuances of different technologies, fuel costs, and operational constraints, which are often oversimplified in less comprehensive models.

This model can serve as a foundational framework for further research and development. It can be adapted and expanded, further discussion found in *Chapter 6*, to include additional variables such as water usage, other GHG emissions, technical aspects of power plant operation, offering a more holistic view of the sustainability of power systems.

For Mexico, which has a diverse energy portfolio that includes significant hydroelectric, geothermal, and increasingly solar and wind capacity, alongside traditional fossil-fuel-based generation, the model's findings are actionable knowledge. They can inform the strategic expansion of renewable energy infrastructure, targeted investments in energy efficiency, and the development of new policies to support clean energy technologies.

This is the first empirical validation of the potential for an optimization model for the Mexican Electricity Network, to balance cost and carbon emissions in a real-world setting. By demonstrating that such a balance is achievable, the model prepares the way for more sustainable power system operations, not just in Mexico but as a case study for other developing nations with similar energy landscapes and challenges.

The model underlines the importance of innovation in energy systems management. As the first of its kind for Mexico, it sets a precedent for the adoption of advanced analytics in the energy sector, promoting a data-driven approach to decision-making.

3.4 Case Study: Strategic Placement of BESS

In order to determine the ideal locations for the testing of BESS incorporation to the System, it is crucial to understand the variation of generation and demand in the different regions of Mexico. As demonstrated in *Table 11*, the Sistema Eléctrico Nacional (SEN) shows a decrease in energy demand in 2020 by 2.2% followed by subsequent increases in 2021 (3.5%) and 2022 (3.4%). The initial drop could be attributed to the economic and social disruptions caused by the COVID-19 pandemic (*Carrillo, J., et al., 2021*), which led to a reduction in industrial, commercial, and residential energy consumption. The recovery in the following years suggests a rebound effect as the country began to emerge from the pandemic's impact.

The Baja California (SIBC) and Baja California Sur (SIBCS) regions present an interesting contrast. While SIBC shows consistent year-over-year growth, with a notable 5.8% increase in 2021, SIBCS experienced a decrease in 2020 followed by a significant surge of 8.4% in

2021 and a steadier growth in 2022. These fluctuations may be reflective of regional economic developments, tourism trends, and possibly the expansion of renewable energy projects. For instance, the notable increase in energy demand in SIBC in 2021 is linked to the economic recovery of the border region and its strong industrial-commercial base, while Baja California Sur’s steadier growth reflects its dependence on residential loads and tourism-driven seasonal consumption. Additionally, regional infrastructure investments and solar energy expansion—especially in Baja California—have influenced demand growth by improving local supply availability and reliability (SENER, 2022).

		2020		**2021**		**2022**	
BY SYSTEM	**CODE**	**GWh**	**% var**	**GWh**	**% var**	**GWh**	**% var**
Eléctrico Nacional	**(SEN)**	311,604	-2.2	322,552	3.5	333,662	3.4
Interconectado	**(SIN)**	294,166	-2.5	304,034	3.4	314,317	3.4
Baja California	**(SIBC)**	14,683	3.9	15,541	5.8	16,233	4.5
Baja California Sur	**(SIBCS)**	2,608	-3.8	2,826	8.4	2,964	4.9
Mulegé	**(SIMUL)**	148	6.8	150	1.9	148	-1.4
BY CONTROL REGION							
Central	**(CEN)**	56,243	-5	56,862	1.1	58,099	2.2
Oriental	**(ORI)**	49,847	-2	52,083	4.5	53,321	2.4
Occidental	**(OCC)**	67,867	-1.6	69,893	3	72,679	4
Noroeste	**(NOR)**	25,421	4.5	25,548	0.5	25,735	0.7
Norte	**(NTE)**	28,572	0.5	28,948	1.3	29,735	2.7
Noreste	**(NES)**	53,769	-4.4	57,152	6.3	60,277	5.5
Peninsular	**(PEN)**	12,447	-10	13,549	8.9	14,470	6.8

Table 11 2020 to 2022 yearly variation of energy demand in the different Control Regions of Mexico. (Own elaboration, data SENER)

The Mulegé region (SIMUL), while representing a smaller absolute value of energy demand, exhibits a notable increase in 2020, a marginal rise in 2021, and then a slight decline in 2022. This could suggest localized factors affecting energy usage patterns, such as changes in population or specific industrial activities. Within the control regions, the Central (CEN) region, encompassing the nation's capital, experienced the sharpest decline in 2020 at 5%, followed by modest recoveries over the next two years. This could reflect the impact of the pandemic on Mexico's most densely populated region and the subsequent economic recovery.

The Oriental (ORI), Occidental (OCC), and Noreste (NES) regions have shown resilience, with a decrease in 2020 followed by stronger recoveries, especially notable in NES with a 6.3% rise in 2021. This could indicate a robust return of industrial activities or growth in these areas. The Peninsular (PEN) region faced the most significant decrease in demand in 2020 at 10%, possibly due to its reliance on tourism, which was heavily impacted by travel restrictions (*Carrillo, J., et al., 2021*). However, the subsequent increase of 8.9% in 2021 and 6.8% in 2022 is noticeable, suggesting a vigorous economic rebound, potentially bolstered by an increase in tourism and development projects. The Noroeste (NOR) and Norte (NTE) regions show relative stability with slight increases, indicative of consistent energy demand that might be driven by agricultural or industrial activities that were less impacted by the pandemic.

Figure 19 Max demand in 2023 registered for each node in the MEN for each Control Region. (SENER, 2023)

The maximum demand values shown in Figure 19 serve as indicators of capacity stress and the potential need for flexibility resources. Nodes with higher peak demand are more likely to require additional reserve margins, fast-ramping generation, or storage solutions such as BESS to manage peak loads and maintain reliability. Therefore, these values were used as a complementary criterion to prioritize regions for testing BESS integration.

3.4.1 Rationale for modelling the incorporation of BESS

Incorporating energy storage systems into power system optimization models is becoming increasingly important as the penetration of variable renewable energy sources, such as wind and solar, continues to grow. These renewable sources, while beneficial for reducing carbon emissions and dependency on fossil fuels, introduce variability and uncertainty into the power systemEnergy storage, particularly at the utility scale, presents a flexible solution to mitigate these challenges, optimize system operations, and lower total dispatch costs (IEA, 2022). This section explores the role of utility-scale energy storage systems, focusing on a battery energy storage system with a capacity of 10 containers each of a 2257 kWh and a PCS of 2500 kW, in enhancing grid operations, reducing total dispatch costs, and minimizing carbon emissions.

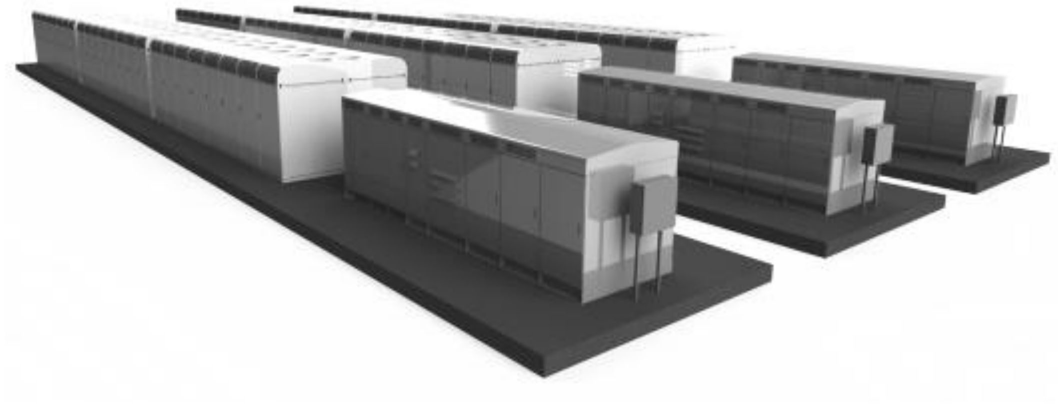


Figure 20 Example of a Canadian Solar multiple container BESS Solution. (Canadian Solar, 2023)

The integration of a BESS into power system models like the one described for Mexico's optimal dispatch can significantly enhance grid reliability and flexibility. A BESS can rapidly respond to fluctuations in demand and supply, providing ancillary services such as frequency regulation and voltage support. This capability is particularly valuable in a system with high renewable penetration, where output can vary significantly over short periods due to changes in weather conditions. By smoothing out these fluctuations, a BESS helps maintain grid stability, reducing the need for fast-ramping fossil-fueled generation units that are traditionally deployed to manage these variations (*Katsanevakis, M.,et al., 2017*). The rapid discharge capability of a BESS can meet sudden spikes in demand more efficiently than ramping up additional generation, thereby optimizing the dispatch of available resources. Although Mexico still does not have a high penetration of renewables, the tendency is for increasingly growing the share of clean energy in the generation mix.

Furthermore, the ability of a BESS to store excess renewable energy during periods of low demand and release it during peak demand periods enhances the utilization of renewable resources (*Datta, U., et al., 2021*) (*Gu, C., et al., 2021*). This shift not only reduces the reliance on more expensive and carbon-intensive peaking power plants but also allows for a higher integration of renewables into the system. By doing so, the BESS directly contributes to lowering the total cost of dispatch, as shown in *Section 3.4.2*. The operational flexibility offered by energy storage enables more cost-effective dispatch decisions by allowing system operators to minimize the use of high-variable-cost generation assets. Additionally, as a recommendation for future work, the strategic charging and discharging of a BESS can exploit price differentials in electricity markets, further reducing the cost of energy procurement and system operation should be studied.

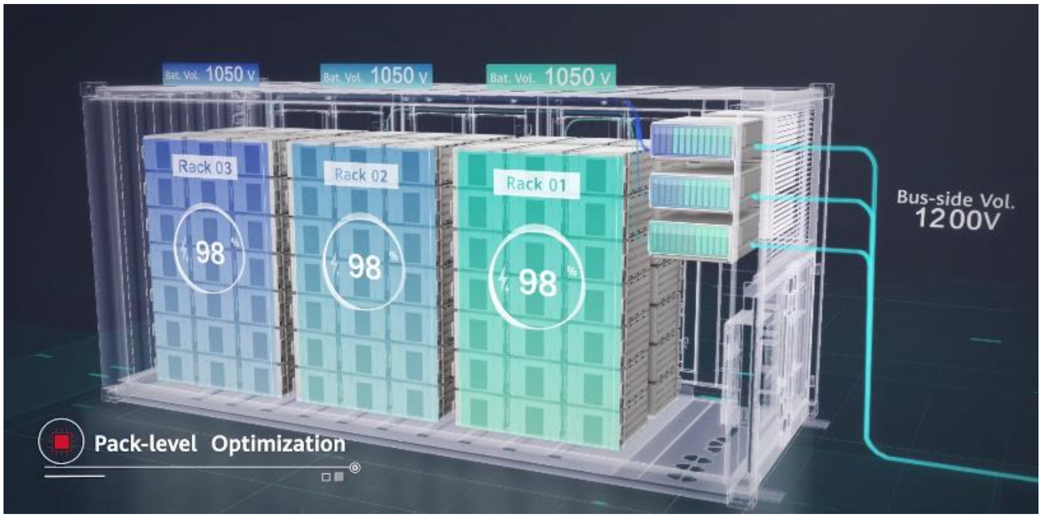


Figure 21 Example of a modern Huawei Battery Energy Storage System solution for Utility Scale applications. (Huawei, 2023)

The economic benefits of incorporating a BESS (*Figure 21*) into power system models extend beyond reducing the operational costs associated with generation dispatch. By deferring or avoiding the need for investment in new generation capacity or transmission and distribution infrastructure upgrades, a BESS can provide significant capital expenditure savings (*Ertugrul, N., 2016*). This deferral capability is particularly relevant in contexts where grid expansion is constrained by geographical, regulatory, or financial barriers. A BESS can be deployed more rapidly than traditional infrastructure projects, offering a flexible and scalable solution to meet growing demand or enhance system resilience.

In terms of environmental impact, the integration of energy storage into power system optimization models plays a critical role in reducing carbon emissions. By enabling a higher penetration of renewable energy sources and optimizing their use, a BESS directly contributes to displacing fossil fuel-based generation. The operational flexibility of a BESS, particularly when paired with renewables, can significantly reduce the system's carbon footprint (*Güney, S, M., et al., 2017*). For instance, storing surplus renewable energy and displacing the need for fossil-fueled generation during peak periods can lead to substantial reductions in carbon emissions. Moreover, by improving the efficiency of the power system through enhanced grid stability and reduced operational costs, a BESS indirectly supports the transition towards a more sustainable energy landscape.

3.4.2BESS System in the model context

The case of a 2257 kWh and a PCS of 2500 kW BESS exemplifies how utility-scale energy storage can be tailored to meet specific operational and environmental objectives within a power system optimization model. The capacity and energy content of this BESS are well-suited for demonstrating the benefits of storage in managing daily fluctuations in demand and renewable generation (*Güney, S, M., et al., 2017)*. For instance, such a system could effectively capture excess solar power generated during midday and release it during the evening peak demand period, thereby aligning energy availability with consumption patterns. This capability not only enhances the economic dispatch of generation assets but also maximizes the environmental benefits by ensuring that renewable energy contributes a larger share of the energy mix.

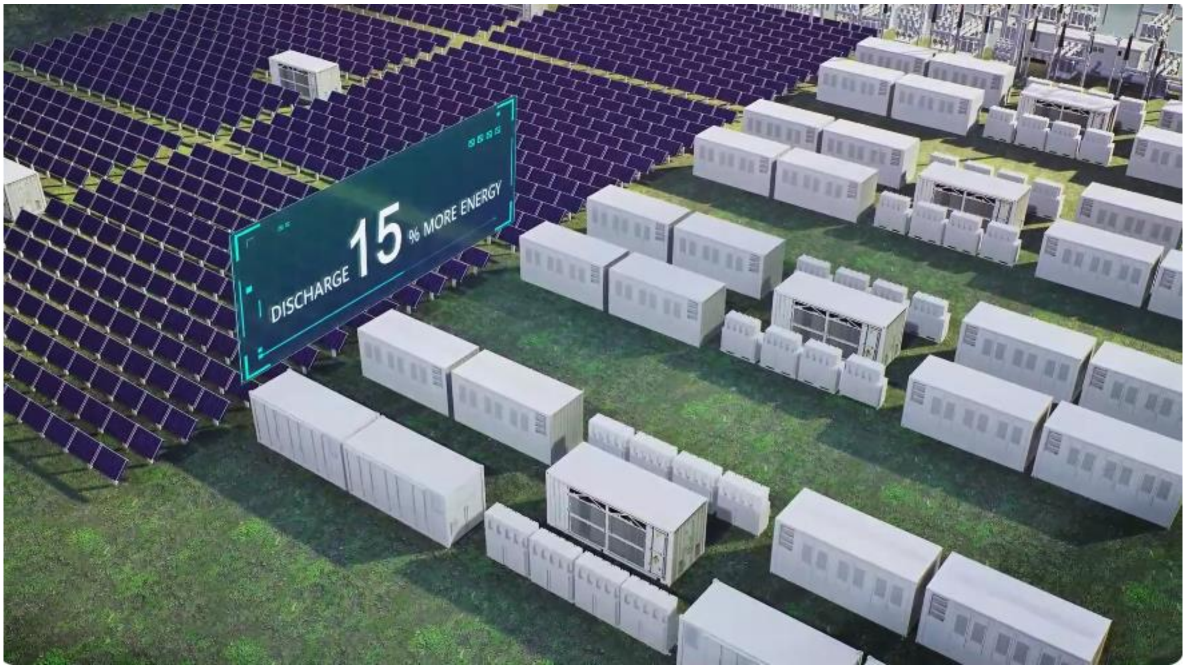


Figure 22 Huawei's example of a coupled PV and BESS Utility-scale system. (Huawei, 2023)

Models like the one developed for Mexico's power system, which incorporate detailed representations of generation assets, network topology, and demand profiles, provide a robust framework for evaluating the impact of energy storage on system operations (example of PV + BESS coupled configuration on *Figure 22*).

The integration of energy storage, particularly through utility-scale BESS, into power system optimization models offers a multifaceted solution to the challenges posed by the increasing penetration of renewable energy sources. A BESS enhances grid stability, operational flexibility, and the economic efficiency of power systems while contributing to the reduction of carbon emissions. The case of a 2257 kWh and a PCS of 2500 kW illustrates how targeted deployment of energy storage can optimize system performance, lower the total cost of dispatch, and facilitate a cleaner, more sustainable energy future.

3.4.3 The selected BESS System for Modelling

The BESS selected is designed for high-density energy storage, leveraging lithium-ion battery technology, and is encapsulated within a modular, scalable containerized solution. The system is assembled by 18 battery modules grouped into racks within each container, 7 battery racks per container (each container includes multiple racks, each containing several modules and connected to a shared Power Distribution Unit) resulting in a total power capacity of 2257 kW. For the purposes of this research, a BESS system composed of 10 modular containers is modelled, each equipped with a PCS rated at 2500 kW, resulting in a total system capacity of 25 MW. This rating reflects the maximum discharge power over a 4-hour duration, corresponding to a total energy capacity of approximately 100 MWh.

This particular BESS was selected due to its commercial availability, scalability, and alignment with grid-scale applications already under deployment globally. The Huawei LFP-based system offers high energy density, modular integration, and proven performance in renewable support applications, making it a representative and technically appropriate choice for modelling future BESS deployments in Mexico. Huawei has been awarded with phase 2 of the Puerto Peñasco project by CFE (CFE, 2024).

The physical configuration of this BESS is modular, consisting of multiple battery containers each housing several battery racks. Each rack is equipped with battery modules and a Power Distribution Unit (PDU). The modularity facilitates scalable deployment and ease of maintenance.

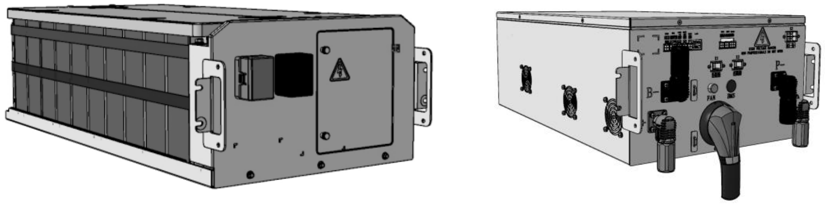


Figure 23 Huawei's Battery cell and PDU (switch and protection circuits). (Huawei, 2023)

The battery cells within the modules are of the lithium iron phosphate (LFP) type, which is known for its safety and long lifecycle, significantly enhancing the reliability and longevity of the BESS. The individual battery modules, assembled in a series or parallel configuration, integrate voltage and temperature acquisition with a Battery Management Unit (BMU) for real-time monitoring and management. The BMU is central to ensuring the operational health of the battery by managing parameters like state of charge (SOC), state of health (SOH), and cell balancing.

SPEC	Units	Parameter
Battery Module		
Rate of Charge and Discharge C-rate		0.5
Type of Cell		Lithium iron phosphate
Nominal energy	kWh	17.92
Nominal Voltage	V	64
Nominal Power	kV	8.96
Voltage Range	V	56-64
Cooling Sytem		air
Battery Rack		
Rate of Charge and Discharge		0.5P
Type of Cell		Lithium iron phosphate
Nominal energy	kWh	322.56
Nominal Voltage	V	1152
Nominal Power	kV	161.28
Voltage Range	V	1008-1314
Cooling Sytem		air

Table 12 Technical Specifications for the Battery Module and Battery Rack of the BESS. (Huawei, 2023)

The main power configuration includes a Power Conversion System that interfaces with the grid and converts AC to DC (and vice versa), ensuring compatibility with the grid's voltage and frequency standards. The PCS is crucial for the integration of the storage system with the grid, enabling applications such as peak shaving, load leveling, renewable integration, and grid support services. Commercial-grade systems typically exhibit round-trip efficiencies between 96–98%, depending on inverter design and cooling system performance (IRENA, 2022).

Figure 24 Empty Battery rack (left) and full rack (right) with battery modules. (Huawei, 2023)

Each main component of the BESS, from the battery cells to the PCS, plays a specific role in the overall functionality of the system:

- Battery Cell: The fundamental unit of energy storage, providing high-density, safe, and long-duration storage capacity.
- Battery Module: A cluster of battery cells packaged together for higher voltage and capacity. Modules allow for the flexibility of system design and ease of replacement or expansion.
- Battery Rack: Houses several battery modules and includes integrated cooling and management systems to ensure optimal operating conditions.
- Battery Container: The physical enclosure that houses racks, providing environmental protection and aiding in the thermal management of the system.
- Power Distribution Unit (PDU): Manages the flow of electrical power within the BESS, ensuring safe distribution and disconnection when necessary.
- Battery Management System (BMS): The brain of the BESS, monitoring and controlling cell-level operations, ensuring safety, and optimizing performance.
- Power Conversion System (PCS): Converts DC from the batteries to AC for the grid and vice versa, enabling energy storage to support various grid services.

The system's design incorporates safety and operational features such as fire suppression systems and emergency disconnects, ensuring compliance with stringent safety standards.

Additionally, the system's smart management capabilities are designed to reduce external energy consumption, indicating a self-sustaining operational approach that contributes to the overall efficiency of the BESS.

3.4.4 Modelling Results for the Integration of BESS technology

This section presents the modelling results of incorporating Battery Energy Storage Systems into the optimal dispatch framework. The aim is to evaluate how BESS integration can improve system performance by reducing dispatch costs, enhancing the utilization of renewable energy, and lowering carbon emissions.

3.4.4.1 Nodes with High Renewable Energy Capacity

For this model run, Node 18, located in the Noreste (Northeast) region, is ideal as a case study for the deployment of a Battery Energy Storage System (BESS) and its potential impacts on dispatch cost and carbon emissions.

Node 18, which corresponds to Valles Region, exhibits a maximum demand of 231.1226 MW. This node is part of a control region where renewable resources are available but are not fully utilized due to the variability of renewable generation and the limitations of the current grid infrastructure. This can be demonstrated by the unusually high levels of curtailment in the are reported by the grid operator (CENACE, 2023). The integration of BESS at Node 18 could serve multiple roles, each contributing to lower dispatch costs and carbon emissions.

The maximum demand value at Node 18 suggests that during peak hours, the local generation or the surrounding network needs to supply a substantial amount of power. If the local generation is primarily from high-cost fossil fuel sources, peak times can lead to high operating costs. BESS can store energy during off-peak periods—when renewable energy production may exceed demand and wholesale electricity prices are generally lower—and discharge it during peak demand, reducing the need to purchase or generate expensive peak energy.

When the solar generation potential in the Noreste region is high during midday, but the demand is not at its peak, BESS could absorb the excess solar energy. Then, in the evening, when the demand rises and solar generation drops, the stored energy can be released, thus avoiding the ramp-up of gas-fired plants, which is a more costly and carbon-intensive operation.

In terms of Carbon Emissions, Node 18 would benefit from BESS through the increased utilization of renewable energy. By storing surplus renewable energy, BESS ensure that the clean energy generated does not go to waste. For instance, if wind patterns at night result in high wind power output when the demand is low, BESS can store this surplus. Consequently, the need for carbon-emitting generation sources during higher demand periods is reduced as the stored renewable energy is used instead.

Node 18 has interconnections to Norte and Central regions. BESS at Node 18 could also facilitate regional energy balancing, providing stability across the interconnected system and potentially reducing the need for additional infrastructure investment in transmission lines that would otherwise be required to handle peak loads. Node 18 was selected as the Node for incorporating BESS.

The results for adding 10 systems of 2257 kWh and a PCS of 2500 kW to Node 18 are shown below:

Technology	Modelled Generation (MWh)	Power Capacity (MW)	Installed Capacity	Available Capacity	Capacity Usage (%)
Oil	129997	5417	11522	9218	59%
Hydro	236406	9850	12443	9954	99%
Gas	346913	14455	25674	20539	70%
Biomass	6629	276	603	482	57%
Solar	7697	321	976	321	100%
Wind	22238	927	1587	927	100%
Coal	53684	2237	5378	4302	52%
Geothermal	14522	605	903	722	84%
Nuclear	25368	1057	1510	1208	88%
Thermal	381	16	2580	2064	1%

Table 13 Inflexible Total Modelled Generation by the mix of Technologies for the 31st January 2023. Case Study: Incorporating 10 x 2257 kW BESS (with 4-hour discharge duration, totalling approximately 100 MWh) and 2500 kW PCS to Node 18. (Own elaboration, modelled)

The flexibility that the BESS system incorporates into generation mix is evident. Oil and Gas generation are not the technology selected to react to changes in demand, but rather it gives opportunity to other Hydro facilities to attend those surges in demand. Oil decreased the capacity usage from 63% to 59% whilst Gas from 71% to 70%. Hydro Installed capacity was almost maximized and the results for total cost of dispatch and carbon emissions is shown below:

	Base Simulation	BESS Renewable	Change	%
Total Variable Cost of Dispatch (MXN)	22,683,616	22,268,614	415,002	2%
Total CO_2 of Dispatch (Kg of CO_2 eq.)	348,707,632	333,679,815	15,027,817	4%

Table 14 Nodal comparison of Cost and Emissions in Base Case simulation vs BESS Incorporation to Node 18. (Own elaboration, modelled)

The incorporation of Battery Energy Storage Systems into the energy mix at node 18 has led to significant improvements in both economic and environmental metrics, as demonstrated by the results from the base simulation versus the BESS renewable scenario.

Economically, the variable cost of energy production and distribution saw a decrease from $22,683,616 in the base scenario to $22,268,614 with the addition of BESS. This reduction, amounting to $415,002 or a 2% decrease, highlights the cost-effectiveness of integrating BESS into the system. BESS can store excess energy during periods of low demand and release it during peak demand times. This not only flattens the demand curve, reducing the need for expensive peaking power plants, but also allows for more efficient use of renewable energy sources (allowing grid operator to lower high-curtailment levels) by mitigating their intermittency. The economic benefits are clear, as BESS helps in reducing operational costs by optimizing energy production and consumption patterns.

From an environmental perspective, the impact of adding BESS is even more pronounced. The CO_2 emissions associated with energy dispatch at node 18 saw a substantial reduction, moving from 348,707,632 in the base scenario to 333,679,815 in the BESS renewable scenario. This reduction of 15,027,817, or 4%, in CO_2 emissions underlines the environmental advantage of deploying BESS. By enabling a higher penetration of renewable energy sources, BESS directly contributes to the reduction of greenhouse gas emissions. The stored energy in BESS, primarily derived from renewable sources, can be dispatched during times of high carbon intensity on the grid, thereby decreasing the reliance on fossil-fuel-based power generation and consequently reducing CO_2 emissions.

3.4.4.2 Fossil Fuel Dominated Nodes

In Locations like Node 32, Poza Rica with a highly intensive Fossil generation, a storage system could dramatically modify the generation profile of power plants there. The technical essence of BESS lies in its ability to store energy during periods of low demand or high renewable generation and discharge it during peak demand. For a substantial facility like Veracruz Oil 2100 MW plant, integrating BESS could enable a more flexible and responsive operation. Typically, plants of this scale, especially those relying on fossil fuels, operate in a less dynamic fashion, primarily due to the challenges in ramping up and down in response to the fluctuating demand and the availability of renewable energy.

By deploying BESS, the plant can shift towards a more balanced generation profile. During times when demand is low or renewable energy supply is high, excess energy can be stored rather than curtailing renewable generation or operating fossil fuel generators at inefficient low loads. Conversely, during peak demand, stored energy can be released, reducing the need to ramp up fossil fuel generation. This capability not only enhances the plant's operational flexibility but also significantly reduces fuel consumption and associated carbon emissions.

The environmental benefits of integrating BESS at such a scale are substantial. The reduction in reliance on fossil fuels for peak demand management directly translates to lower carbon emissions. Moreover, the efficiency gains from operating the plant closer to its optimal capacity reduce the overall carbon footprint per unit of electricity generated.

Economically, the adoption of BESS can lead to considerable cost savings. The ability to store and release energy on demand mitigates the need to operate costly peaking power plants, which often use more expensive and polluting fuels.

The results for adding 10 x 2257 kW BESS (with 4-hour discharge duration, totaling approximately 100 MWh) and 2500 kW PCS to Node 32 are shown below, in Table 15:

Technology	Modelled Generation (MWh)	Power Capacity (MW)	Installed Capacity	Available Capacity	Capacity Usage (%)
Oil	128317	5347	11522	9218	58%
Hydro	238014	9917	12443	9954	100%
Gas	346913	14455	25674	20539	70%
Biomass	6629	276	603	482	57%
Solar	7697	321	976	321	100%
Wind	22238	927	1587	927	100%
Coal	53684	2237	5378	4302	52%
Geothermal	14522	605	903	722	84%
Nuclear	25368	1057	1510	1208	88%
Thermal	381	16	2580	2064	1%

Table 15 Inflexible Total Modelled Generation by the mix of Technologies for the 31st January 2023. Case Study: Incorporating 2257 kWh BESS and 2500 Kw PCS to Node 32. (Own elaboration, modelled))

	Base Simulation	BESS Renwable	Change	%
Variable Cost (MXN)	22,683,616	22,196,674	486,942	2%
CO_2 of dispatch (Kg of CO_2 eq.)	348,707,632	332,211,423	16,496,209	5%

Table 16 Comparison of Cost and Emissions in Base Case simulation vs BESS Incorporation to Node 32. (Own elaboration, modelled)

For this simulation, the impact of Energy Storage is more evident, since it allows for a full usage of the Hydro resource, limits even more the generation of Oil in that node and achieves an additional 1% savings for Carbon Emissions without additional cost.

The incorporation of BESS at Node 32 results in a measurable improvement in both economic and environmental performance. The system achieves a 2.2% reduction in dispatch cost, equivalent to approximately MXN 494 million, and a 3.4% reduction in CO_2 emissions. This improvement occurs without additional renewable capacity, highlighting the value of storage for optimizing the use of existing assets.

3.4.5 Sensitivity of BESS Size on System Performance

To assess the impact of BESS configuration on system performance, a sensitivity analysis was conducted by varying both the power and energy capacity of the storage system. This approach enables a structured comparison of how different levels of investment in energy storage affect the economic and environmental outcomes of the dispatch model. The analysis includes four scenarios: a base case with the BESS system studied in Section 3.4.4.2, a configuration of 2 identical BESS systems (each 25 MW / 100 MWh), a downscaled system (12.5 MW / 50 MWh), and an upscaled system (75 MW / 300 MWh), as summarized in *Table 17*.

Case	BESS Strategy	Capacity / Energy	Variable Cost (MXN)	CO_2 Emissions (kg of CO_2 eq.)
Base Scenario	BESS System	25 MW / 100 MWh	22,683,616	348,707,632
Scenario A	2 BESS Systems	2*(25 MW / 100 MWh)	22,196,674	332,211,423
Scenario B (Downscaled)	BESS half capacity	12.5 MW / 50 MWh	23,355,202	374,443,902
Scenario C (Upscaled)	BESS triple capacity	75 MW / 300 MWh	21,921,566	315,674,381

Table 17 Results of Modelled Sensitivity Scenarios for modifying BESS capacity at Node 32. (Own elaboration, modelled)

The results confirm a consistent trend: increasing BESS capacity leads to a measurable reduction in both variable generation costs and CO_2 emissions. Scenario C (triple capacity) demonstrates the highest impact, reducing variable cost by 762,050 MXN and emissions by 33 million kg of CO_2 equivalent relative to the base case. Scenario A, with two BESS systems, achieves a 486,942 MXN reduction in cost and lowers emissions by 16.5 million kg. In contrast, Scenario B, which assumes half the capacity, results in increased cost (+671,586 MXN) and higher emissions (+25.7 million kg), indicating that under-sizing the BESS system can be counterproductive. This suggests that economic benefits are less sensitive to capacity variations than environmental outcomes.

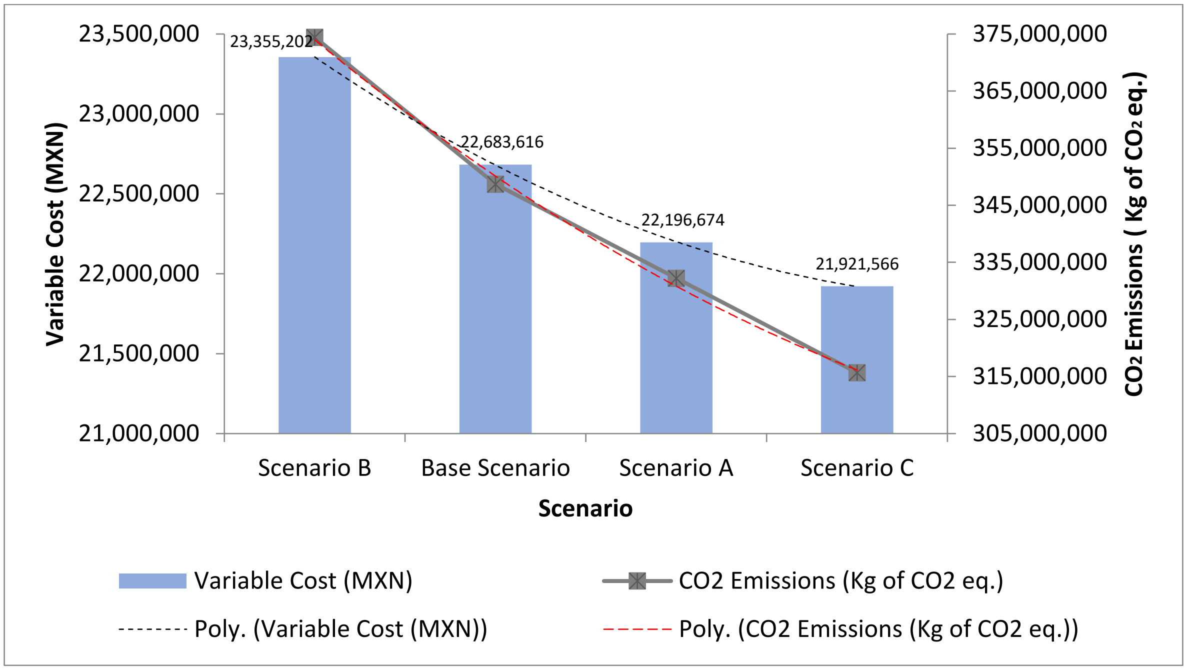


Figure 25 Sensitivity Analysis of four BESS Sizing Scenarios at Node 32 (Own elaboration, Modelled). BESS scenarios are ordered by increasing capacity.

In contrast, CO_2 emissions and variable costs exhibit non-linear responses to BESS scaling. When scenarios are ordered by increasing capacity (Scenario B to Scenario C), the trendlines in *Figure 25* reveal a concave pattern for costs and an almost linear but slightly concave pattern for emissions. This suggests that while increasing BESS capacity delivers consistent environmental improvements, the modelled cost benefits decline at a faster rate with scale. The results highlight the early efficiency of storage deployment in capturing low-cost generation and displacing high-cost fossil units; however, as BESS capacity increases, the incremental savings from further deployment appear to diminish within the scope of this model.

These diminishing returns should not be interpreted as a limitation of BESS itself, but rather as a function of the model's assumptions. The model captures short-term operational flexibility but does not fully account for broader system-wide benefits such as long-term capacity deferral, network reinforcement savings, or enhanced resilience. As such, the concave cost trendline may reflect the saturation of benefits within the modeled node rather than a hard limit in real-world applications. Meanwhile, the nearly linear emissions reduction supports the central argument of this thesis.

This chapter examined the integration of Battery Energy Storage Systems into an optimal dispatch modelling framework for the Mexican electricity network. By incorporating energy storage into the model, the analysis addressed key challenges associated with high shares of renewable energy, such as variability, limited dispatchability, and peak demand pressures. The chapter demonstrated that modelling BESS within the dispatch framework provides a meaningful improvement in system flexibility, enhances the operational efficiency of existing generation assets, and enables a more effective alignment between supply and demand across time and space.

The modelling results presented in this chapter confirm the practical value of BESS in reducing system-wide operational costs and in lowering carbon emissions by enabling greater use of low-emission technologies such as hydro and solar. The analysis of selected nodes showed how storage supports system reliability and carbon mitigation simultaneously, reinforcing its strategic relevance in the context of decarbonization goals in emerging economies.

Chapter 4

Distributed Generation in Mexico: Case Study of a Hybrid PV and BESS System as a cost reduction solution for the Mexican Electricity Market

4. Distributed Generation in Mexico

This chapter will present how Distributed Generation can be an efficient mechanism to reduce the gap between a rapid growing demand and lack of infrastructure development. Building upon the modelling foundations presented in *Chapters 2* and *3*, this chapter shifts the focus to a real-world application of distributed energy resources in Mexico. While earlier chapters explored energy system modelling trends and environmental optimization frameworks, this chapter applies those insights to a case study that combines hybrid PV and BESS as a cost-effective distributed generation strategy. The aim is to assess how such systems can address infrastructure gaps and policy constraints, particularly under the current regulatory framework. This case study also serves as a bridge to the proposed dispatch model in *Chapter 7* by illustrating key techno-economic variables that influence system design and value creation.

4.1 Mexico's Energy Reform impacts on Distributed Generation

Under the new energy reform, Distributed Generation and BESS (Battery Energy Storage Systems) have been obliged to comply with the following regulation *(LIE, 2014*) to obtain operation permits: Power plants with capacity below 0.5 MW do not require a generation permit (Exempt Generators) from CRE (Regulatory Energy Commission). To sell energy to the power market, Exempt Generators must be represented by a Supplier. End users or loads are allowed to satisfy totally or partially their electricity needs through isolated supply (self-generation), which can be either off-grid or connected to the distribution or transmission networks. Recent modifications (DOF, 2014) to isolated supply include restricting the possibility of selling excess production to the grid. These conditions were outlined under the modifications to the Ley de la Industria Eléctrica and related CRE resolutions, restricting third-party access to the distribution grid, particularly for DG systems not owned by the final offtaker and established stricter requirements for net injection to the grid (DOF, 2021; CRE, 2022). In order to sell excess energy, the investment and control of the generation assets have to be performed by the same economic group as the end consumer.

Clean Energy Certificates (CEL) will also be an important consideration for the new proposed scheme in Baja California, since a CEL is awarded to certified generators at a conversion factor of 1 CEL = 1MWh of clean energy generation. Currently, one CEL is priced at 4 USD to 7 USD. As of 2023, CEL prices in Mexico have shown volatility, ranging between 4 and 7.1 USD per certificate depending on compliance cycles and oversupply in the market (CRE, 2023; SENER, 2023). All clean energy generation facilities under the Power Industry Act can credit CELs but require certification from a verification unit. In the case of cogeneration, in order to receive CELs, cogeneration must be evaluated and certified as efficient cogeneration. Efficient co-generators receive CELs for a portion of their generation. CELs produced from clean energy power plants that are not certified are accumulated by CRE and are transferred at the end of year to all obliged participants (load-serving entities and large consumers).

Distributed Generation is defined as the power generation interconnected to a distribution network with high concentration of loads. It can be located within the facilities of the load or outside of them. In Mexico, according to the LIE (Electrical Industry Law) (*LIE, 2014*), capacity must be below 0.5 MW and an interconnection request must be submitted to the distribution company. The market is monopolized by the CFE, there is only one distribution company: CFE Distribution Services. For rooftop solar systems, a net metering or net billing contract must be signed with CFE and requires a change of meter. There are two possible schemes for this. Net metering: surplus energy injected to the grid is not remunerated but accumulated for future period use. Net billing: surplus energy injected to the grid is paid according to the marginal price of the node.

A cost-benefit analysis must be performed in order to evaluate the convenience of certifying each unit as a clean-energy generator. If the generator capacity is too low, it might be too expensive to certify the asset.

In the latest version of the reform (LIE, 2018), there is no clear distinction between storage equipment associated to generation or independent storage facilities. Therefore, stand-alone BESS must obtain a generation permit and operate as generator. Behind-the-meter storage is permitted for distributed generation as long as energy injected to the grid does not exceed 0.5 MW capacity restriction. The CENACE (National Center for Energy Control) has requested large-scale solar projects in Baja California Sur's isolated grid to install batteries (*García, J., 2023*) as an early example of the trend of the market. There is still no clear regulation defined for energy storage regarding:

- Compensation for grid services not in place (virtual inertia).
- Interconnection requirements and standards are not clear.
- Unclear whether large power storage facilities will be developed freely by market players or through a planned mechanism (e.g. auction).
- Sizing of the systems capped to match generation capacity (DG).

These regulatory gaps significantly impact the viability and scalability of energy storage projects in Mexico. Without defined mechanisms for compensating grid services that BESS can provide—such as black start capability, virtual inertia, and grid-forming or grid-following support—developers lack clear revenue streams to justify investment. The absence of standardized interconnection procedures further increases project uncertainty and soft costs, limiting the ability of storage systems to participate in both utility-scale and distributed applications. Furthermore, uncertainty around whether storage can be deployed independently or only as an add-on to generation restricts innovation and business model diversification.

Beyond utility-scale roles, storage systems in distributed generation configurations can deliver clear benefits through peak shaving, time-of-use energy arbitrage, and enhanced power quality—particularly for commercial and industrial users. However, the lack of regulatory clarity around behind-the-meter dispatch rights, net-metering interaction, and certification for Clean Energy Certificates also affects these applications. As a result, many distributed BESS opportunities remain underutilized, especially in areas with high demand variability or constrained grids.

This fragmented policy environment has already contributed to Mexico lagging behind other regional and global leaders. For instance, California ISO and Chile's Coordinador Eléctrico Nacional have implemented frameworks that clearly define market participation rules and compensation for energy storage, which has accelerated deployment across both grid-scale and distributed segments (CAISO, 2022; Coordinador Eléctrico Nacional, 2023). In contrast, Mexico’s current limitations—including capacity caps linked to DG systems and the lack of a regulatory identity for standalone storage—continue to constrain the full exploitation of BESS, even in critical areas like Baja California Sur where grid reliability is a strategic concern (Kindle, 2015).

4.2 Energy Investment Climate and Policy Trends in Mexico

Mexico is ranked as one of the best places to invest in LATAM (Demoro et al., 2021), achieving a high power-sector score even when utility-scale projects are paused. Recent policy changes have led to the suspension of permits for several large-scale wind and solar plants, with over 5,000 MW installed development (MBN, 2024). Additionally, foreign investment has slowed due to regulatory uncertainty and changes to dispatch rules favouring state-owned assets (International Trade Administration, 2023). Although utility-scale investment is currently limited, attractive opportunities remain in the distributed generation market. Further market characteristics are shown in Table 19.

Investment Attractiveness(	**Mexico**	**Colombia**	**Peru**	**Brazil**
Global Rank (max. 136)	52	27	63	31
Global Score (max. 5)	1.72	2.03	1.66	2.01
Power Sector Investment (max. 5)	1.86	2.16	2.02	2.29
Corruption Index (100 = no corruption)	31	39	36	38

Table 18 Investment attractiveness according to (Demoro, A., et al., 2021) and (Transparency.org, 2022) (S&P, 2022)

Mexico’s annual GDP growth in the last decades has settled around 2% on average. The country is still expected to grow at stable rates around 2%. Credit rating has been fluctuating between BBB, BBB-, BBB+ for the past years, but in recent years BBB- has been ratified in the past two assessments. Some economic metrics can be observed in *Table 20*.

Year	GDP growth %	Population Millions	GDP per capita (US$)	Credit rating	Energy Intensity (kWh/p)
2020	-8.2	125.9	8,923	BBB-	2,310.1
2021	4.8	126.7	9,255	BBB-	2,286.7
2022*	*1.9*	*127.5*	*9,431*		*2,636.7*
2023*	*2.1*	*128.4*	*9,629*		*2,700.5*

Table 19 Mexico´s main Macroeconomic factors including Credit Rating (S&P, 2022)

4.3 Installed Capacity and Electricity Demand in the Context of Distributed Generation

Installed capacity in Mexico is heavily dominated by CCGT and Hydro, with a total 53.6% of the overall capacity. Wind and PV only sum up to 14% of the installed capacity, but with expectations for rapid growth in the country from 2025 onwards.

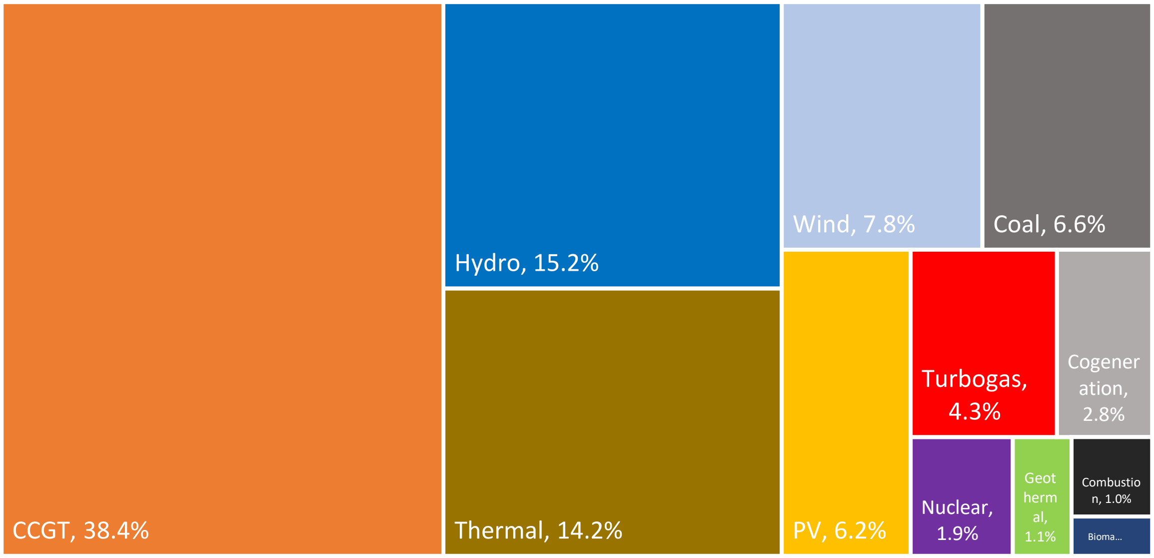


Figure 26 Different technologies Real Installed Capacity by the end of 2021. (SENER, 2023)

In terms of electricity consumption and demand, the country's total electricity consumption in 2021 was 322 TWh (37.9 GW of active capacity during the year) (*SENER, 2023*). Average demand fluctuates depending on the weather and the use of air-conditioning and cooling systems. In 2021, the lowest demand level was of 20.4 GW, observed on the 24th of December, whereas the maximum demand level reached 45.2 GW on 6th of June (*SENER, 2023*).

According to the National Electric System Development Program published in 2023 by Mexico's Ministry of Energy, electricity demand growth is projected under three distinct planning scenarios beginning in 2024. The low-growth scenario anticipates a 2.3% annual increase, the base case estimates a 2.7% rate, and the high-growth scenario forecasts 2.9% annual growth through 2038.This implies that by 2030, Mexico's annual electricity consumption will surpass 400 TWh. The regions of interest, where most of the Commercial and Industrial users are located represent approximately 60% of the total electricity consumption.

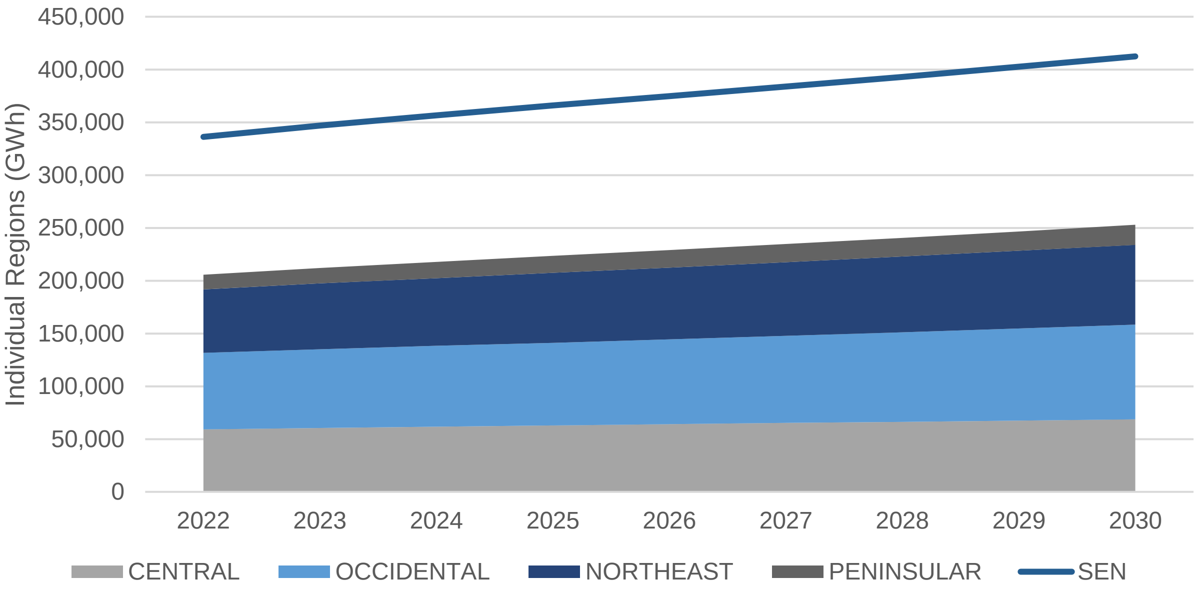


Figure 27 Expected Demand Growth until 2030 for the regions of Interest. (Own elaboration, data SENER)

The case study is situated in the Peninsular control region. This region is expected to grow at an annual electricity demand rate of approximately 3% between 2022 and 2030, slightly above the national average for the Mexican electricity system (SENER, 2023). This sustained growth opens opportunities for distributed generation to gain market share, particularly as fossil fuel-based generation declines in alignment with national decarbonisation targets and the gradual phase-out of aging thermal plants. Distributed generation is defined as electrical energy generated which is interconnected within a distribution circuit where there are several load centers. Distributed generation can be localized inside or outside the load centers. From 2017 to 2020, according to the CRE and CFE (*CFE, 2023*) (*ASOLMEX, 2022*), the interconnection contracts registered have seen an increase of approximately 21%, this means 35,483 additional contracts from 2017 to date. Similarly, installed capacity has grown 22% in the same period of time, growing from 212 to 468 MW in 2020.

The Peninsular region was selected due to a combination of structural and resource-specific factors. Notably, it is not physically interconnected to the National Electric System, which limits its access to backup capacity from other regions and makes it more susceptible to supply constraints (SENER, 2023). As a result, the region operates with narrower reserve margins and reduced system flexibility, heightening the need for localized, reliable sources of electricity. Furthermore, the Peninsula ranks among the highest in solar irradiation levels nationally, making it a prime candidate for distributed photovoltaic generation (IRENA, 2021). These conditions together present a compelling context for hybrid PV and storage solutions that can reinforce grid stability, mitigate local reliability risks, and reduce dependence on fossil-fuel-based peaking generation during high-demand periods.

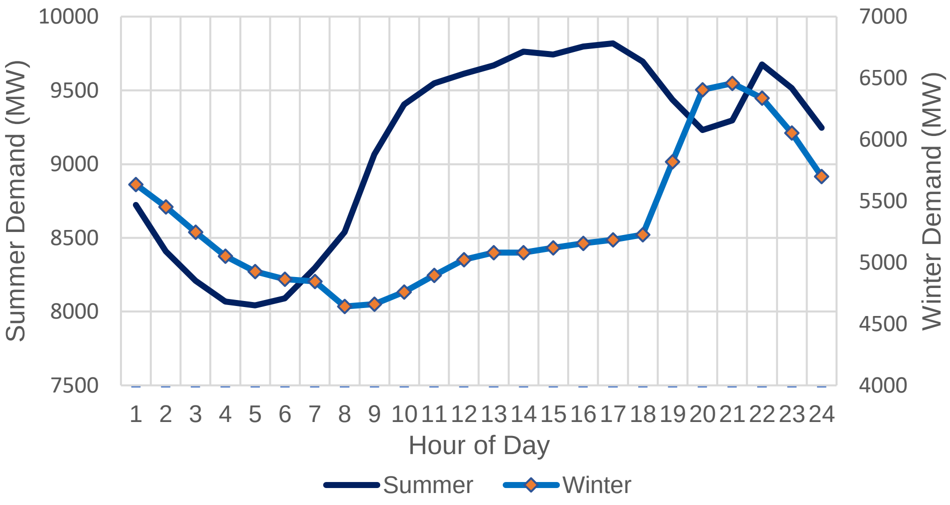


Figure 28 Representative average Daily Demand (Peninsular), summer vs winter months. (Own elaboration, data SENER)

Electricity demand in the Peninsular region varies between 4.5 GW and 5.5 GW in winter, and 8 GW and 9.7 GW in summer. Peak demand is observed around 16:00 hours in summer and 20:00 hours in winter. A distinct seasonality in power usage is evident, with the demand curve for summer showing significantly higher peaks compared to winter. The summer months, characterized by higher temperatures and increased use of cooling systems, consistently register elevated electricity consumption. Peak demand during summer is observed in the late afternoon and early evening hours, which aligns with the hottest part of the day when air conditioning and other cooling appliances are in maximum use.

In contrast, the winter months show a more subdued demand for electricity. This suggests that the peninsular region, likely having a warmer climate, does not experience the same intensity of cold as it does heat, hence the heating requirements, which would typically elevate winter power consumption, are not as pronounced. The peak during winter, while lower than in summer, occurs around the same time of day, possibly indicating a pattern of daily human activity that leads to increased energy use, regardless of the season.

Figure 28 also indicates two periods of increased demand during the day for both seasons – one in the morning and another in the late afternoon to evening. These periods likely correspond to routine daily activities such as starting the workday and returning home, cooking, and using appliances more frequently. The morning peak in winter is relatively closer to the evening peak when compared to the summer months. This could be attributed to the shorter daylight hours in winter, which may lead to earlier starts for various activities that require electricity.

4.4 Commercial, Industrial & Tourism market

Commercial, industrial & tourism electricity demand in Mexico is located in the industrial corridors of the country along touristic areas. This includes manufacturers in border cities such as Ciudad Juárez, Reynosa and Matamoros; large industrial groups in the metropolitan areas of Monterrey, Saltillo and the State of Mexico; new automotive and aerospace industry in San Luis Potosí and the Bajío corridor; large hotels and airports in touristic points such as Baja California Peninsula and the Mayan Riviera.

Mexico has more than 350 industrial parks located over 24 states (*INEGI, 2024*) but there is a large concentration of this demand in central parts of the country. Large clusters of automotive and aerospace companies (Tier 1, 2 and 3) have settled here, with newcomers arriving at high rates. These companies require reliable power supply to cope with blackouts and voltage peaks. Hotels in Baja California base their business models on high quality service, so they always need low cost and reliable energy.

Figure 29 Distributed Generation Installed Capacity. Size of the ballons represents the size of the Installation. (Own elaboration, data SENER)

At the end of 2020, CFE Basic Service Supply had over 45.6 million users (*CFE, 2023*) along the country, of which, industrial commercial and hotel users represented just over 1/10 of the total (4.7 million users) (*INEGI, 2024*). However, in terms of electricity consumption, C&I users represented 57% of the total, as shown in the following *Table 21*:

Sector	Number of Clients	Total Consumption (GWh)	Average consumption (kWh/year)
Residential	40,610,337	68,977	1,698
Commercial	4,294,233	13,745	3,200
Services	176,300	3,961	22,467
Agriculture	133,605	14,009	104,853
Industrial & Tourism	411,657	105,872	257,184

Table 20 Potential Market for DG systems in the MEN. (Own elaboration, data ASOLMEX)

4.5 Distributed Generation market and investment trend

In the last two years, Mexico has added almost 500 MW of rooftop solar capacity per year (*SENER, 2023*). Total distributed generation capacity in the country has surpassed 2 GW.

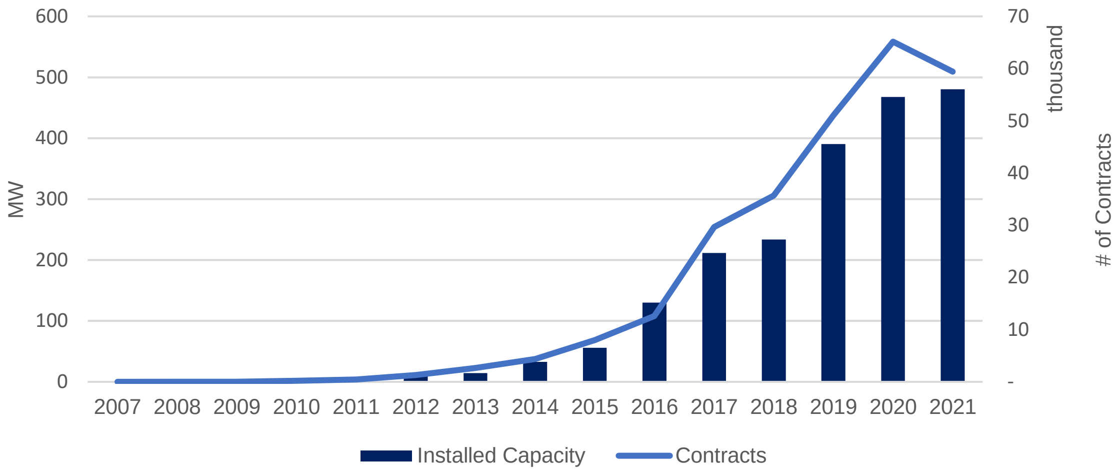


Figure 30 New Contracts and New Capacity installed per year 2007 - 2021. (Own elaboration, data ASOLMEX)

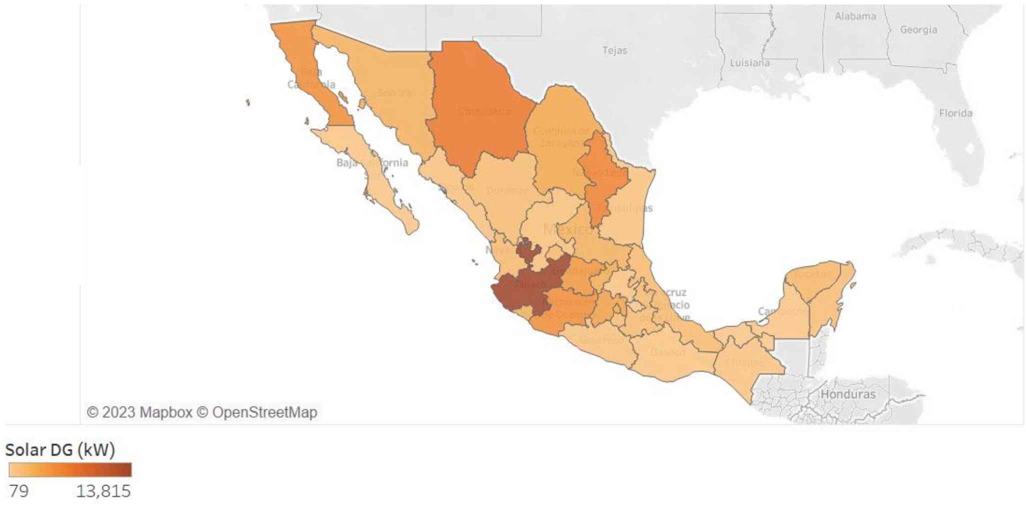


Figure 31 Distributed Generation installed capacity by Region in Mexico. (Own elaboration, data SENER)

According to the Mexican Solar Association (*ASOLMEX, 2022*), there are over 2,000 companies dedicated to the solar distributed generation market in Mexico. Most of them are focused on installations for residential and small commercial units. More than 90% of the distributed generation contracts are below 10 kWp of capacity. The most common compensation scheme is net metering, which represents 87% of total contracts *(ASOLMEX, 2022*).

Total installation costs (excluding value-added tax) and O&M costs (excluding insurance) reported by (*ASOLMEX, 2022*) are shown in the following *Table 22*:

Price (USD/W_p)	**100-250 kW_p**	**250-500 kW_p**
Minimum	0.79	0.79
Median	0.90	0.85
Maximum	1.01	0.91
O&M	0.04	0.04

Table 21 Unitary cost of installation depending on capacity installed range. (Own elaboration, data ASOLMEX)

Asolmex (*ASOLMEX, 2022)* also reports that the most used solar module brands are: Trina Solar (17%), Risen Energy (13%), Canadian Solar (13%), Seraphim (9%) and Longi (9%). With respect to inverters, the most used brands are Fronius (23%), SMA Solar (22%), Solis (21%), ABB (12%) and Sungrow (6%).

4.6 Energy Storage in DG projects for Mexico

The Energy Storage market in Mexico is in development phase. Lack of sufficient regulatory clarity, specifically for large-scale storage, has deterred its evolution. Current developments are concentrated on behind-the-meter solutions for CI & T (Commercial Industrial & Tourism) users for energy quality/backup services or peak-shaving & load shifting.

Company name	**OEM**	**Developer**	**Sponsor**	**O&M**
Tesla	☒	☐	☐	☐
Huawei	☒	☐	☐	☐
CHINT	☒	☒	☐	☐
Fluence	☐	☒	☒	☒
FRV	☐	☒	☒	☒
On.Energy	☐	☒	☒	☒
Enlight	☐	☒	☒	☒
Solar 180	☐	☒	☐	☒
Quartux	☐	☒	☐	☒

Table 22 Companies participating in the DG market according to ASOLMEX. (Own elaboration, data ASOLMEX)

This trend reflects the emergence of a foundational ecosystem to support distributed generation and hybrid storage systems at scale in Mexico. While the sector is still nascent, increasing participation from international OEMs, developers, and integrators points to a growing market structure. According to ASOLMEX (2022), distributed energy resources, particularly battery storage paired with solar PV, are gaining traction in the commercial and industrial sectors, as companies seek greater energy reliability and cost stability. This early-stage infrastructure development is a necessary condition for enabling broader deployment of distributed systems and creating the technical and operational basis for a more efficient and decentralized electricity market.In recent years, 2017 – 2021, the sales registered by Distributed Generation companies has followed an incremental profile. Enterprises reported estimated sales of 19 mUSD, 44 mUSD, 58 mUSD and 62 mUSD, for the years 2017, 2018, 2019, and 2020 respectively (*ASOLMEX, 2023*).

Group	Installed Capacity Range (kWp)	Companies able to install that range of capacity
A	0 - 5	33%
B	05 - 15	50%
C	15 - 30	20%
D	30 - 50	10%
E	50 -100	10%
F	100 - 250	7%
G	250 -500	21%

Table 23 Range of Installed Capacity projects and Companies able to install those ranges. (Own elaboration, data ASOLMEX)

Out of the sample of companies that were used for the representative study by *ASOLMEX (2022*), half of the companies responded that they were able to do installations of the range 5 – 15 kWp. There is also high proportion of companies installing household systems. Only 21% of the companies in the study, responded that they had the infrastructure capabilities to install larger systems (250 – 500 kWp). This means that there is a wide range of companies with experience to install distributed generation and that the EPC (Engineering, procurement and construction) market prices will continue to decrease due to natural market competition.

Group	Range of installed capacity (kWp)	Cost for installation (USD/Wp)
A	0 - 5	1.24
B	5 - 15	1.14
C	15 - 30	1.08
D	30 - 50	1.04
E	50 - 100	0.93
F	100 - 250	0.9
G	250 - 500	0.85

Table 24 Cost of Installation depending on the range of capacity that has been installed. (Own elaboration, data ASOLMEX)

Cost for installation follows a pattern of economies of scales, where the cost is inversely proportional to the capacity installed. Bellow, we can see the cost for O&M which also decreases as the installed capacity increases. Table 24 and Table 25 are essential for understanding the current structure and maturity of the distributed generation market in Mexico, which directly supports the development of hybrid PV and storage systems. A strong base of installers and EPC providers with experience across varying system sizes indicates growing technical capacity and standardisation within the sector. This is particularly relevant for energy storage deployment, as the integration of batteries with PV systems often depends on existing project delivery capabilities and the economies of scale associated with full hybrid installations. The observed decline in installed cost per watt as capacity increases highlights a positive trend for larger, more complex systems that may incorporate storage. As the International Energy Agency (2022) notes, distributed energy resources are more likely to succeed when they are deployed within an ecosystem that supports both technological diversity and competitive pricing across complete system configurations.

Group	Range of installed capacity (kWp)	Cost for O&M (USD/Wp)
A	0 - 5	0.05
B	5 - 15	0.05
C	15 - 30	0.05
D	30 - 50	0.04
E	50 - 100	0.04
F	100 - 250	0.04
G	250 - 500	0.04

Table 25 O&M Cost given the range of capacities installed. (Own elaboration, data ASOLMEX)

	Reference capacity for cost estimations (kWp)						
Component	0 - 5	5 - 15	15 - 30	30 - 50	50 - 100	100 - 250	250 - 500
Panels	0.5	0.5	0.47	0.44	0.47	0.37	0.4
Inverter	0.25	0.22	0.19	0.22	0.15	0.15	0.17
Structures	0.22	0.21	0.13	0.12	0.12	0.14	0.14
Electrical Material	0.1	0.09	0.09	0.09	0.16	0.09	0.08
Man Power	0.11	0.11	0.1	0.1	0.1	0.1	0.07
Accesories	0.04	0.04	0.06	0.05	0.04	0.05	0.04
Additional Costs	0.07	0.07	0.08	0.07	0.07	0.1	0.09
UVIE - Electrical Installations Verification Unit	0.08	0.05	0.02	0.13	0.02	0.01	0.01
UIE - Electrical Inspection Unit	0.11	0.25	0.04	0.13	0.02	0.01	0.01

Table 26 Breakdown of cost (USD/kWp) for the different components of the system given the range of capacities installed. (Own elaboration, data ASOLMEX)

The previous tables show the data estimation inputs selected for the cost analysis presented in the following sections. Total CAPEX for a range of capacity installations can be calculated using the information in *Table 27*.

While the tables above focus on photovoltaic system components, it is important to note that battery energy storage costs are also considered in the overall hybrid system evaluation. For systems in the 250–500 kWp range, typical BESS costs in Mexico currently fall between 400 and 600 USD/kWh, depending on configuration, technology, and integration scope. These costs include battery modules, inverters, enclosures, and balance-of-system elements, though installation and controls may vary. A detailed breakdown of storage system CAPEX is presented later in Section 4.8.

4.7 Regulated tariffs in Mexico from de CFE

In Mexico, Commercial and Industrial users with demands below 1 MW are supplied electricity by CFE Basic Service Supply. Users with demands greater than 1 MW can become Qualified Users and contract their power supply with alternative suppliers.

Electricity tariffs charged by CFE Basic Service Supply are regulated by the Energy Regulatory Commission. The tariff category for each user depends on the region, tension level and demand of the load.

Tariff	Description	Tension level	Demand
PDBT	Low demand, low voltage	< 1 kV	≤ 25 kW
GDBT	High demand, low voltage	< 1 kV	> 25 kW
GDMTO	High demand, medium voltage, ordinary tariff	1 kV ≤ x < 35 kV	≥ 100 kW
GDMTH	High demand, medium voltage, hourly tariff	1 kV ≤ x < 35 kV	≥ 100 kW
DIST	High demand, sub-transmission level	35 kV ≤ x < 220 kV	Industrial
DIT	High demand, transmission level	≥ 220 kV	Industrial

Table 27 Different Tariffs for the Distributed Generation in Mexico. (Own elaboration, data CFE)

For purposes of this case study, the case study will focus on the GDMTH tariff, which is the most common electricity tariff found in large commercial facilities and small/medium-sized industrial loads. The tariff consists of various charges as shown in the following graph for the Peninsular region, where the Case Study is located:

Concept	Charge	Cost	Unit
Energy	Base	$0.8125	P$/kWh
	Intermediate	$1.5858	P$/kWh
	Peak	$1.8320	P$/kWh
Demand	Demand (capacity)	$370.09	P$/kW
T&D	Transmission	$0.1758	P$/kWh
	Distribution	$107.45	P$/kW
Other	Fixed charge	$277.76	P$/month
	CENACE's operation	$0.0074	P$/kWh
	Ancillary services	$0.0060	P$/kWh

Table 28 Breakdown of how the Electricity Tariff is broken down for the GDMTH. (Own elaboration, data CFE)

For the greatest part of the country, during workdays (Monday to Friday) 00:00 to 06:00 hours are considered Base hours. Peak hours fall between 20:00-22:00 hours in summer months and 18:00-22:00 hours in winter months. The remaining hours of the day are considered Intermediate hours. Saturday and Sunday do not have peak hours.

Variable charges are charged according to the monthly electricity consumption, whereas demand and distribution are charged according to the maximum demand (in kW) of the month, which is estimated as follows:

$$Demand = min\left\{Dmax_{month}, \left[\frac{Q_{month}}{24*d*FC}\right]\right\} \qquad \text{(Eq. 4.1)}$$

Where,

$Dmax$ = maximum demand of the month

Q = Electricity consumption

d = Days

FC = Load factor

The final electricity cost for a typical user varies depending on their consumption profile, level of demand and location in the country. Demand charge is relevant since it can represent around 35% of the total electricity bill, as shown *Figure 32*.

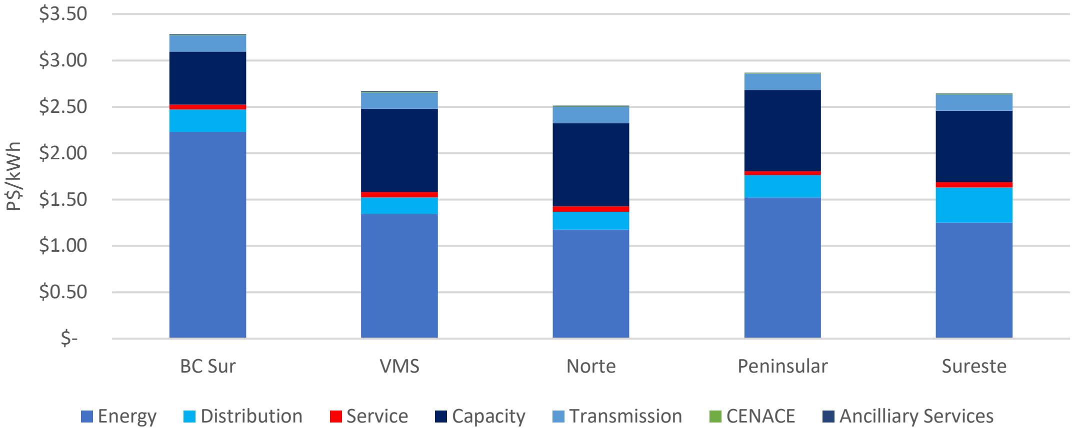


Figure 32 Breakdown of cost (GDMTH tariff) for the different components of the system given the range of capacities installed

Since the beginning of this political administration, regulated tariffs, including energy charges, have only been adjusted according to inflation. This provides visibility on the evolution of electricity costs for final users, however, variations in fuel prices for conventional generation must be absorbed by CFE Basic Service Supply.

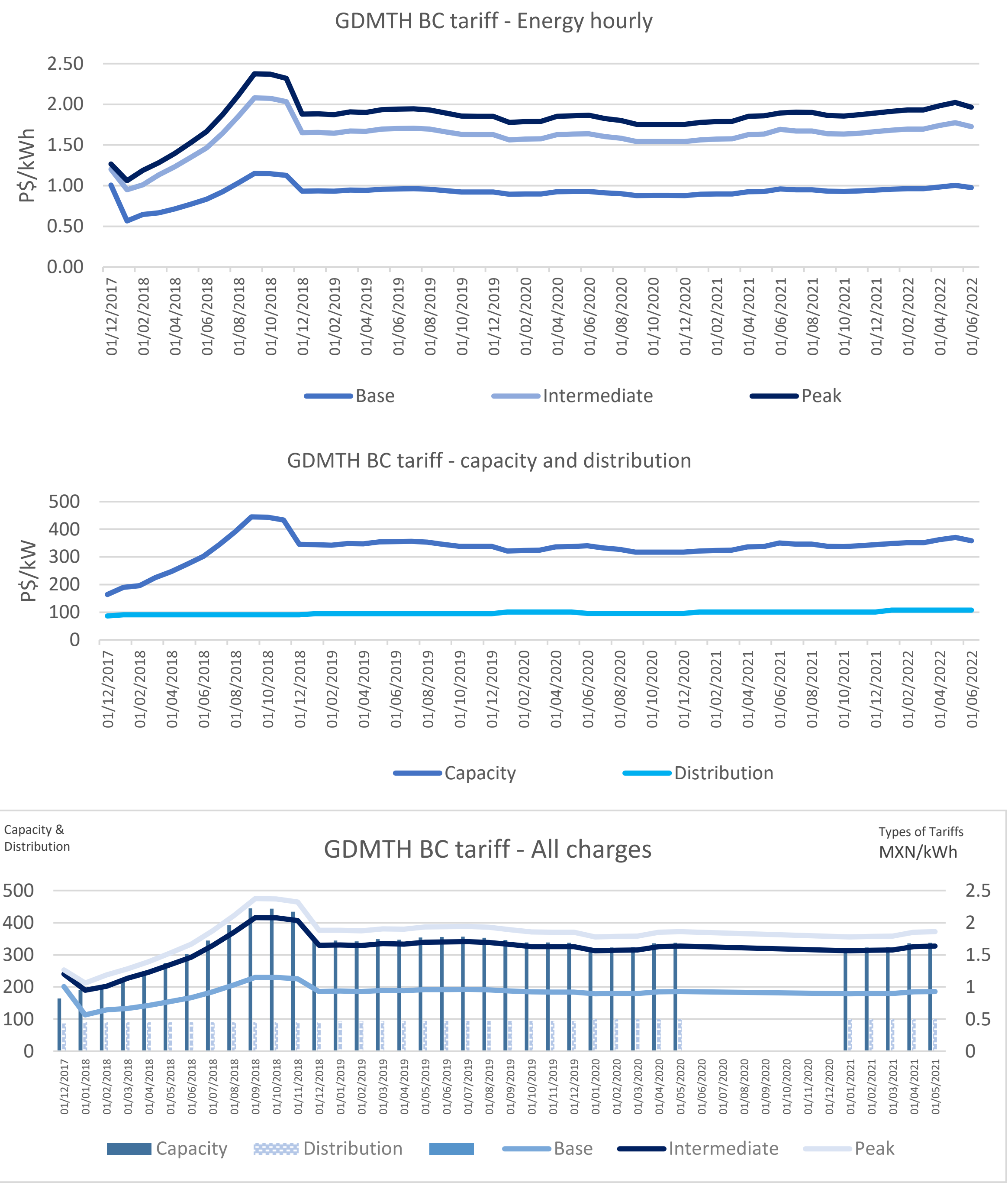


Figure 29 –CFE Basic Service Supply historical behavior for the tariff. (Own elaboration, data SENER)

Figure 30 shows that CFE tariffs for Baja California, in the Medium Voltage range for distributed generation, have remained stable for the most recent years. Therefore, we can imply that the development of this case study using this data as input information will deliver a comprehensive analysis.

4.8 Case Study: Economic Benefit (user-side) for BESS incorporation

The technical solution consists on a combined rooftop solar and battery storage system to reduce consumption during intermediate and peak hours. To avoid requiring a generation permit from the Energy Regulatory Commission, the distributed solar generation capacity is limited to 500 kWp.

The distributed solar generation at the site was estimated with PV Watts (*NREL PW, 2024*):

Concept	**PV Watts**
Solar irradiation	2,394.4 kWh/m^2/year
PV capacity	500 kW$_p$
Gross Yield	1,778 kWh/kW$_p$
Capacity factor	20.9%
System Losses	11.42%
Annual generation	831,153 kWh

Table 30 PV Watts simulation for the proposed system. (Own elaboration)

For purposes of this research analysis, we assume the net annual generation as the main input for the sizing of the hybrid system proposed. In the case of the battery, we assumed a solution for peak/load shaving, trying to maximize the size of the battery to cover the load, resulting in a battery size of 0.5MW/1MWh to reduce demand charges during summer months.

The sizing of the battery system was based on a combination of the site's daily load profile and the corresponding CFE tariff structure, as illustrated in *Figure 33* and *Table 34*. The PV + BESS system was designed to target peak shaving and demand charge reduction, particularly during late afternoon and early evening hours when the PV output declines, and electricity tariffs reach their highest levels. From the operational profile, it can be observed that the critical peak demand window occurs between approximately 18:00 and 20:00, requiring roughly 500 kW of dispatchable capacity to flatten the demand curve and reduce the adjusted load below the threshold that triggers the highest demand charges. A 1 MWh energy capacity allows the battery to discharge at 500 kW for two hours, covering the full peak window without depleting prematurely. This configuration also supports strategic charging during base tariff hours (e.g., midnight to 7:00 AM), where the electricity cost is as low as $0.8125 MXN/kWh and discharging during peak periods that exceed $1.8302 MXN/kWh, as shown in *Table 34*. The selection of this size therefore reflects a balance between technical performance, tariff arbitrage opportunities, and investment viability, optimizing both energy cost avoidance and capacity charge reduction without oversizing the system unnecessarily.

4.8.1 Financial assumptions

The estimated turnkey CAPEX for a 500 kWp distributed solar PV installation is the following:

Item	USD/W_p	Total (USD)	Total (MXN)
Solar modules	0.35	175,000	3,500,000
Inverters	0.10	50,000	1,000,000
Structures	0.10	50,000	1,000,000
Electric supplies	0.08	40,000	800,000
Labor	0.07	35,000	700,000
Verifying and inspection units	0.02	10,000	20,000
Other	0.04	20,000	400,000
EPC margin	0.09	45,000	900,000
Total Project	**0.85**	**425,000**	**8,500,000**

Table 31 Estimated CAPEX for the System. (Own elaboration, data ASOLMEX)

The estimated CAPEX for a BESS of 0.5MW/1MWh is:

Item	USD/Wh	Total (USD)	Total (MXN)
BESS	0.3715	371,500	7,430,000
Supplementary System	0.0390	39,000	780,000
Total Project	**0.4105**	**821,000**	**16,420,000**

Table 32 Estimated CAPEX for the DG BESS. (Own elaboration, data ASOLMEX)

Valuation for this kind of projects usually includes financing. For these projects, the government needs to incentivize the market by using an instrument which will allow this sector to make large investments which will benefit the whole Mexican Electricity Network.

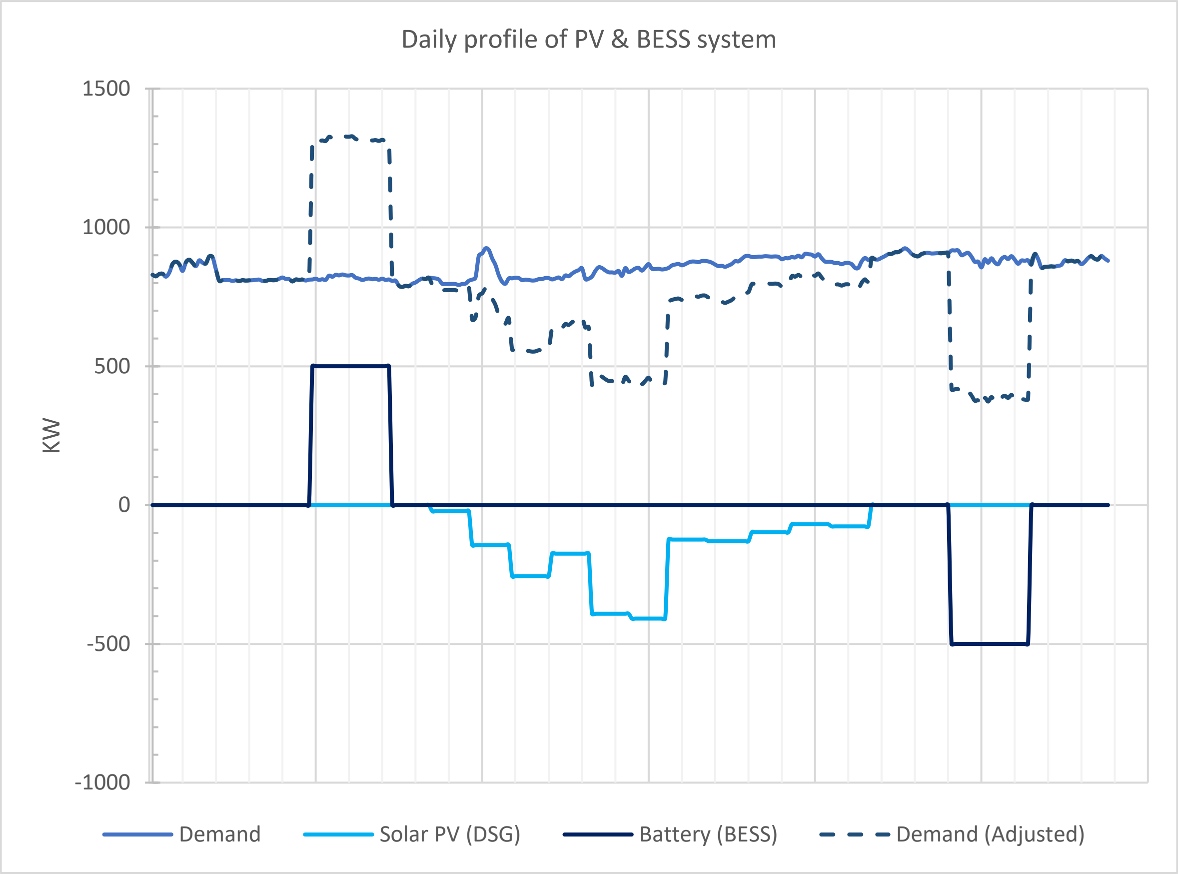


Figure 33 Daily profile operation of the PV & BESS hybrid System. (Own elaboration)

The solution for this case study will base the technical operation on a "peak shaving" approach which allows the operation of the system to charge the BESS during base tariff hours, use all the PV generation during intermediate hours, and discharge stored energy during peak hour periods. This allows system operators to generate savings of up to 30% of the monthly CFE charges.

Figure 33 presents the simulated daily operation of the proposed PV + BESS hybrid system. The solid dark blue line labeled "Demand" shows the original load profile of the facility, which maintains a relatively stable baseline during the day but exhibits distinct peaks in the early morning and especially in the late afternoon and evening. The light blue curve labeled

“Solar PV (DGS)” reflects the generation from the distributed solar system, concentrated around midday. The solid black line labeled “Battery (BESS)” shows battery operation, where positive values correspond to charging, typically scheduled during base tariff hours, and negative values represent discharging to supply energy during peak hours.

The dashed dark blue line, labeled “Demand (Adjusted)”, represents the net demand after accounting for solar generation and battery discharge. It highlights the extent to which the system reduces peak load during high-tariff periods. This adjustment is especially relevant under Mexico’s GDMTH tariff scheme, where electricity costs increase substantially during peak periods (typically 18:00–22:00), and a demand capacity charge is applied based on the maximum measured demand during peak hours over the billing period. By lowering this peak through BESS operation, the system not only reduces energy charges but also achieves significant savings in capacity-based charges. The illustrated profile demonstrates the effectiveness of the hybrid system in both flattening demand and minimizing exposure to the highest tariff components under the current regulatory framework.

The estimated OPEX for a 500 kWp distributed solar PV and 0.5MW/1MWh installation is the following:

Item		**Units**	**Base Case**	**Optmized Case**	**Base Case**	**Optimized Case**	**Total MXN**	**Total USD**
Base	$0.8125	P$/kWh	103,200	121,454	$83,860	$98,681	$24,821	
Intermediate	$1.5858	P$/kWh	264,773	264,773	$419,877	$419,877	$0	
Peak	$1.8320	P$/kWh	30,129	13,700	$55,205	$25,098	-$30,107	
Demand (capacity)	$370.09	P$/kW	917	417	**$339,372**	**$154,327**	-$185,045	
Transmission	$0.1758	P$/kWh	398,102	398,102	$69,986	$69,986	$0	
Distribution	$107.45	P$/kW	917	417	$98,531	$44,806	-$53725	
Fixed charge	$277.76	P$/month			$277	$277	$0	
CENACE’s operation	$0.0074	P$/kWh	398102	398,102	$2,945	$2,945	$0	
Ancillary services	$0.0060	P$/kWh	398102	398,102	$2,388	$2,388	**$0**	
					$1,072,445	**$818,385**	**-$254,060**	**$12,700**

Table 33 Economic analysis for the reduced total cost that a customer can achieve from the installation of DG system. (Own elaboration)

On average, the Project will generate $12,700 USD of savings per month. This means a yearly saving of $152,400 USD and a payback time of 5.4 years for the BESS system and 8 years for the PV + BESS hybrid system.

4.8.2 Importance of DG BESS system incorporation to the MEN

Renewable Distributed Generation can be an alternative for the decarbonisation and efficient operation of the Mexican electricity Network. The benefits of displacing carbon intensive generation by an adequate integration of the type of technologies analysed in this chapter and the possibility of scaling up the systems to achieve more impactful benefits will be thoroughly analysed and presented in *Chapter 5*.

A full analysis for the economic benefit that large clusters of distributed generation, including BESS systems, could bring to the cost-optimal operation of the Mexican Electricity market are part of the findings in *Chapter 3, but further work is required to confirm benefits*. The electricity in Mexico is still substantially expensive in comparison with other more mature markets that have been liberalised. Therefore, there is still an opportunity for the private sector to obtain benefits from investing in distributed generation, achieve relatively short payback times, and then create earnings in the medium term. As more and more private companies decide to invest in distributed generation, the CFE might decide to take control of the DG market. This strategy might mean that the targets for decarbonization aligned with the Paris Agreement (*IPCCC, 2015*) will take longer to be met, but Mexico has made clear its intention to continue growing rapidly as an emerging economy rather than fulfilling its environmental commitments.

The DG market development is necessary for an adequate performance of the transmission network. There are currently four transmission lines with critical levels of congestion in the whole network topology (*SENER, 2023*). The role of distributed generation is expected to be critical in reducing the need for large-scale investment in transmission infrastructure. The expected growth of DG capacity can be seen in *Figure 34*. Distributed Generation is expected to bridge the dispersing growth of demand vs utility scale capacity installed.

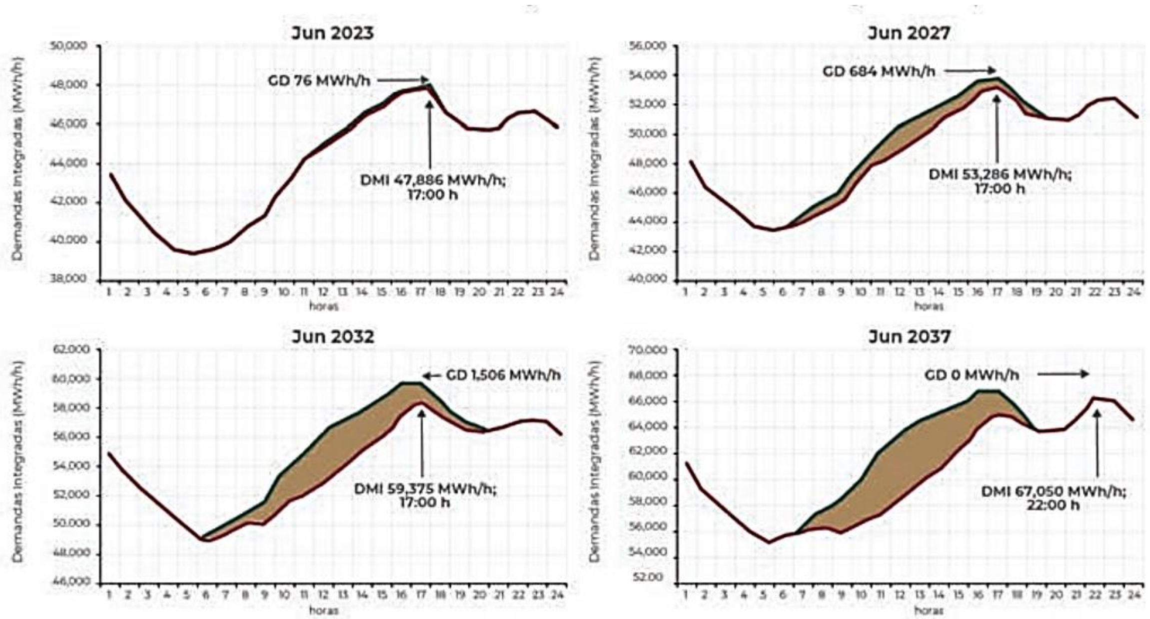


Figure 34 Expected growth of DG capacity installed in Mexico as a means to bridge demand growth and utility scale capacity installed. (SENER, 2023)

The role of distributed generation is increasingly recognized as critical in enhancing grid flexibility and reducing the need for extensive investments in transmission infrastructure. By decentralizing power generation, DG systems can alleviate congestion in the grid, especially during peak demand periods, and provide localized energy solutions that are more resilient and adaptable to changing energy needs. Recent studies have demonstrated that leveraging distributed flexibility can be a cost-effective alternative to traditional grid reinforcement strategies, offering significant savings while maintaining system reliability (Holweger et al., 2021).

Hybrid systems that combine DG with energy storage technologies further amplify these benefits by enabling better demand-side management, reducing operational and maintenance costs, and lowering CO_2 emissions through decreased reliance on fossil-fuel-based peaking plants. Such configurations not only support the integration of renewable energy sources but also contribute to the overall stability and efficiency of the power system. For instance, optimized planning of distributed energy resources, including battery storage, has been shown to minimize total costs and enhance carbon reduction efforts in power systems (Nguyen et al., 2025).

This chapter has explored the role of distributed generation and battery energy storage systems in the Mexican electricity market, particularly within the context of regulatory developments, market characteristics, and user-side economic benefits. Emphasis was placed on the regulatory and economic conditions influencing the adoption of hybrid PV + BESS solutions, including their sizing logic, tariff structures, and impact on reducing demand charges and transmission bottlenecks.

Chapter 5

Adaptation and lessons learned from Heat Storage LCA analysis: Case Study to support the implementation of a Carbon Tax in Mexico

5. Adaptation and lessons learned from Heat Storage LCA

In this Chapter an LCA analysis of a PCM ESS will be presented to understand the significance of quantifying all life cycle impacts of new technologies.

Efforts to decarbonize the UK's energy network need to be highly effective in both of the main sectors: heat and electricity. Sunamp Ltd. (*Sunamp, 2023*) has developed a heat storage technology based on a highly efficient patented phase change material. This enables cost-effective and low-carbon storage from household to utility-scale level. This is a crucial contribution towards the national and global efforts to curb carbon emissions and achieve net zero status by 2050. Climate change has to be tackled with technological solutions, as substantially modifying our consumption habits will not be enough for the 1.5 degree threshold (*Khanna, 2020*). Therefore, it is critical for all technological solutions to be assessed from a sustainability perspective, guaranteeing the effectiveness of the technology to mitigate carbon emissions.

While earlier chapters focused on distributed generation and lithium-ion BESS as near-term solutions to decarbonize the Mexican electricity market, this chapter introduces a broader systems-level perspective by analysing a novel thermal energy storage technology. PCM-based storage is explored here not as a competing solution, but as a complementary pathway that can decarbonize sectors less suited for electrification, such as industrial heat. Its inclusion expands the thesis's scope beyond grid-side applications, offering insights into how diverse energy storage technologies can contribute to meeting climate targets—especially in the context of designing a carbon tax framework grounded in life cycle emissions accounting.

5.1 Assumptions for the LCA of UniQ

Sunamp is a UK-based energy storage company that specialises in compact thermal energy storage systems, offering an alternative to conventional hot water tanks and electric heaters. At the core of its technology is the UniQ product line, which utilises phase change materials to store and release thermal energy efficiently. The UniQ devices are designed to deliver domestic hot water on demand, while significantly reducing energy consumption and carbon emissions. Their modular design, long service life, and recyclability make them attractive for applications in buildings aiming to decarbonise heat supply.

This piece of work is an extension from a previous study investigating the life cycle environmental impacts of 1kWh of thermal energy output from the SunampPV product (*Sunamp, 2023) (Rosales, E., 2017).* In general, assumptions and modelling processes applied in the previous study have been retained, except where detailed here. New features and characteristics for the UniQ6 have been incorporated into the model and obsolete components have been removed.

The structure for the life cycle was assumed to be generally similar to the UniQ (Sunamp's recent PCM system) and is shown in *Figure 35*. The main differences are that the new system is bigger (the size ratio between the outer cases is 2:3 for the UniQ to UniQ6), and the newer system doesn't require a hydraulic pumping system. Furthermore, the production of the new UniQ6 is carried out in one of the newest Sunamp facilities, so new processes have been added to the original model in order to account for additional production of components or manufacturing processes which had been outsourced in the past.

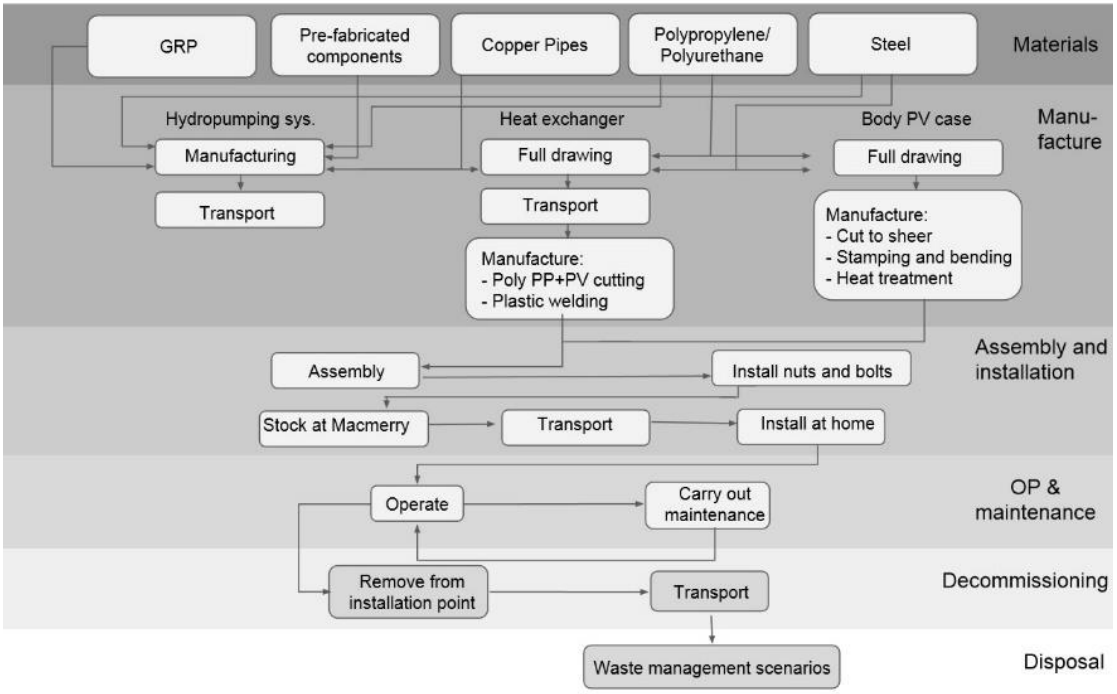


Figure 35 Summary of the materials and resulting masses in the UniQ6. (Own elaboration)

Figure 35 illustrates the full life cycle stages of the UniQ6 system, from raw material extraction and manufacturing through to decommissioning and disposal. It highlights key changes in the new unit's design and production chain, particularly the in-house assembly processes and expanded casing size, which increase embodied material use.

Note that operational impacts are not actually included in either study. In (*Rosales, E., 2017*), this was because the supply electricity was assumed to come from an existing photovoltaic array, and therefore the impacts lay outside the system boundary. This assumption remains valid, as most Sunamp installations are now powered by rooftop PV. Given the low emission factor of solar electricity, typically ranging between 25.2 and 43.6 gCO_2-eq/kWh, which significantly reduces the lifecycle emissions compared to grid-supplied electric heating. This is consistent with recent findings reported by the IEA Photovoltaic Power Systems Programme, which confirms the environmental advantage of PV-supplied heating over conventional alternatives (IEA-PVPS, 2022). It has since emerged that the most common installation configuration for Sunamp devices is currently as a direct replacement for electric immersion hot water tanks, and the carbon impacts of this are examined separately in *Section 5.6*.

The analysis was carried out with SimaPro Classroom v8.0.3.14 software. Background life cycle data for materials and processes was gathered from the ecoinvent database v3.01.

5.2 Method, scope, allocation, cut-off criteria and functional unit

Life Cycle Impact Assessment (LCIA) is a crucial phase within Life Cycle Assessment, aimed at evaluating the potential environmental impacts associated with a product system based on its life cycle inventory. This phase involves classifying inventory data into specific impact categories and characterizing them using scientific models to quantify potential environmental effects, such as global warming, acidification, and eutrophication. LCIA facilitates a structured comparison of environmental trade-offs across different impact categories, thereby informing sustainable design and policy decisions. The methodologies and frameworks for LCIA have been extensively developed and standardized, notably through initiatives by United Nations Environment Programme, culminating in comprehensive guidelines and consensus on best practices (Hauschild & Huijbregts, 2015).

The Life Cycle Impact Assessment (LCIA) method chosen for this analysis is CML-IA baseline 3.01, which is the same as that used in the previous analysis to allow a fair comparison between the devices (Appendix 1). This is a standard impact assessment method that is widely used to evaluate a range of different environmental impacts, including climate change or Global Warming Potential (GWP). The characterisation factors for greenhouse gases are developed from the method published by the Intergovernmental Panel on Climate Change (IPCCC).

The scope of the analysis, allocation method and cut-off criteria have also been kept the same as in the initial study to ensure consistency when comparing the results. This work has focused on Global Warming potential, but all the impact categories that are included in this LCIA method are presented for future analysis. The functional unit is 1 kWh of thermal energy produced by the Sunamp UniQ6, representing the useful heat delivered by the storage system during operation. This unit was chosen as it aligns with the thermal output capacity of the device and allows comparability with other thermal technologies.

5.3 Materials and Manufacture

Most of the materials used for the manufacture of the UniQ6 are the same as those in the UniQ (Sunamp, 2018). The total amount of each different material is different, however, since the new device is larger in both capacity and size. The main raw materials used in the device are shown in the Table 35:

Material	Mass (kg)
PCM	74
Aluminium	23.5
Copper	13.05
Plastics	7.15
Steel	1.10
Brass	0.540
Others	5.20

Table 34 Summary of the materials and resulting masses in the UniQ6. (Own elaboration)

The Phase Change Material (PCM) for the UniQ6 has the following composition: Sodium acetate 57%, Water 39%, Disodioum Hydrogen Phosphate 2%, and a Polymer Solution of 2%. The ecoinvent database does not include data for these exact compounds, so it has been assumed that the impacts of substances with similar compositions will resemble the actual impacts of the PCM. This assumption merits further investigation, as the results of this analysis, it is shown that the PCM (along with aluminium) is responsible for the largest proportion of carbon emissions in the UniQ6 life cycle, as shown in Table 38. Further modelling of all of the life cycle stages of this material is recommended to further refine the assessment of the environmental impacts.

5.4 End-of-life and decommissioning

It has been assumed that at the end-of-life 20% of all inputs to the UniQ6 will be reused. This is modelled as 20% of input material leaving the system boundary with no impact. Furthermore, it is expected that steel and aluminium components will be recycled; of the 80% remaining after a share has been removed for re-use, it is assumed that 90% is sent for recycling. The remainder of the waste (8% of steel and aluminium, and 80% of other materials) is sent to a typical municipal waste stream for the UK. This is a pessimistic assumption, which means there is a large potential for the emissions to be reduced with a more realistic circular economy scenario, as discussed by Gentil et al. (2010).

Note that in accordance with most standard practice for LCA, this study has employed the Recycled Content allocation method for attributing impacts for recyclable materials. In order to avoid double-counting the benefits of recycling, full credit is given for the use of recycled material during the manufacturing stage, and all materials sent for recycling are assumed to have left the system boundary with no impact or credit for the UniQ6. This may be pessimistic, as the end-of-life recycling rate may be much higher than the recycled content of the input materials but is a recommended assumption when considering technologies with a long design life.

A set of results has been produced in order to quantify the total amount of carbon emissions of the Sunamp's UniQ6. Additional results have been produced for the robustness of the analysis as well as the possibility of future comparison to newer versions of this device.

Similarly to the UniQ, it is evident that the manufacturing stage is the highest contributor across all of the different categories. This is particularly due to the impacts associated with the production of the metals and the manufacturing of the phase change material. There is a high potential for emissions reductions (or a decrease in GWP value) if sustainability is prioritised during the in-house manufacturing and procurement stage.

There are two main carbon streams which contribute to the total impact in kg CO_2 eq. The first is from aluminium, which is mainly used in the outer structure of the device, and second is the compound which has been used to simulate the PCM.

5.5 Comparison of UniQ and UniQ6

The main features of the two different Sunamp devices are shown in *Table 36*. In order to compare the impacts of the two devices, the results are normalised per unit of thermal energy output.

The total energy output over 20 years of operation of the UniQ was estimated as 31,300 kWh (Rosales, E., 2017). In order to calculate the energy generation of the UniQ6 throughout its expected 50 years of operation we have used data from the East Heat study (Sunamp, 2018). We have selected the average daily use for a 2-bedroom home with the device installed and generating energy. For this system, it has been estimated a daily generation of 2.9 kWh, resulting in 52,925 kWh over the 50 years of expected operation for the newer model. Typical potential savings could be higher if installed in a property appropriate to its capacity.

	Capacity (kWh)	Mass (kg)	Operational Lifetime (yr)
UniQ6	6.4	124.4	50
UniQ	5.5	53.8	20

Table 35 Device comparison UniQ6 vs UniQ. (Own elaboration)

In Table 37, we can see the contribution of the GHG towards the total value of GWP. Other substances, including methane, are less than 15% for both devices, while CO_2 is the main contributor, as expected.

Gas		UniQ GWP (kg CO_2 eq/kWh)	UniQ6 GWP (kg CO_2 eq/kWh)
CO_2	Carbon Dioxide	0.023	0.0157
CH_4	Methane	0.0011	0.0015
Remaining Substances		0.0002	0.0013

Table 36 The contribution of different greenhouse gases to the global warming potential of the UniQ and UniQ6. Data for the UniQ is from (Rosales Ortega, 2017) (Own elaboration)

The total global warming potential for the UniQ and UniQ6 are 671 and 1040 kg CO_2 eq respectively. This represents a 35% increase in the total embedded carbon from the old UniQ to the new UniQ6 device; however, the latter is around 30% larger than the previous device, so such an increase is to be expected. There is a direct correlation between the embedded carbon and the size and capacity of the devices, as the materials and manufacturing contribute the most to the GWP.

Impact category	Unit	UniQ	UniQ6	UniQ	UniQ6
		per device		per kWh	
Abiotic depletion	kg Sb eq	0.02	0.03	5.18 x10^{-7}	6.27 x10^{-7}
Abiotic depletion (fossil fuels)	MJ	10827	17327	0.35	0.33
Global warming (GWP)	kg CO2 eq	671	1040	0.026	0.019
Ozone layer depletion	kg CFC-11 eq	5.07x10^{-5}	9.19 x10^{-5}	1.62 x10^{-9}	1.74 x10^{-9}
Human toxicity	kg 1,4-DB eq	1497	3096	0.05	0.05
Fresh water aquatic ecotox.	kg 1,4-DB eq	855	1907	0.03	0.03
Marine aquatic ecotoxicity	kg 1,4-DB eq	5307758	9522749	170	180
Terrestrial ecotoxicity	kg 1,4-DB eq	0.61	1.03	1.96 x10^{-5}	1.96 x10^{-5}
Photochemical oxidation	kg C_2H_4 eq	0.43	0.79	1.37 x10^{-5}	1.49 x10^{-5}
Acidification	kg SO_2 eq	7.52	13.8	2.40 x10^{-4}	2.61 x10^{-4}
Eutrophication	kg PO_{43}- eq	3.23	6.75	1.03 x10^{-4}	1.27 x10^{-4}

Table 37 LCA results for UniQ and UniQ6, shown as a total per device, and normalised per unit of thermal energy output. Data for the UniQ is from (Rosales Ortega, 2017)(Own elaboration)

The full life-cycle results are shown in *Table 38*, and it can be seen that when the results are normalised per unit of thermal energy output the newer UniQ6 device has a GWP 26% lower than its predecessor. This is because amount of energy stored by the UniQ6 is expected to be significantly greater due to the longer life and larger capacity of the newer model.

This analysis focuses on the GWP of Sunamp devices, however, a full LCA has been performed using SimaPro. Therefore, all other impact categories have also been reported. There is an expected trend across all impact categories, which show an absolute increase in impacts per device from the UniQ to the UniQ6 of 30 to 100%. When these impacts are normalised by the lifetime energy output, however, the results converge to a difference of less than 5% in most cases. It is also important to note that larger capacity UniQ6 device has the potential for displacing more carbon emissions over its life.

The embedded carbon of the two devices, excluding operational emissions, are found to be 0.026 and 0.019 kg CO_2 eq/kWh for the UniQ and the UniQ6 respectively. These are comparable to the embedded carbon of solar thermal collectors, air source heat pumps and LED lighting (Finnegan, Jones, and Sharples, 2018).

5.6 Savings calculation from Sunamp's operational fleet

In order to estimate the total carbon emissions savings from the operational fleet of Sunamp devices to date, it has been assumed that all Sunamp devices in operation are replacing an electric immersion hot water tank. This is currently the most common installation configuration according to Sunamp Ltd.

The Sunamp PCM technology offers an efficiency saving over conventional hot water tanks, due to the reduced heat losses. The energy saving of this has been estimated based on results for a case study property used in the East Heat study (*Sunamp, 2018*). The analysis is shown in Table 39, based on the following data (*Sunamp, 2018*):

1. Average hot water use 1.6 kWh/ day.
2. Hot water tank heat losses 2.3 kWh/ day.
3. UniQ battery heat losses 0.6 kWh/ day.

	Tank kWh	UniQ6 kWh
Daily heat requirement	1.6	1.6
Daily losses	2.3	0.6
Daily gross heat req.	3.9	2.2
Efficiency	70%	95%
Daily net heat input req.	5.5	2.4
Daily balance (savings)		3.1
Savings per annum		1131.5
Roundtrip efficiency	29%	67%

Table 38 Roundtrip efficiency and energy savings calculation for the UniQ6 when replacing a hot water tank. (Own elaboration)

Table 39 compares the energy efficiency and roundtrip performance between a conventional hot water tank and the UniQ6 thermal battery. The daily hot water requirement is assumed to be 1.6 kWh in both cases. However, the conventional tank incurs significantly higher daily losses (2.3 kWh/day), leading to a gross heat input of 3.9 kWh/day to meet the demand, resulting in an efficiency of just 29%. In contrast, the UniQ6 system has much lower thermal losses (0.6 kWh/day), requiring only 2.2 kWh of input, and operates at a much higher roundtrip efficiency of 67%. This demonstrates the potential of phase change material (PCM) systems like UniQ6 to reduce overall energy consumption, particularly in domestic water heating applications.

This shows that the installation of an UniQ6 device in place of an electric immersion hot water tank saves 1131.5 kWh of energy per annum due to its high efficiency and the reduction in energy losses through storing the energy as latent heat. This value was, however, calculated from a case study for a 1-bedroom flat, but the study also shows that the UniQ6 is very over-sized for such an installation. The UniQ6 has a capacity of 6.4 to 7.2 kWh, while the assumed installation case is for an average of only 1.6 kWh/day, with a typical peak demand of 3.2 kWh/day.

It is likely that a UniQ6 would have the capacity to cope with twice this daily heat requirement – equivalent to the hot water demand for a 2-bedroom residence, which is still smaller than the average property size in the UK (*LABC Warranty, 2019*). While the empirical data is for an installation that is undersized, for the purposes of this study it is assumed that the typical potential savings could be 2263 kWh per annum, if installed in a property appropriate to its capacity.

For the UniQ device, the annual energy savings are estimated to be 85% of that of the newer device (1924 kWh), based on the relative capacities of the two devices.

This analysis is based on a real-world case study conducted in the United Kingdom, where UniQ6 devices have been installed and monitored. The UK case provides a reference for typical domestic hot water demand in temperate climates. However, it is important to acknowledge that the demand profile in Mexico differs significantly, particularly due to higher usage of air conditioning and lower reliance on electric heating. Therefore, while the savings estimated here are useful benchmarks, actual performance in Mexico may vary and would require local empirical validation, which is outside of the scope of this work.

5.7 Carbon emissions saving per device

In the configuration of replacing an electric hot water tank, the energy savings of the Sunamp devices are a reduction in electrical power consumption. Therefore, the corresponding carbon emissions saving can be estimated from the carbon emissions intensity of UK electricity. These change each year, but are reported by the UK government, as shown in *Table 40*.

Year	Emissions intensity of GB electricity kg CO_2 eq/kWh	Annual saving per device kg CO_2 eq		Reference
	Total	UniQ6	UniQ	
2016	0.449	1017	864	(Ricardo-AEA, 2016)
2017	0.384	870	740	(BEIS and DEFRA, 2017)
2018	0.307	695	591	(BEIS and DEFRA, 2018)
2019	0.277	628	533	(BEIS and DEFRA, 2019)
2020	0.253	573	487	(BEIS and DEFRA, 2020)

Table 39 Emissions intensity of UK electricity and the corresponding annual carbon emissions savings for a Sunamp device operating during that year. (Own elaboration)

In order to estimate the net carbon emissions saving of the installed Sunamp devices to date, the total emissions saving since installation needs to be calculated. For the purposes of this analysis, it is assumed that there are no emissions savings during the year of installation – essentially assuming that the devices are all installed on the 31st December. This is a conservative assumption. Therefore, the emissions saving to date for a device installed in 2015 is the sum of the annual savings from 2016 to the end of 2020, inclusive, while a device installed in 2018 is only the sum of the annual savings from 2019 to 2020. These values are shown in *Table 40*. The total embedded carbon emissions *Table 37* are then subtracted from this value to get the net emissions reduction to date. Note that this will be a negative value for devices installed more recently (corresponding to a net emission of carbon or contribution to climate change), as the devices have not been installed for long enough to achieve carbon payback.

Installation year	Emissions saving to date kg CO2 eq		Net emissions reductions to date kg CO2 eq	
	UniQ6	UniQ	UniQ6	UniQ
2015	3782	3215	2743	2544
2016	2766	2351	1726	1680
2017	1896	1611	856	940
2018	1200	1020	161	349
2019	573	487	-467	-184

Table 40 Emissions reductions to date per device. (Own elaboration)

A simple analysis of the latest Future Energy Scenarios published by National Grid also shows that full carbon payback should be achieved for all devices installed in the next few years; however, as electricity is further decarbonised, it is likely that the greatest emissions reduction potential for the Sunamp technology will be realised by using the configurations that displace gas in residential heating and hot water applications, rather than making efficiency savings on electricity consumption (*National Grid ESO 2020*). Currently the average emissions intensity of UK electricity is roughly equal to that of heat from a gas-fired combination boiler (based on an analysis of data from ecoinvent v3.6). This is only expected to reduce further. Also, the Sunamp devices are able to exploit flexible energy tariffs to store the lowest carbon electricity, creating further potential for emissions reduction.

This combined effect of fuel switching and optimized time-of-use electricity storage positions PCM storage as a compelling contributor to decarbonisation and system flexibility objectives. Rather than focusing solely on energy efficiency improvements, the greatest emissions reduction potential is likely to arise when devices displace gas for space heating and hot water. Simultaneously, by charging during periods of low grid carbon intensity, typically aligned with off-peak or high-renewable generation, these systems reduce overall emissions relative to average grid consumption. This dual benefit makes PCM-based heat storage especially relevant in energy systems with ambitious climate targets and an evolving renewable mix (BEIS, 2021). Moreover, their compatibility with flexible electricity tariffs enables additional cost and carbon savings, reinforcing their value proposition across both household and utility planning scenarios.

5.8 Carbon reduction of all installed Sunamp devices

In order to calculate the total emissions reductions of all Sunamp devices installed to date, installation data is required. Sunamp Ltd. provided detailed sales data for their UniQ and UniQ6 devices, and this is summarised in *Table 41*. It is assumed that all devices sold in a given year are installed in that year, and that there are no emissions savings within that calendar year.

The installation data is multiplied by the data in *Table 40* to calculate the total emissions saving, and net emissions reduction, which are also shown in *Table 42*.

Table 41 Total emissions savings and net carbon reduction of all Sunamp devices to date. (Own elaboration)

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Installation year	Number of devices installed		Total emissions saving to date t CO_2 eq		Net emissions reduction to date t CO_2 eq		Cumulative net emissions saving
	UniQ6	UniQ	UniQ6	UniQ	UniQ6	UniQ	t CO_2 eq
2015	-	382	-	1,228	-	972	972
2016	-	702	-	1,650	-	1,179	2,151
2017	-	-	-	-	-	-	2,151
2018	428	-	514	-	69	-	2,220
2019	2,170	-	1,243	-	-1,013	-	1,207
Sub-total	2,598	1,084	1,757	2,878	-944	2,151	
Total	3,682		4,636		1,207		

Table 41 Total emissions savings and net carbon reduction of all Sunamp devices to date. (Own elaboration)

There have been 1084 and 2598 UniQ and UniQ6 devices produced respectively. If these have all been used to replace electric immersion hot-water tanks, then they have reduced carbon emissions by 4.6 kt CO_2 eq to date. When the embedded carbon of the devices is taken into account, this is equivalent to a net emissions reduction of 1.2 kt CO2 eq. It is estimated that carbon payback has already been achieved for all Sunamp devices sold until the end of 2018, and these devices all have at least 75% of their expected operational life remaining.

In order to place these carbon savings in context, *Table 43* shows the carbon savings of the Sunamp devices installed to date as a percentage of both total 2019 UK territorial GHG emissions per capita and 2019 UK residential CO_2 emissions per capita.

			Reference
UK 2019 territorial GHG emissions	435.2	Mt CO_2 eq/yr	(BEIS, 2020)
UK population 2019	67	M people	(ONS, 2019)
UK 2019 emissions per capita	6.5	t CO_2 eq/yr/person	
UK 2019 residential CO_2 emissions	65.2	Mt CO_2 eq/yr	(BEIS, 2020)
UK 2019 residential CO_2 emissions per capita	1.0	t CO_2 eq/yr/person	
Total Sunamp emissions saving	4.6	kt CO_2 eq	
Time period considered	5	years	
Average annual saving (total)	927	t CO_2 eq/yr	
Number of devices installed	3682	devices	
Average annual saving per device	0.252	t CO_2 eq/device/yr	
Proportion of UK annual territorial GHG emissions per capita	3.9%		
Proportion of UK annual residential CO2 emissions per capita	26%		

Table 42 Total carbon savings expressed as a percentage of the UK's annual emissions per capita. (Own elaboration)

In order to put the carbon savings in context, they have been compared to the total UK annual territorial emissions per person, and sub-set of this that is attributed to the residential sector. This shows that the carbon savings are significant, with one UniQ6 device saving about 4% of one British person's total emissions each year, corresponding to 26% of carbon emissions only from the residential impacts per person.

Table 44 shows a similar calculation for the net emissions reduction, having taken the embedded carbon into account.

Concept	Value	Units
Sunamp net emissions reduction	**1.2**	**kt CO2 eq**
Average annual net reduction	241	t CO2 eq/yr
Average annual net reduction per device	0.066	t CO2 eq/device/yr
Proportion of UK annual territorial GHG emissions per capita	1.0%	
Proportion of UK annual residential CO2 emissions per capita	6.7%	

Table 43 Net carbon reduction expressed as a percentage of the UK's annual emissions per capita.(Own elaboration)

Table 44 shows that each Sunamp device achieves annual carbon savings equivalent to approximately 26 percent of the average UK residential CO_2 emissions per person. This figure is based on the cumulative emissions avoided over the lifetime of the device due to its high thermal efficiency and its ability to displace conventional electric water heating. To account for the environmental cost of manufacturing the device, the analysis includes the embedded carbon—calculated based on a life cycle assessment using Ecoinvent data and typical embodied energy factors. Assuming that each device has approximately 75 percent of its operational life remaining, the adjusted emissions saving per device is still equivalent to about 7 percent of the UK residential CO_2 emissions per capita. This approach provides a conservative yet realistic estimate of the net benefit of the technology, taking into account both operational savings and production-related emissions. This case study has evaluated the total carbon emission savings attributable to the Sunamp technology from 2015 to date. The first step was to extend an earlier life cycle assessment of the UniQ device to examine the environmental impacts of the newer UniQ6 model. This found that the embedded carbon of the UniQ6 device compares well with that of the earlier UniQ. While the environmental impacts per device have increased, this is in proportion to the increase in size. There is also a trend that most of the embedded carbon impacts come from the manufacturing of the device, and this life cycle stage would benefit from more thorough analysis to confirm these results.

The embedded carbon of the UniQ and UniQ6 are found to be 0.026 and 0.019 kg CO2 eq/kWh respectively, which is comparable to the embedded carbon of LED lighting.

The second stage of the analysis was to evaluate the emissions savings of all Sunamp devices installed to date. This is estimated to be 4.6 kt CO2 eq if they have all been used to replace electric immersion hot-water tanks. When the embedded carbon of the devices is taken into account, this is equivalent to a net emissions reduction of 1.2 kt CO2 eq. It is estimated that carbon payback has already been achieved for all Sunamp devices sold until the end of 2018, and these devices all have at least 75% of their expected operational life remaining.

In order to put these values in context they have been compared to UK annual territorial emissions. The annual emissions saving per device is equivalent to 4% of UK annual territorial greenhouse gas emissions per capita, or 26% of annual CO2 emissions per capita from the residential sector. Even when this is adjusted to account for embedded carbon (and bearing in mind that the devices all have a further 75% or more of their operational life remaining), the net emissions reduction is still 7% of the UK annual residential CO2 emissions per capita (based on 2019 data).

This analysis has only considered the carbon benefits of Sunamp devices providing a higher roundtrip efficiency than other electrical heat storage devices. Electricity is being continuously decarbonised in the UK. This means that following the current forecasts for grid carbon intensity, the positive impacts of future Sunamp devices could be nullified. One of the benefits of these devices is their versatility, and it is likely that the greatest future benefits will lie in using Sunamp technology to replace gas heating and hot water systems, where impacts could be even greater than what has been achieved so far. This analysis makes a further case that ESS (Energy Storage Systems) have an overall positive impact towards the decarbonization of electricity grids. In the following section we will discuss the implications for the Mexican Electricity Market.

5.9 Implications for a Carbon Tax in Mexico

The in-depth analysis conducted on the Sunamp device installed in the UK presents a case study that can be applied to inform the development of energy storage technologies and related policies in other regions such as Mexico. This emerging economy is grappling with climate change mitigation and the need to transition to low-carbon, sustainable energy sources while maintaining a healthy economic growth (*SENER, 2023*). Given the distinct differences in energy usage patterns, climatic conditions, and policy frameworks between Mexico and the UK, the transposition of this study to the Mexican context requires careful consideration of these variables.

The Sunamp case study provides a valuable framework for Mexico to develop its own policies to promote energy storage technologies. Adopting these technologies could make a significant contribution to Mexico's decarbonization targets, promoting energy efficiency, reducing GHG emissions, and fostering a more sustainable, resilient energy sector.

As Mexico strives towards achieving its decarbonization goals outlined in the INDC submission to the UNFCCC (UNFCCC, 2015), the adoption of renewable energy sources and the implementation of energy storage technologies play an essential role.

5.10 The Case for a Carbon Tax

A carbon tax, defined as a levy on the carbon content of fuels, primarily targets carbon dioxide (CO2) emissions, the major driver of global warming (*World Bank, 2020*). By implementing such a tax, the Mexican government could internalize the social costs of carbon emissions, effectively increasing the cost of fossil fuel use and making renewable energy sources and storage technologies more competitive

The influence of a carbon tax on energy storage technologies lies in its potential to change the economics of renewable energy systems. By increasing the cost of fossil fuel energy, a carbon tax makes energy storage systems more attractive because these technologies can help integrate higher levels of variable renewable energy into the grid, like discussed in *Section 3.4*. Moreover, as in the case of the Sunamp technology, energy storage systems can contribute directly to carbon reduction by improving the efficiency of energy use, thus reducing total energy demand and displacing fossil fuel energy.

Empirical analyses indicate that carbon pricing can effectively reduce CO_2 emissions. Best et al. (2020) found that countries with carbon pricing mechanisms experienced a significant decrease in emissions growth rates compared to those without such policies. However, the success of carbon taxes also depends on public acceptability. Carattini et al. (2017) emphasize that transparent communication and the use of tax revenues for environmental purposes can enhance public support for carbon taxation. In the context of Mexico, Black et al. (2021) suggest that progressively increasing carbon prices from current levels to $75 per ton by 2030 could significantly contribute to the country's climate mitigation commitments.

The rate of the carbon tax should be set at a level that sufficiently incentivizes the deployment of renewable energy and storage technologies while minimizing the impact on energy consumers and competitiveness. Empirical studies suggest that a moderate initial rate could be implemented, with a pre-announced escalating schedule to provide certainty for investors and signal the long-term commitment to decarbonization (*Palmer, K., et al., 2005*).

Revenue from the carbon tax could be used to support the deployment of energy storage systems, such as offering subsidies or tax breaks for their installation. This approach could mitigate the upfront costs of these technologies, one of the significant barriers to their adoption, like discussed in *Chapter 4*. Furthermore, revenue recycling could also be used to address distributional concerns, particularly the impact on low-income households. Despite the potential benefits, the implementation of a carbon tax in Mexico would face several challenges. Public acceptability could be a significant hurdle, especially considering the potential impact on energy prices (Best et al., 2020). Therefore, effective communication about the benefits of the tax, transparency about its use, and measures to mitigate any adverse effects will be crucial.

Additionally, a carbon tax should not be viewed as a standalone solution. It should be part of a broader policy package that encourages energy efficiency, renewable energy, and particularly the deployment of energy storage systems. The Mexican government should continue to explore other policy mechanisms such as renewable portfolio standards, feed-in tariffs, or carbon trading schemes, which could work in conjunction with a carbon tax to support the deployment of energy storage technologies. The transition towards a low-carbon energy system in Mexico requires dedicated policy efforts. The implementation of a carbon tax represents a promising policy option that could encourage the integration of renewable energy and energy storage technologies into the country's energy landscape. The successful application of this policy mechanism, however, would rely on careful design, effective implementation, and the simultaneous pursuit of complementary policies.

The successful Implementation of carbon taxes in various jurisdictions, such as British Columbia in Canada (*Duff, G, D., 2008*) and Sweden (*Jagers, C, S, et al., 2009*), provide valuable insights for Mexico. These jurisdictions have achieved significant emissions reductions while experiencing economic growth, demonstrating that decarbonization and economic prosperity are not mutually exclusive. The experience of British Columbia, which introduced a carbon tax in 2008, shows that transparency about revenue use is essential to gain public support. The province returned all revenue to households and businesses through tax cuts and rebates, minimizing the impact on energy costs and reducing income taxes (*Duff, G, D., 2008*). This approach could be highly relevant in the Mexican context to address concerns about energy affordability and competitiveness. Sweden, with one of the world's highest carbon taxes (*Government Sweden, 2023*), has achieved substantial CO2 reductions while maintaining a strong economy. The country's approach of gradually increasing the tax rate over time, in line with international commitments, offers a model for Mexico to consider.

The discussion on carbon taxation in *Section 5.10* builds upon the earlier analysis of the life cycle performance of the Sunamp thermal storage devices. *Sections 5.1* to *5.8* provided detailed estimates of greenhouse gas savings per device, as well as the cumulative impact of widespread deployment in the UK. These quantified benefits are essential for shaping climate policy, particularly fiscal instruments such as carbon taxes. The carbon reduction potential identified through life cycle assessment supports the argument that targeted taxation can accelerate the adoption of low-emission technologies. This is particularly true when the tax revenues are reinvested into infrastructure, innovation, or financial incentives. Therefore, the life cycle results presented in this chapter do not only offer a technical benchmark. They also provide a robust justification for internalising the environmental costs of emissions through well-designed economic instruments.

This chapter has shown how life cycle analysis can inform both technology development and climate policy. Through a detailed evaluation of the Sunamp devices, it demonstrated that efficient thermal storage systems such as UniQ6 can significantly reduce carbon emissions over their operational life. The aggregate data revealed a meaningful reduction in emissions when these devices are deployed at scale. Building on these results, the chapter then examined the potential of carbon taxation as a complementary policy tool. A carbon tax, especially when aligned with real-world performance data and long-term decarbonisation targets, can support the broader adoption of storage technologies. By linking life cycle data to economic policy, this chapter reinforces the central idea of the thesis. Energy storage is not only a technical solution but also a key instrument for achieving systemic and cost-effective decarbonisation in emerging economies like Mexico.

Chapter 6

Conclusions

6 Conclusions

This chapter synthesises the key findings from the preceding analysis and highlights their implications for the integration of energy storage technologies within Mexico’s decarbonisation strategy.

6.1 Thesis Summary

This research was a detailed examination on the impacts that BESS systems have upon the total carbon emissions and cost of dispatch in the Mexican Electricity Network, moving forward to the benefits of the adoption of BEESS systems in the Distributed Generation marker, and concluding with an LCA of a heat storage device to support the implementation of policy mechanisms in Mexico for supporting the decarbonisation of the economy. The first section (*Chapters 2 and 3*) concentrated in setting battery storage systems in the context of an emerging economy like Mexico and describe influential aspects for renewable energy penetration into the electricity mix. Moreover, an optimal dispatch model was built for the precise topological frame of Mexico, including all control regions, 53 regional nodes, transmission particularities, and 251 real generation assets. The second part (*Chapter 4*) demonstrates the economic viability of distributed generation from the perspective of investors or end-users, which signifies a deeper incorporation of BESS into the system. Finally, the last section of this piece of work (*Chapter 5*) uses an example of an LCA methodology to explain the importance of incorporating all life cycle impacts into studies like this, for the purpose of robustness. Lastly a Carbon Tax policy is proposed to further ensure Mexico meets its challenging sustainability goals.

6.2 Optimal Dispatch Model for the Mexican Electricity Network

The Julia model for optimal dispatch presents a pioneering approach to understanding and optimizing the power generation and distribution landscape, specifically tailored to the unique conditions of Mexico. This model, leveraging the JuMP package with the GLPK solver, offers a comprehensive framework for analysing the dynamics of power systems, incorporating a wide array of elements including generation assets, storage facilities, network topology, and demand characteristics. Its significance and unique contribution to the field stem from its holistic integration of these components, addressing a gap in existing models that often overlook the intricate interplay between them, particularly in the Mexican context.

One of the critical advancements of this model is its detailed representation of the network topology, encompassing buses, lines, and their respective characteristics such as line reactance and capacity. This level of detail facilitates a more accurate simulation of power flow across the network, allowing for a robust analysis of transmission constraints and their impact on dispatch decisions. By considering the spatial distribution of generation assets and demand, the model can identify bottlenecks in the network and propose solutions that enhance efficiency and reliability.

The explicit modelling of storage assets, including their locations, capacities, and efficiencies, is a notable feature that sets this framework apart. Energy storage is increasingly recognized as a critical component for enhancing grid flexibility and integrating renewable energy sources. In the Mexican context, where the transition to renewable energy is gaining momentum, the ability to accurately model storage operations (charging, discharging, and energy levels) is invaluable. It provides insights into how storage can be leveraged to balance supply and demand, reduce reliance on fossil fuels, and mitigate the variability of renewable generation.

The model's approach to demand representation, using a detailed dictionary indexed by time periods and buses, allows for a dynamic analysis of demand patterns and their implications for optimal dispatch. This feature is crucial for capturing the temporal variations in electricity consumption and understanding their effects on generation scheduling, emissions, and system costs. It enables the identification of peak demand periods and the assessment of strategies to meet these demands efficiently, such as demand response or strategic deployment of storage assets.

A unique aspect of this model is its incorporation of carbon emissions into the optimization criteria, using emissions factors for different generators. This approach aligns with global and national priorities to reduce carbon footprints and combat climate change. For Mexico, where energy sector emissions are a significant concern (*SENER, 2023*), this feature provides a powerful tool for assessing the environmental impacts of different dispatch strategies and for exploring pathways to a more sustainable energy future.

By minimizing the objective function that includes both generation costs and carbon emissions, the model addresses the dual challenge of economic efficiency and environmental sustainability. This optimization reflects on understanding of the trade-offs involved in power generation and transmission, offering a balanced approach to meeting energy needs while minimizing costs and emissions. The model's capacity to provide such comprehensive optimization is of critical importance, offering insights that can guide policymaking, investment decisions, and operational strategies in the energy sector. Further work is required and more in-depth analysis at the sensitivities of different variables in the model needs to be done to achieve substantial and more comprehensive results. This would enable decision-makers to focus on the more critical and urgent system nodes.

The customization of this model to the specific conditions of Mexico, including its unique network configuration, real demand characteristics, and energy mix, makes it an invaluable resource for stakeholders in the Mexican energy sector. By accounting for local particularities, the model offers relevant and actionable insights that generic models cannot provide. This specificity is critical for developing strategies that are not only theoretically sound but also practically feasible and aligned with national goals and constraints. While tailored to Mexico, the model is designed for reusability by local grid planners, regulatory agencies, or academic institutions. Users can update demand forecasts, modify generation portfolios, or refine nodal constraints to reflect evolving planning scenarios within Mexico’s regional grids. Since the model is built on JuMP and GLPK, it remains accessible for public-sector institutions or universities, and could be extended to support prospective studies under long-term electricity planning, reliability analyses, or expanded carbon pricing mechanisms discussed in Chapter 5

The Julia model for optimal dispatch represents a significant advancement in energy modelling, particularly for Mexico. Its comprehensive approach, integrating a wide array of system components, storage dynamics, and environmental considerations, offers a tailored understanding of the energy landscape. This model stands as a unique contribution to the field, providing a robust tool for optimizing energy systems in a way that balances economic, environmental, and operational objectives. Its development and application can catalyse more informed and effective energy planning, policy formulation, and system operation.

6.3 Optimizing for Cost and Carbon Emissions

The optimization process under relaxed and fixed nodal constraints showcases the potential of flexible generation dispatch in achieving a more cost-effective and environmentally sustainable energy mix. The initial results indicate a total variable cost of dispatch at $22,683,616 USD, with total carbon dioxide emissions from dispatch at 348,707,632 kg CO2. After applying the optimization constraints to ensure nodal and system-level optimality, the total variable cost of dispatch slightly increases to $22,753,465 USD, whereas the total CO2 emissions decrease to 343,517,722 kg CO2. This subtle increase in cost—merely 0.31%—is justified by the 1.49% reduction in carbon emissions. Such a trade-off is particularly noteworthy given the global urgency to reduce greenhouse gas emissions and combat climate change.

These values make a case towards significance of incorporating carbon emissions into the dispatch optimization models. Traditional dispatch models have prioritized the minimization of costs, often at the expense of the environment. By contrast, the innovative approach taken in this thesis (integrating carbon emissions) aligns with modern energy policies that aim to balance economic with ecological considerations. This is of critical importance for Mexico, given its commitments under international agreements, and its own national policies geared towards a sustainable energy transition.

The optimization model's ability to incorporate a variety of generation sources, including renewable energies, and to simulate their impact on both costs and emissions is a unique contribution to the knowledge base. It enables stakeholders to make more informed decisions that consider not only the immediate financial implications but also the long-term environmental and social costs.

The changes in the generation and demand profile further illustrate the model's capability to closely align modelled generation with actual historical data, enhancing the model's accuracy and reliability.

The incorporation of carbon emissions into the model represents a significant step forward in energy dispatch optimization for Mexico. This novel approach acknowledges the full cost of energy production, including the externalities traditionally ignored in economic dispatch models. By doing so, it provides a more holistic and realistic assessment of energy generation options.

The presented model stands as an innovative tool that extends beyond traditional cost-centric optimization, embracing the complexities of modern energy systems. It reflects a critical evolution in local energy modelling, embracing the dual imperatives of economic efficiency and environmental sustainability.

6.4 Strategic Placement of BESS

This section discusses the conclusions drawn from the nodal optimization results in Chapter 3, focusing on how the strategic placement of BESS in areas with high renewable potential supports both cost efficiency and emissions reduction within the Mexican electricity system.

6.4.1 Nodes with High Renewable Energy Capacity

The addition of Battery Energy Storage Systems (BESS) into nodes with a high penetration of renewable energy sources marks a significant stride in optimizing energy dispatch to meet both economic and environmental imperatives. The results shown in *Chapter 3*, highlight the integration of BESS at a nodal level, revealing its impact on operational efficiency and carbon emissions reduction. This integration encapsulates a dual benefit stream: enhancing economic viability through cost reductions and advancing environmental goals by mitigating carbon emissions.

The implementation of BESS offers a distinctive advantage by enabling the storage of excess renewable energy, particularly during periods when supply exceeds demand. This capability ensures that the clean energy generated, for example from wind during off-peak hours, is not wasted. Instead, it can be stored and then released during peak demand times, alleviating the need for carbon-intensive generation sources. This shift not only signifies a more efficient use of renewable resources but also reduces operational costs associated with energy production and consumption patterns.

From an economic perspective, the model indicates a reduction in the variable cost of energy production and transmission, which is reflected in a 2% decrease from the base scenario to the BESS renewable scenario. This translates into significant savings, underscoring the cost-effectiveness of BESS. The optimized use of storage assets during periods of low demand and release during peak times bypasses the necessity for expensive peaking power plants, thus leading to a more efficient use of capital and operational expenditure.

Environmentally, the impact of BESS is even more pronounced. The results demonstrate a 4% decrease in carbon emissions upon the integration of BESS into the energy mix. By facilitating a higher penetration of renewable sources, BESS directly contributes to the reduction of the grid's carbon footprint. The stored energy, primarily derived from renewable sources, can be dispatched during times of high carbon intensity on the grid, thereby decreasing the reliance on fossil-fuel-based power generation and consequently reducing CO2 emissions.

The flexibility that BESS introduces into the energy dispatch process is not solely a matter of immediate economic and environmental benefit. It also prepares the energy system for a future where renewable sources will inevitably become the backbone of energy production. By smoothing out the variability inherent in renewable energy sources like solar and wind, BESS enables a more reliable and stable energy supply, which is particularly crucial for areas like node 18, where renewable generation is significant.

The results further reveals that the incorporation of BESS allows for a remarkable optimization in the use of various renewable technologies. For instance, hydro generation, operating at 99%-100% capacity usage, showcases the ability to adjust output to meet demand surges, illustrating the dynamic capability of BESS to synergize with other forms of renewable generation.

The integration of BESS into nodes with substantial renewable energy resources represents a crucial advancement in the energy sector. The model serves as a blueprint for future implementations across other nodes and regions, potentially leading to a more resilient, cost-effective, and low-carbon energy grid. This innovation is not just an incremental step but a transformative approach that can be used as support for a more sustainable energy dispatch and sets a new precedent for the integration of renewable energy on a large scale for the Mexican Electricity Network.

6.4.2 Fossil Fuels Dominated Nodes

The integration of Battery Energy Storage Systems (BESS) into nodes dominated by fossil fuels represents a substantial shift in energy dispatch strategy. In locations such as Node 32, characterized by high fossil fuel generation, the technical essence of BESS is leveraged not only to reshape the generation profile but also to decarbonise those nodes.

The presence of BESS in such a context is a significant stride towards balancing the trilemma of energy security, economic efficiency, and environmental sustainability. By storing excess energy during periods of low demand or high renewable output, and releasing it during peak demand, BESS minimizes the need to rely on fossil fuels. This strategic shifting of load handling away from traditional, carbon-intensive sources during high-demand periods mitigates some of the environmental impacts of energy generation, aligning with broader climate change mitigation efforts.

The environmental advantages are further underscored by the results indicating a 5% reduction in CO_2 emissions upon integrating BESS into the node's energy mix. This reduction exemplifies the potential of BESS to enhance the environmental footprint of energy systems that have historically been dependent on fossil fuels.

Economically, the addition of BESS heralds notable cost savings. The results reflect a 2% reduction in the variable cost of dispatch, which, when scaled across a national energy system, can translate to significant financial savings. These savings are particularly noteworthy in the context of the operational costs associated with fossil fuel generation, which includes not just the cost of fuel but also the operational and maintenance expenses that are higher for fossil fuel plants compared to their renewable counterparts.

The model's results, reflecting an 1% savings in carbon emissions without affecting dispatch cost, encapsulate the essence of what BESS brings to fossil fuel-dominated nodes: a sustainable way to maximize the usage of existing infrastructure while setting the stage for the increased incorporation of renewable energy sources.

The incorporation of BESS within fossil fuel-dominated nodes is an essential step towards redefining the operational paradigms of these power systems. It is a clear proof to the evolving nature of energy systems, reflecting a conscious move towards optimizing not just on the basis of economic metrics but also incorporating the critical dimension of carbon emissions. This approach not only provides immediate benefits in terms of cost and emissions reductions but also lays the groundwork for a more resilient and sustainable energy future. The model is an example for other regions with similar energy profiles, demonstrating that the path towards sustainability can be forged without compromising on the pillars of reliability and economic viability.

6.5 BESS Economic viability in Distributed Generation Systems (Mexico)

The integration of Battery Energy Storage Systems in Distributed Generation frameworks, underscores a transformative economic benefit for end-users of energy systems. The "peak shaving" approach, enabled by the BESS, serves as an axis in this new paradigm, allowing for the strategic charging of batteries during off-peak hours with cheaper, often renewable energy and discharging during peak hours to alleviate demand charges. This operation not only optimizes energy costs but also reinforces the grid, supported by bespoke site design, delivering substantial savings and promoting the assimilation of renewable energy sources into the energy mix.

The economic analysis for the incorporation of a BESS in a distributed system in Mexico, points to a palpable reduction in operational expenditures for a 500 kW solar PV and 0.5MW/1MWh BESS installation, evidencing savings of up to 30% on monthly CFE charges. This level of cost efficiency is a crucial motivator for the private sector, enhancing the appeal and viability of investing in renewable and storage solutions. With an average monthly generation of savings and a calculated payback period, the benefits of adopting BESS at the DG level have been made evident.

Results from the DG system case study, indicate that the decentralized generation through BESS not only aligns with the decarbonization and efficiency goals of the Mexican Electricity Network but also serves as a conduct for the liberalization of the energy market. As DG and BESS systems become more prevalent, they could significantly disrupt the traditional energy market structures, leading to a more competitive environment that benefits the end-users with lower costs and the environment. Flexible, distributed generation markets with bi-directional generation and storage, like EV infrastructure, are predicted to be the future for the energy sector in Mexico (*Oropeza-Perez, I., et al., 2021) (Luo, L., 2020*).

The case study projected payback time frames—5.4 years for BESS systems and 8 years for the PV + BESS hybrid system—highlight the economic feasibility and long-term benefits of such investments. These projections, after methodological confirmation by more case studies, can be influential in policymaking, potentially spurring the development of supportive regulatory frameworks and financial incentives that accelerate the adoption of renewable energy and storage technologies. Mexico is currently considering the limit augmentation of DG max capacity installations from 0.5MW to 1MW, a policy that would further promote the adoption of these systems (*Alavez, M., 2023*).

The incorporation of BESS systems at the DG level offers a compelling economic incentive for final energy users, bolstering the case for a more rapid transition to renewable energy. The financial benefits, combined with the environmental merits, present a robust case for the adoption of such systems.

6.6 Lessons learned from LCA of Storage System

Understanding the potential of storage systems in regions like the UK is instrumental for several reasons. First, it provides empirical data on the effectiveness of these systems in reducing carbon emissions. The net emissions reduction of Sunamp devices, when the embedded carbon is accounted for, demonstrates a tangible impact of a net emissions reduction of 1.2 kt CO2 eq., achieved with an additional 75% left of their expected operational life remaining. This kind of data can offer a benchmark for what Mexico might expect from implementing similar technologies.

Second, the analysis of the carbon savings and the net emissions reduction relative to the overall emissions profile provides a contextual understanding of the scale at which storage systems can contribute to national emissions goals. The results indicate that Sunamp devices could account for up to a 1.0% reduction in the annual territorial GHG emissions per capita, which is significant when considering the broader push for decarbonization. Transferring this contextual understanding to Mexico, with its unique emissions profile and energy mix, can help policymakers and energy strategists identify the scale and type of storage systems that would be most effective for their specific needs.

Third, the case study emphasizes the importance of lifecycle assessments in evaluating the total carbon savings of storage systems. This comprehensive approach to calculating the carbon footprint—including the embedded carbon of the device—ensures that all stages of the device's lifecycle are considered, from production to disposal. This holistic view is essential for Mexico as it seeks to understand the full environmental impact of integrating storage systems into its energy infrastructure.

Moreover, the focus on the embedded carbon in the analysis serves as a crucial reminder of the need for sustainable manufacturing processes and the use of materials that minimize environmental impact. This is particularly relevant for Mexico, where the manufacturing sector plays a significant role in the economy and where there is a growing interest in developing green technologies domestically.

Lastly, the results suggests that continuous decarbonization and improvements in roundtrip efficiency are key drivers for maximizing the benefits of storage systems. For Mexico, which is actively working to decarbonize its grid and improve energy efficiency, the lessons from the UK's experience with Sunamp devices can inform the development of more effective policies and technologies that support these goals.

Learning from the deployment and impact of storage systems like Sunamp in the UK can be invaluable for Mexico as it continues to develop and refine its energy strategy. The results demonstrate the potential for significant emissions reductions and provides a comprehensive framework for assessing the full lifecycle impact of such technologies.

6.7 Recommendations for Further Work

This thesis has accomplished the main objectives and scope of work intentioned in Chapter 1. However, it is important to suggest how this piece of research could be carried forward.

6.7.1 Comparative Analysis Across Different Geographical Conditions

In the quest to harness the full potential of Battery Energy Storage Systems, a specific understanding of their operation across diverse geographical landscapes becomes critical. The proposition to conduct comparative studies across varied environmental conditions is a recognition of the complex interplay between BESS performance and the geographical particularities of solar irradiation, wind resource, and others like ambient temperatures. This research is imperative for tailoring BESS solutions that are not only region-specific but also optimized for the unique challenges and opportunities presented by each region or Node.

BESS, as a cornerstone of modern energy infrastructure, is not a one-size-fits-all solution. Its ability to store and dispatch energy on-demand is a function that can be affected by extreme heat, which may degrade battery performance, or by suboptimal solar exposure, which can limit the charging capacity of batteries paired with photovoltaic systems (*Mazzeo, D., et al., 2020*). In windier regions, the variability of wind profiles can result in fluctuating input to BESS, requiring sophisticated management strategies to ensure stability and reliability. Therefore, future work must delve into the granularity of local climate data to inform BESS deployment strategies that align with the temporal and spatial energy availability inherent to each region.

Understanding these geographical influences will facilitate the development of advanced predictive models that can accurately forecast energy storage needs and battery degradation over time (*Wang, X., et al., 2018*). This is essential not only for enhancing operational efficiency but also for extending the lifespan of BESS, thereby ensuring economic viability and sustainability. The investigation will also contribute to the development of robust design standards that take into account the stressors imposed by different environmental conditions, leading to the production of more resilient and adaptable energy storage systems (Yüksel, T., et al., 2015).

Moreover, the optimal sizing of BESS is a critical factor for its successful integration into the energy grid. By comparing how BESS operates under a spectrum of climatic conditions, stakeholders can better estimate the capacity and scalability required to meet energy demands. This will also aid in the formulation of regulatory frameworks and incentive programs that accurately reflect the regional variabilities and promote equitable access to energy storage technologies.

In essence, comparative studies of BESS implementation across different geographical conditions will enable a more intelligent and adaptive energy storage ecosystem. They will pave the way for tailored, efficient, and resilient energy storage solutions that can withstand the tests of diverse environmental conditions, contributing to the resilience and sustainability of global energy systems. This future research will not only benefit the regions directly involved but also provide a template for other regions to evaluate the suitability of BESS within their own environmental contexts.

While this thesis already incorporates region-specific demand profiles in the dispatch optimization model, further extensions could integrate advanced geographical factors through operational roles of BESS such as black start capability, grid-forming vs. grid-following modes, or system support in regions with high outage frequency due to renewable intermittency. These functionalities can be reflected in the model by including binary variables representing service availability per node, or by constraining the state of charge and dispatch dynamics to meet grid resilience requirements under different network conditions. For example, in areas prone to frequent blackouts, storage could be required to maintain a minimum reserve (e.g. SOH never below 40% or 50%) or enable fast frequency response, which would affect both the operational cost and sizing recommendations. Such additions would enhance the model's applicability for supporting regulatory planning and network reliability at a more granular regional level.

6.7.2 Investigate the Impacts of Large-scale BESS on grid stability and reliability

The imperative to integrate Battery Energy Storage Systems (BESS) into the Mexican power grid at scale comes with the promise of enhancing stability and reliability, essential attributes for any modern energy network. A systematic investigation into how BESS affects these critical aspects of grid performance is not just a technical necessity but a strategic imperative.

The recommendation to focus on the impacts of BESS on grid stability and reliability recognizes the multifaceted role that energy storage can play. BESS can act as a dynamic buffer, absorbing fluctuations in power generation and consumption, thereby maintaining the delicate balance required for grid stability. As renewable energy sources, which are inherently intermittent, become more prevalent, the ability of BESS to provide immediate response to frequency deviations becomes increasingly important. Their capacity to quickly inject or absorb power can help in maintaining the frequency within the tight tolerances required for grid stability (*Paiva and Castro, 2024; He et al., 2022*).

Voltage control is another critical area where BESS can offer substantial benefits. Voltage fluctuations can lead to inefficient grid operations and even damage to infrastructure and consumer electronics. BESS can respond to these fluctuations in real-time, providing reactive power support where necessary and thereby ensuring a consistent quality of power supply.

Furthermore, the role of BESS in black start capabilities — the process of restoring power in the event of a blackout — is an area ready for exploration in the Mexican Electricity Network. BESS could provide the initial power necessary to jump-start generators, which in turn can bring the grid back online. This capability could significantly reduce recovery times after outages, minimizing the economic and social impact of blackouts.

For grid operators and planners, understanding these impacts is critical. It ensures that investments in BESS are not just economically justified but also enhance the operational resilience of the power grid. This research should incorporate not only theoretical modelling and simulations but also empirical studies involving actual BESS installations.

6.7.3 End-of-life management of BESS to ensure decarbonization

The rapid adoption of Battery Energy Storage Systems globally indicates a significant step towards a renewable-driven future. However, with this uptick comes the responsibility of addressing the end-of-life phase of these systems to mitigate potential environmental impacts. The recommendation to proactively delve into EOL management strategies for BESS is a clear remark towards sustainability and environmental stewardship.

Effective EOL management is critical for BESS, as it ensures that the environmental benefits accrued during operational life are not overshadowed by unsustainable disposal practices. The investigation should include a full spectrum of EOL strategies, including recycling of valuable materials like lithium, cobalt, and nickel, which can be reintegrated into the manufacturing supply chain, thus reducing the need for virgin material extraction and the associated environmental degradation.

Repurposing represents another strategic EOL pathway for BESS. Batteries that may no longer meet the stringent requirements for energy storage applications could still hold sufficient capacity for less demanding uses, such as stationary storage applications in residential or commercial settings. This second life can extend the value derived from the embodied energy and resources invested in battery production.

Lastly, when batteries are beyond repurposing, safe and environmentally responsible disposal methods must be developed. This necessitates research into novel dismantling techniques that minimize environmental risk and the development of landfill guidelines that prevent soil and water contamination.

Given the expected surge in BESS deployment, establishing robust, scalable, and economically viable EOL processes is not an option but an imperative. It is essential to foster a circular economy within the energy sector, ensuring that the transition to renewable energy systems like BESS is genuinely sustainable. Engaging in this research will not only safeguard environmental health but also reinforce the sustainability credentials of BESS, bolstering public and investor confidence in energy storage technologies.

6.8 Thesis Conclusion

The comprehensive analysis conducted within this research thesis has culminated in a profound understanding of the transformative potential of Battery Energy Storage Systems within the renewable energy sector in Mexico. This thesis has not only reinforced the crucial position of BESS as a catalyst for grid stability and decarbonization but has also presented an optimal dispatch model, a unique contribution to the regional body of knowledge, particularly as an open-source tool for the Mexican electricity network.

Central to this thesis is the innovative optimal dispatch model developed for the Mexican electricity network, tailored to address the specifics of integrating BESS alongside diverse renewable resources. The model stands as evidence to the synergy between technological advancement and sustainability. It serves as a groundbreaking open-source framework that future researchers and practitioners can utilize to further refine energy strategies within Mexico and potentially adapt for other global contexts.

The strategic application of this model has clarified pathways to not only stabilize the grid amidst the variable nature of renewable energy sources but also to optimize the economic and environmental performance of the energy system.

This research has demonstrated the multifaceted role of Battery Energy Storage Systems (BESS) in the dynamic landscape of renewable energy integration. The findings presented herein reinforce the narrative that BESS is not just an adjunct to the energy mix but a critical pivot point for the transformation of power systems.

This thesis has demonstrated that BESS, when deployed strategically, can lead to significant reductions in carbon emissions and enhance the operational reliability and efficiency of the grid. The results revealed that the integration of BESS across varied geographical conditions has profound implications for the stability and flexibility of energy networks, especially in the context of Mexico's unique energy landscape. This is the first such analysis for this country.

The core of this thesis has been the optimization of energy dispatch with BESS. The analyses have shown that BESS can provide stabilization against the variability inherent in renewable energy sources like solar and wind, thereby improving the reliability of power supply.

In regions with high renewable energy capacity, such as Mexico, the adoption of BESS has been found to offer a dual benefit: mitigating the intermittency of renewables while also shaving peaks off energy demand, thus deferring the need for costly and environmentally damaging Peaker plants. The data demonstrated the importance of conducting comparative analyses across different geographic conditions to optimize the deployment of BESS for each unique setting, maximizing both environmental and economic benefits.

Additionally, *Chapter 4* broadened the scope of the thesis by examining the economic feasibility of Battery Energy Storage Systems when integrated into distributed generation projects. This user-side analysis demonstrated that BESS not only enhance self-consumption and reduce electricity bills for commercial and industrial users, but also contribute to grid resilience by smoothing demand peaks. The case study presented quantified cost savings for consumers under specific tariff structures, highlighting that BESS in DG configurations offer a compelling business case in regions with changing demand patterns. These insights are crucial to understanding how decentralized energy systems can complement utility-scale strategies to accelerate Mexico's energy transition.

Chapter 5 complemented the core dispatch modelling with electrical storage by evaluating the decarbonisation potential of energy storage through a Life Cycle Assessment of heat-based storage systems using Phase Change Materials. The analysis revealed that these systems can offer substantial reductions in greenhouse gas emissions over their lifetime when compared to traditional heating technologies. By accounting for emissions from production to end-of-life, the study underscored how storage technologies—beyond lithium-ion BESS—can contribute meaningfully to broader decarbonisation goals. The findings reinforce the role of diverse storage solutions in reducing indirect emissions, particularly in applications such as residential or commercial heating. For policymakers and industry stakeholders, the insights from this thesis offer actionable guidance for the strategic incorporation of BESS into energy systems. It emphasizes the need for informed policy that supports the scaling of BESS, accounting for the particularities of regional variability and lifecycle sustainability. The thesis underscores the importance of fostering partnerships between governments, industry, and academia to drive innovation in BESS technology and its application.

In summary, the conclusions drawn from this body of work reinforce the notion that BESS is a cornerstone technology for achieving a sustainable and resilient energy future in Mexico. It provides an Open-Source tool and methodology to ensure future research continues to enhance a more efficient energy network. Resulting in a critical contribution towards the decarbonisation of the local economy.

6.9 Limitations of the Work

This thesis is subject to limitations inherent to the scope and assumptions of the optimization framework. The dispatch model was developed using a linear programming approach that does not account for stochastic variations in renewable generation or real-time market dynamics. While this allowed for clarity and transparency in interpreting the results, it limited the model’s ability to capture uncertainty and variability—factors that are increasingly relevant as renewable penetration grows.

The spatial and temporal granularity of the model also represents a simplification. The system was modelled over a single 24-hour period with a fixed nodal structure, based on a snapshot of the Mexican Electricity Network. This means that seasonal variations, demand growth projections, or long-term storage behaviour were not explored in detail. As a result, the findings should be interpreted as representative rather than predictive, offering directionally correct insights under controlled scenarios.

Additionally, while the Life Cycle Assessment of heat-based storage provided valuable environmental insights, the environmental evaluation of lithium-based BESS systems was limited to operational emissions within the dispatch model. A full cradle-to-grave comparison of BESS technologies was beyond the scope of this study but remains essential for a holistic decarbonisation strategy. These limitations open opportunities for future research to build upon and refine the findings presented in this work.

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8. Appendix A

Hourly demand and Max demand for all Nodes modelled.

Max Demand	Node	Code	Name	Control Region	12:00:00 a. m.	01:00:00 a. m.	02:00:00 a. m.	03:00:00 a. m.	04:00:00 a. m.	05:00:00 a. m.
746.5264	1	A	Hermosillo	Noroeste	625.37222	592.64954	585.01624	578.14061	571.0597	570.0526
630.6228	2	B	Cananea	Noroeste	580.30594	571.93645	564.39	561.66578	551.34934	566.8719
282.6504	3	C	Obregón	Noroeste	223.83988	216.28103	212.35672	210.90976	209.34029	209.60268
154.3588	4	D	Los Mochis	Noroeste	108.73429	100.26374	97.24465	95.29312	93.31833	94.19827
432.3798	5	E	Culiacán	Noroeste	317.24045	295.55438	283.69176	276.29011	271.12514	271.00597
219.5313	6	F	Mazatlán	Noroeste	170.65556	160.54908	155.56158	151.19374	147.82241	147.37931
2466.069				Total	2026.14834	1937.23422	1898.26095	1873.49312	1844.01521	1859.11073
811.7404	7	G	Juárez	Norte	623.89116	596.69762	579.50592	573.05422	571.54684	597.81713
166.2151	8	H	Moctezuma	Norte	100.72274	100.55267	99.97747	99.80245	100.13678	104.00672
743.5753	9	I	Chihuahua	Norte	559.56697	547.59957	540.78984	544.53932	559.42376	584.88774
297.6612	10	J	Durango	Norte	219.01409	211.43035	206.58222	202.02466	203.18738	206.1697
1347.571	11	K	Laguna	Norte	1116.2194	1087.80639	1076.38351	1067.53764	1067.25577	1088.11676
3366.763				Total	2619.41436	2544.0866	2503.23896	2486.95829	2501.55053	2580.99805
424.9518	12	L	Río Escondido	Noreste	252.48079	244.74923	240.90035	239.69477	241.79297	251.64163
582.2771	13	M	Nuevo Laredo	Noreste	360.15343	347.04261	339.08672	334.9935	331.89561	342.90016
541.2619	14	N	Reynosa	Noreste	398.6137	376.48844	371.57331	366.24776	366.76286	361.59896
426.7996	15	O	Matamoros	Noreste	287.28842	275.31136	268.48206	264.90758	271.12299	282.81949
3240.431	16	P	Monterrey	Noreste	2254.10198	2142.24959	2091.71937	2067.85397	2111.79358	2156.83221
872.2696	17	Q	Saltillo	Noreste	680.24443	657.821855	680.77633	649.03938	682.47415	651.514135
231.1226	18	R	Valles	Noreste	163.34934	161.66913	161.14708	161.61688	160.91311	165.80163
810.1618	19	S	Huasteca	Noreste	649.42149	633.04512	621.79616	610.64912	615.43039	622.98863
56.85672	20	T	Tamazunchale	Noreste	30.3935	28.72077	27.90632	27.53366	28.015	29.34221
226.4146	21	U	Güémez	Noreste	158.95111	151.42164	145.71314	142.56315	141.52905	146.81425
7412.546				Total	5234.99819	5018.519745	4949.10084	4865.09977	4951.72971	5012.253305
590.1697	22	V	Tepic	Occidental	454.9031	433.73828	420.7121	414.26643	410.18347	413.53061
1605.248	23	W	Guadalajara	Occidental	1095.468603	1043.895527	1013.91315	1000.51843	1004.774567	1041.68348
1255.527	24	X	Aguascalientes	Occidental	794.0332	763.94265	747.27339	745.47508	760.21573	793.82794
1048.496	25	Y	SLP	Occidental	789.21418	801.68794	755.81246	774.84612	775.15814	811.27786
631.3144	26	Z	Salamanca	Occidental	399.1482633	380.0539367	370.76076	368.96135	371.5533967	382.92815
179.3307	27	AA	Manzanillo	Occidental	143.33171	138.75118	137.4018	134.12066	135.05203	137.89708
163.1306	28	BB	Carapan	Occidental	109.06319	104.18656	100.93155	98.5944	97.6047	98.65518
9224.83				Total	6436.235173	6255.543911	6093.267706	6100.272807	6153.897756	6323.030931
3775.219	29	CC	Lázaro Cardenas	Central	2497.430174	2364.421937	2305.815355	2256.124046	2277.85656	2465.206178
3751.614	30	DD	Querétaro	Occidental	2651.072926	2589.287838	2546.462496	2563.490337	2599.355723	2643.230631
4169.766	31	EE	Central	Central	2684.679106	2514.292572	2439.299268	2389.700756	2417.28854	2632.479236
7944.986				Total	5182.10928	4878.714509	4745.114623	4645.824802	4695.1451	5097.685414
870.164	32	FF	Poza Rica	Oriental	664.63569	686.38361	673.47895	640.83503	675.6206	677.01861

1223.069	33	GG	Veracruz	Oriental	992.78253	959.79781	934.92714	918.24297	912.17235	930.92566
1705.733	34	HH	Puebla	Oriental	1287.91094	1227.39994	1213.27153	1205.10306	1219.44044	1249.52093
551.3445	35	II	Acapulco	Oriental	443.97569	426.93531	415.22076	403.75252	396.08817	395.83632
243.8974	36	JJ	Temascal	Oriental	144.48977	135.65485	131.53307	129.49631	131.34958	143.35826
735.1426	37	KK	Coatzacoalcos	Oriental	606.09177	588.11511	573.52074	564.01091	557.83901	565.91025
800.8274	38	LL	Tabasco	Oriental	641.77219	607.06799	572.98359	548.40247	528.4171	513.93744
943.2855	39	MM	Grijalva	Oriental	712.63036	687.98656	684.98004	677.27895	708.13979	733.75113
85.50924	40	NN	Ixtepec	Oriental	63.03724	60.69915	58.74295	57.17627	56.6369	57.70539
7158.972				Total	5557.32618	5380.04033	5258.65877	5144.29849	5185.70394	5267.96399
76.77706	41	OO	Lerma	Peninsular	65.69032	61.97435	57.95389	54.33451	51.79829	49.97829
726.1711	42	PP	Mérida	Peninsular	599.3256	564.15102	535.21656	513.73834	499.89089	493.32479
545.4871	43	QQ	Cancún	Peninsular	434.71321	416.21685	399.06756	389.63875	386.15714	392.59162
176.8412	44	RR	Chetumal	Peninsular	146.51992	139.52089	133.84836	130.24293	129.00414	132.32896
305.4817	45	SS	Cozumel	Peninsular	232.51051	223.76691	216.34213	213.49289	214.38767	220.12131
1830.758				Total	1478.75956	1405.63002	1342.4285	1301.44742	1281.23813	1288.34497
871.3245	46	TT	Tijuana	Baja California	752.6878	758.97409	745.50959	729.14462	713.23564	701.84176
165.9967	47	UU	Ensenada	Baja California	140.89573	135.90772	132.06577	133.1691	129.50009	130.35464
522.4298	48	VV	Mexicali	Baja California	433.41326	426.80288	415.89984	402.69156	405.08044	401.5432
114.8498	49	WW	San Luis Rio Colorado	Baja California	96.33293	93.20858	91.10938	90.19748	89.88862	90.63471
1674.601				Total	1423.32972	1414.89327	1384.58458	1355.20276	1337.70479	1324.37431
40.16801	50	XX	Villa Constitucion	Baja California Sur	35.47375	34.19172	33.49738	33.18835	32.94702	33.03126
77.33935	51	YY	La Paz	Baja California Sur	59.78665	56.79968	54.49734	53.03682	52.20143	53.27805
161.3029	52	ZZ	Los Cabos	Baja California Sur	121.97257	117.07421	113.62493	112.28554	111.80928	113.93387
278.8103				Total	217.23297	208.06561	201.61965	198.51071	196.95773	200.24318
28.42836	53	AAA	Mulegé	Mulege	15.19675	14.360385	13.95316	13.76683	14.0075	14.671105
					30190.75052	29057.0886	28390.22774	27984.875	28161.9504	28968.67599

06:00:00 a. m.	07:00:00 a. m.	08:00:00 a. m.	09:00:00 a. m.	10:00:00 a. m.	11:00:00 a. m.	12:00:00 p. m.
594.69485	645.86502	682.6313	700.66857	707.391	708.91389	712.08404
580.92207	582.56452	603.36766	621.12578	621.35014	616.49407	607.58469
218.28993	231.93436	240.36152	245.7419	252.71363	252.29943	256.7105
99.35453	110.35452	116.57478	120.43329	126.49684	131.46001	133.91813
284.11508	309.35068	325.29468	345.88967	367.36215	382.17043	399.75298
152.01767	160.64221	164.55103	172.09987	184.02335	193.09749	200.34771
1929.39413	2040.71131	2132.78097	2205.95908	2259.33711	2284.43532	2310.39805

640.05931	734.92281	780.63888	789.6441	789.52067	779.082	769.81257
109.55198	116.33387	124.36859	135.35674	143.46319	145.88072	145.50233
645.43169	696.63901	711.35811	702.53774	683.72376	662.67811	638.30934
219.84997	238.11682	252.83057	264.13559	265.76237	266.3386	265.66701
1147.49179	1216.40592	1247.41493	1265.68624	1286.74074	1288.09722	1282.00351
2762.38474	3002.41843	3116.61108	3157.36041	3169.21073	3142.07665	3101.29476
273.69632	303.01317	318.13614	332.93343	354.10013	362.24125	356.8681
367.80611	429.40247	465.2951	441.22052	448.9044	455.88667	462.83104
388.22526	489.44963	522.69261	465.4836	478.69177	494.76185	501.98755
309.33327	340.47289	357.64062	373.84905	387.21126	399.74647	402.7612
2293.30413	2383.48747	2476.3206	2592.746	2661.77132	2738.64487	2799.22149
749.497425	795.707445	822.17238	866.763035	804.953645	872.269645	844.155305
176.2628	189.89478	205.58152	210.35513	209.61353	206.70631	206.2834
639.88944	644.76921	667.23253	680.36677	688.44516	708.33988	720.59068
33.06443	37.46115	40.7467	42.78315	43.82793	45.22441	45.87793
158.66009	165.60162	171.23489	177.41915	179.29652	184.84353	189.55615
5389.739275	5779.259835	6047.05309	6183.919835	6256.815665	6468.664885	6530.132845
429.41994	451.92966	467.59061	480.35341	490.20733	495.44951	495.93255
1156.56021	1299.221337	1387.49977	1430.533953	1429.190367	1455.50398	1466.74832
880.11106	997.13758	1120.85222	1175.01479	1167.12798	1159.62871	1172.23463
847.34335	932.50996	1027.11578	1021.42299	1003.70351	1023.20391	1044.14891
432.64244	483.7773767	512.40218	526.3106933	531.4244267	536.86266	538.45633
145.87677	158.33064	168.2068	171.90098	174.57227	171.93474	176.39361
104.15682	116.62346	126.56186	130.9149	133.33055	137.30339	141.12382
6924.163717	7692.039378	8299.614273	8492.25798	8517.484407	8621.604186	8658.903702
2709.136164	2946.939458	3065.978765	3172.580292	3284.404133	3355.558752	3338.585124
2928.053127	3252.509365	3489.385053	3555.806263	3587.927974	3641.717286	3623.865532
2944.23698	3220.271386	3379.424652	3544.38013	3696.588052	3789.77271	3785.40931
5653.373144	6167.210844	6445.403417	6716.960422	6980.992185	7145.331462	7123.994434
671.65615	716.18191	754.85557	780.6288	787.90506	807.80254	793.61291
965.22699	988.45977	1019.31258	1064.41943	1087.91508	1131.2661	1150.83494
1336.81064	1403.82612	1468.04088	1523.38722	1617.87369	1629.65506	1653.1497
406.90814	414.58334	424.97938	444.42603	460.38754	473.60934	480.70622
164.1443	164.53978	161.73745	163.55235	165.72471	169.84075	172.62338
589.59514	589.69607	601.56033	621.20772	634.89799	647.4667	660.53202
504.45295	482.34837	489.96924	512.07002	527.64117	548.31087	576.40338
744.03801	727.14956	751.50247	736.92405	764.5158	771.14101	779.56813
60.05614	57.93488	59.25639	62.27975	64.47628	66.50421	67.8173
5442.88846	5544.7198	5731.21429	5908.89537	6111.33732	6245.59658	6335.24798
48.4622	47.61979	52.23299	53.2375	54.52774	56.70277	59.64003
494.89459	508.26331	541.75183	574.56622	597.44394	624.32323	632.04094
407.67699	437.71851	477.1713	500.83754	513.72483	521.67675	523.74488
137.01076	145.09713	153.4217	159.34414	162.2686	162.85937	162.06735

230.6708	246.77974	265.88513	278.31872	281.74836	284.58343	288.11369
1318.71534	1385.47848	1490.46295	1566.30412	1609.71347	1650.14555	1665.60689
715.16483	727.47391	761.37978	830.33576	830.09684	859.64463	871.32445
132.85343	135.08529	142.01124	145.66306	146.87666	148.15147	148.2851
411.81399	406.60164	424.98092	431.66575	433.4166	436.12563	449.6816
93.25583	95.9366	100.33002	101.94598	101.40477	100.51268	99.75669
1353.08808	1365.09744	1428.70196	1509.61055	1511.79487	1544.43441	1569.04784
34.13495	35.07954	36.94828	38.10005	39.022	39.42213	38.97039
54.60447	55.22276	59.63568	64.0726	64.19303	65.25144	66.64404
118.61334	124.35666	132.93622	138.28261	141.0087	142.57939	144.12223
207.35276	214.65896	229.52018	240.45526	244.22373	247.25296	249.73666
16.532215	18.730575	20.37335	21.391575	21.913965	22.612205	22.938965
30997.63186	33210.32505	34941.73556	36003.1146	36682.82345	37372.15421	37567.30213

01:00:00 p. m.	02:00:00 p. m.	03:00:00 p. m.	04:00:00 p. m.	05:00:00 p. m.	06:00:00 p. m.
695.56218	694.81272	699.78611	699.39686	703.41084	711.75224
598.46162	589.56651	572.39835	585.7497	594.43258	601.14003
255.28004	256.43369	259.4137	261.91289	265.08431	268.65079
131.75186	131.10272	132.32413	133.12901	133.86521	135.77054
405.82359	409.20929	418.33973	415.68965	411.63392	411.68029
198.60469	202.30717	207.10267	209.40158	209.24105	204.68661
2285.48398	2283.4321	2289.36469	2305.27969	2317.66791	2333.6805
746.63806	734.70656	725.958	709.47948	713.74971	738.51618
145.42446	149.58897	152.91675	154.61494	155.32036	160.38486
636.35908	652.31659	653.39763	672.33911	679.96521	690.69075
261.53739	263.48993	265.56826	266.57982	263.28376	267.05438
1273.45092	1284.2127	1305.32148	1323.67225	1326.53711	1297.95579
3063.40991	3084.31475	3103.16212	3126.6856	3138.85615	3154.60196
364.17506	370.35387	375.70372	378.92484	384.46021	399.953
479.93127	487.0986	491.78982	501.57945	539.5176	565.04481
513.99446	494.01257	494.15472	475.47717	541.26192	475.09732
414.32699	423.50862	426.79963	426.09589	410.73896	404.57578
2864.5162	2942.97289	3001.88889	3011.08522	2933.0964	3040.83702
861.15696	814.07785	781.355545	853.488305	864.437665	844.16693
212.91651	212.45627	211.67858	218.16284	218.06423	220.02311
739.97653	748.33036	754.81425	730.48818	755.40505	749.06895
45.82966	46.0277	46.75529	46.27947	46.68845	49.2039
196.65335	201.84718	206.87099	208.09553	209.43745	219.97208
6693.47699	6740.68591	6791.811435	6849.676895	6903.107935	6967.9429
495.49471	510.37608	523.90283	535.3453	543.5145	553.09408

1478.418127	1490.243257	1521.85974	1556.197767	1564.340393	1526.653653
1188.5147	1193.30417	1226.87424	1255.5265	1251.8019	1216.83939
1040.04169	1048.49606	991.69622	1008.0118	1020.50473	983.07735
539.4855067	541.8888567	548.80488	551.2599967	551.9737233	576.6911033
179.33068	179.26591	171.61467	172.35662	173.20237	166.33964
143.41736	146.32666	147.76427	150.07306	148.76927	149.62856
8750.582377	8817.584435	8884.130966	8918.77057	8874.777575	8636.126344
3337.887252	3355.817086	3408.362647	3462.394354	3448.690913	3543.737551
3685.879604	3707.683442	3751.614116	3689.999527	3620.670688	3463.802567
3788.59956	3805.283884	3858.669098	3900.084904	3880.906382	3976.507988
7126.486812	7161.10097	7267.031745	7362.479258	7329.597295	7520.245539
798.25686	811.43552	826.06649	854.87983	837.75978	838.24188
1173.57927	1186.88611	1193.65246	1199.97043	1172.56891	1160.96704
1648.40553	1670.79005	1666.18983	1705.73317	1692.27948	1593.4551
489.85504	498.23699	502.42725	504.15233	495.71706	506.3174
176.92947	178.37811	180.78715	181.99232	183.62178	212.67239
658.60045	701.27254	717.41305	689.83367	671.91122	699.09614
594.95395	618.15444	634.78911	634.45227	624.70682	702.96027
790.81258	750.34697	810.96207	782.3744	819.63072	926.53015
69.63821	70.83102	72.6492	72.78974	72.51335	76.21622
6401.03136	6486.33175	6604.93661	6626.17816	6570.70912	6716.45659
61.20723	63.51121	66.84347	68.56692	67.55126	69.86944
640.82321	656.50339	683.2946	700.86276	697.36806	726.17107
526.57038	532.08793	533.85873	528.4908	525.38905	545.11655
162.52749	160.04629	161.79629	159.49603	161.4353	176.84123
293.07042	298.47086	302.67113	301.24542	299.0034	305.48166
1684.19873	1710.61968	1748.46422	1758.66193	1750.74707	1823.47995
859.86007	850.62204	863.96446	713.84274	737.28045	735.91816
147.63429	145.82802	146.51411	150.75684	161.03712	165.99672
452.27005	441.2991	453.25199	455.95702	463.27536	512.65903
97.71547	96.23844	96.57502	97.919	107.95521	114.63747
1557.47988	1533.9876	1560.30558	1418.4756	1469.54814	1529.21138
38.20584	38.41406	38.55827	38.95882	38.78919	40.16801
68.39165	67.67147	67.88424	67.05734	68.53555	75.76666
145.50107	146.47743	148.57335	151.32944	153.8204	161.30292
252.09856	252.56296	255.01586	257.3456	261.14514	277.23759
22.91483	23.01385	23.377645	23.139735	23.344225	24.60195
37837.16343	38093.634	38527.60087	38646.69304	38639.50056	38983.5847

07:00:00 p. m.	08:00:00 p. m.	09:00:00 p. m.	10:00:00 p. m.	11:00:00 p. m.	Max Demand
737.04707	746.52641	744.72457	727.51744	693.76163	746.5264

612.09428	619.54085	630.6228	627.59093	618.10825	630.6228
279.78682	282.65037	278.36123	269.5546	256.3733	282.6504
149.6675	154.35876	151.8194	143.89142	131.21763	154.3588
431.91914	432.37977	419.768	397.61668	368.10216	432.3798
218.92693	219.53128	214.92042	205.76072	194.47393	219.5313
2429.44174	2454.98744	2440.21642	2371.93179	2262.0369	2466.069
784.37348	805.30117	811.74038	795.38428	759.70101	811.7404
166.21512	165.98206	164.61416	158.37357	152.69723	166.2151
737.44778	743.57534	727.24541	698.73039	663.91825	743.5753
294.55237	297.66117	289.90424	266.3782	242.86955	297.6612
1347.57144	1341.91028	1310.33668	1297.77831	1238.00971	1347.571
3330.16019	3354.43002	3303.84087	3216.64475	3057.19575	3366.763
416.8328	424.95175	419.95669	402.31638	381.21505	424.9518
582.27706	573.04755	563.87251	544.46841	518.85461	582.2771
466.74481	413.32779	401.57338	386.92577	395.74774	541.2619
409.44964	402.43101	382.61131	359.58542	336.0571	426.7996
3240.4307	3174.61079	3047.57479	2842.64864	2594.241	3240.431
856.985155	864.45183	845.48447	829.94296	839.650385	872.2696
224.99246	231.1226	228.86653	222.2685	212.10478	231.1226
810.16177	799.38866	782.4515	743.98263	717.70843	810.1618
53.69567	56.85672	55.74094	52.71506	48.44433	56.85672
226.41457	222.87526	216.57634	202.51939	186.44619	226.4146
7287.984635	7163.06396	6944.70846	6587.37316	6230.469615	7412.546
586.80664	590.16968	573.52307	541.21868	501.86659	590.1697
1605.247783	1586.801253	1514.759817	1454.703473	1356.92307	1605.248
1233.38728	1208.70573	1176.93304	1123.72591	1044.42121	1255.527
977.22132	1025.60249	985.6268	962.82861	990.48386	1048.496
631.3144233	621.0612033	589.8270467	538.3753333	480.12806	631.3144
175.82626	167.41001	159.01387	154.33624	154.14072	179.3307
163.13059	159.65798	153.33466	142.34985	129.79267	163.1306
9005.20939	8998.813928	8729.767632	8454.799165	8101.021907	9224.83
3775.219426	3768.679858	3597.012871	3329.689222	3021.420629	3775.219
3632.275093	3639.405581	3576.749329	3537.261068	3443.265727	3751.614
4169.766104	4127.047084	3924.281598	3611.685294	3252.697782	4169.766
7944.98553	7895.726942	7521.294469	6941.374516	6274.118411	7944.986
870.16398	855.18191	820.96796	817.05121	812.80991	870.164
1223.06854	1208.25623	1174.23188	1180.30146	1136.71764	1223.069
1623.5342	1604.61317	1536.15597	1465.04482	1441.04593	1705.733
551.34452	549.85113	538.0876	512.24547	478.66064	551.3445
243.89741	237.08912	219.96048	190.4473	162.82859	243.8974
735.1426	729.40294	722.62172	614.27692	593.79409	735.1426
770.4951	794.29935	800.82743	790.71162	754.63277	800.8274
932.29201	943.28549	896.74502	800.92969	743.61426	943.2855

85.50924	84.35111	80.51535	75.6498	68.87815	85.50924
7035.4476	7006.33045	6790.11341	6446.65829	6192.98198	7158.972
71.76566	73.0564	75.67194	76.77706	75.19018	76.77706
723.80479	722.29253	721.55962	724.03165	700.50245	726.1711
545.4871	540.66971	534.35302	512.87936	486.49734	545.4871
176.30727	174.94735	173.601	169.29291	160.46337	176.8412
302.71227	299.71092	292.54431	273.16575	258.42239	305.4817
1820.07709	1810.67691	1797.72989	1756.14673	1681.07573	1830.758
746.7176	749.97039	807.5964	786.55056	694.044	871.3245
165.44938	161.87698	153.95316	144.92997	137.38042	165.9967
522.4298	489.02506	477.33325	463.36843	436.34214	522.4298
114.84975	112.37389	105.07456	96.63989	89.90889	114.8498
1549.44653	1513.24632	1543.95737	1491.48885	1357.67545	1674.601
39.91823	38.86336	37.2827	35.11794	32.96541	40.16801
77.33935	76.31521	72.96281	66.62281	61.36674	77.33935
161.30128	158.35029	151.87038	140.44833	128.38709	161.3029
278.55886	273.52886	262.11589	242.18908	222.71924	278.8103
26.847835	28.42836	27.87047	26.35753	24.222165	28.42836

8.1 Appendix B

All Nodes modelled.

Node	Code	Name	Control Region	latitud	longitud
1	A	Hermosillo	Noroeste	29.072967	-110.955919
2	B	Cananea	Noroeste	30.990178	-110.300499
3	C	Obregón	Noroeste	27.482773	-109.930367
4	D	Los Mochis	Noroeste	25.790465	-108.985886
5	E	Culiacán	Noroeste	24.809065	-107.394012

6	F	Mazatlán	Noroeste	23.249414	-106.411142
7	G	Juárez	Norte	31.690364	-106.424548
8	H	Moctezuma	Norte	29.807178	-109.674833
9	I	Chihuahua	Norte	28.632996	-106.0691
10	J	Durango	Norte	24.02772	-104.653176
11	K	Laguna	Norte	25.542844	-103.406786
12	L	Río Escondido	Noreste	28.8832	-100.634
13	M	Nuevo Laredo	Noreste	27.477936	-99.549573
14	N	Reynosa	Noreste	26.05071	-98.297898
15	O	Matamoros	Noreste	25.869029	-97.502738
16	P	Monterrey	Noreste	25.686613	-100.316116
17	Q	Saltillo	Noreste	25.438255	-100.973665
18	R	Valles	Noreste	21.983879	-99.011863
19	S	Huasteca	Noreste	21.9839	-97.8432
20	T	Tamazunchale	Noreste	21.262225	-98.789162
21	U	Güémez	Noreste	23.966576	-99.087097
22	V	Tepic	Occidental	21.509451	-104.89569
23	W	Guadalajara	Occidental	20.659699	-103.349609
24	X	Aguascalientes	Occidental	21.881796	-102.291294

25	Y	SLP	Occidental	22.15647	-100.985541
26	Z	Salamanca	Occidental	20.571956	-101.191544
27	AA	Manzanillo	Occidental	19.050961	-104.31879
28	BB	Carapan	Occidental	19.058	-102.1
29	CC	Lázaro Cardenas	Central	17.958333	-102.2
30	DD	Querétaro	Occidental	20.588793	-100.389888
31	EE	Central	Central	19.062	-99.7234
32	FF	Poza Rica	Oriental	20.533153	-97.45946
33	GG	Veracruz	Oriental	19.173773	-96.134224
34	HH	Puebla	Oriental	19.04144	-98.206273
35	II	Acapulco	Oriental	16.853109	-99.823653
36	JJ	Temascal	Oriental	17.8634	-95.0965
37	KK	Coatzacoalcos	Oriental	18.134478	-94.458986
38	LL	Tabasco	Oriental	17.9583	-91.7343
39	MM	Grijalva	Oriental	16.568	-92.1453
40	NN	Ixtepec	Oriental	16.569045	-95.095326
41	OO	Lerma	Peninsular	19.28786	-99.512093
42	PP	Mérida	Peninsular	20.96737	-89.592586
43	QQ	Cancún	Peninsular	21.161908	-86.851528
44	RR	Chetumal	Peninsular	18.514133	-88.30381
45	SS	Cozumel	Peninsular	20.423	-86.9223
46	TT	Tijuana	Baja California	32.514947	-117.038247

47	UU	Ensenada	Baja California	31.859577	-116.60643
48	VV	Mexicali	Baja California	32.624539	-115.452262
49	WW	San Luis Rio Colorado	Baja California	32.456111	-114.771389
50	XX	Villa Constitucion	Baja California Sur	25.790465	-110.823
51	YY	La Paz	Baja California Sur	24.14437	-110.312753
52	ZZ	Los Cabos	Baja California Sur	22.890533	-109.916737
53	AAA	Mulegé	Mulege	26.882423	-111.982232

8.2 Appendix C

All Generators modelled.

Gen Node	Generator	Type	Control Region	Capacity	Name	Ext Code	Latitude	Longitude
32	Gen1	Oil	Oriental	2100	Adolfo LÃ³pez Mateos (Tuxpan)	MEX0001766	21.0151	-97.3334
22	Gen2	Hydro	Occidental	960	Aguamilpa Solidaridad	MEX0001856	21.8395	-104.8038
31	Gen3	Hydro	Central	7	Alameda	MEX0006565	18.8452	-99.4619
22	Gen4	Hydro	Occidental	750	Alfredo ElÃas Ayub (La Yesca)	MEX0001859	21.1979	-104.1047
19	Gen5	Oil	Noreste	500	Altamira	MEX0001776	22.4351	-98.0081
19	Gen6	Gas	Noreste	495	Altamira II	MEX0001794	22.4978	-97.9017
19	Gen7	Gas	Noreste	1036	Altamira III y IV	MEX0001774	22.4939	-97.9014
19	Gen8	Gas	Noreste	1121	Altamira V	MEX0001773	22.4997	-97.9053
12	Gen9	Gas	Noreste	180.3	Altos Hornos de MÃ©xico	MEX0001834	28.4658	-100.7001

38	Gen10	Biomass	Oriental	2.5	Aszuremex	MEX0006643	17.4559	-91.42
30	Gen11	Biomass	Occidental	1.1	Atlatec	MEX0006644	20.5959	-100.4716
23	Gen12	Biomass	Occidental	2.9	Atlatec Planta El Ahogado	MEX0006645	20.5055	-103.2596
24	Gen13	Solar	Occidental	3.8	Autoabastecimiento Renovable	MEX0006702	21.9083	-102.2709
32	Gen14	Biomass	Oriental	9.6	Azucarera Independencia	MEX0006647	20.0592	-97.0476
33	Gen15	Biomass	Oriental	4.2	Azucarera La ConcepciÃ³n	MEX0006654	19.6062	-96.8993
39	Gen16	Biomass	Oriental	13.1	Azucarera La FÃ©	MEX0006648	16.2767	-92.4541
4	Gen17	Biomass	Noroeste	14	Azucarera Los Mochis	MEX0006649	25.7854	-109.0018
18	Gen18	Biomass	Noreste	7.5	Azucarera del Rio Guayalejo	MEX0006646	22.939	-99.017
4	Gen19	Hydro	Noroeste	92	Bacurato	MEX0006592	25.8537	-107.9021
48	Gen20	Oil	Baja California	162.7	Baja California Sur I	MEX0001845	32.6024	-115.6276
30	Gen21	Gas	Occidental	495	BajÃo (El SÃ¡uz)	MEX0001795	20.4584	-100.1208
39	Gen22	Hydro	Oriental	900	Belisario DomÃnguez (Angostura)	MEX0001857	16.4018	-92.7784
7	Gen23	Oil	Norte	316	Benito JuÃ¡rez (Samalayuca)	MEX0001818	31.3314	-106.486
40	Gen24	Wind	Oriental	26.4	Bii Nee Stipa I	MEX0006704	16.4842	-94.9945
27	Gen25	Biomass	Occidental	15.5	Bio Pappel Atenquique	MEX0006650	19.5268	-103.4368
16	Gen26	Biomass	Noreste	17	BioenergÃa de Nuevo LeÃ³n	MEX0006651	25.852	-100.2956
39	Gen27	Hydro	Oriental	5.2	Bombana	MEX0006563	16.9575	-93.0258
9	Gen28	Hydro	Norte	25	Boquilla	MEX0006578	27.5445	-105.4141
26	Gen29	Hydro	Occidental	18	Botello	MEX0006574	19.9266	-101.6704
33	Gen30	Biomass	Oriental	12.8	Bsm EnergÃa de Veracruz	MEX0006652	18.6063	-96.6858
18	Gen31	Hydro	Noreste	18	Camilo Arriaga (El Salto)	MEX0006575	22.5881	-99.381
43	Gen32	Oil	Peninsular	102	CancÃºn	MEX0001852	21.069	-86.8467
12	Gen33	Coal	Noreste	1400	CarbÃ³n II	MEX0001768	28.4682	-100.7003
35	Gen34	Hydro	Oriental	600	Carlos RamÃrez Ulloa (El Caracol)	MEX0001860	17.9505	-99.9943
3	Gen35	Oil	Noroeste	484	Carlos RodrÃguez Rivero (Guaymas II)	MEX0001802	27.937	-110.8628
33	Gen36	Biomass	Oriental	20	Central Motzorongo	MEX0006653	18.6421	-96.7292
48	Gen37	Solar	Baja California	150	Cerro Prieto	MEX0006619	32.4169	-115.2341

48	Gen38	Geothermal	Baja California	570	Cerro Prieto	MEX0001868	32.3916	-115.2252
48	Gen39	Geothermal	Baja California	30	Cerro Prieto I	MEX0006611	32.3985	-115.2379
33	Gen40	Hydro	Oriental	10	CervecerÃa CuauhtÃ©moc-Moctezuma	MEX0006636	18.8715	-97.1256
9	Gen41	Gas	Norte	619.4	Chihuahua II (El Encino)	MEX0001784	28.4461	-105.92
36	Gen42	Hydro	Oriental	26	Chilapan	MEX0006579	18.4195	-95.1538
23	Gen43	Hydro	Occidental	51.2	Colimilla	MEX0006584	20.7847	-103.3247
9	Gen44	Hydro	Norte	3	Colina	MEX0006561	27.5763	-105.382
35	Gen45	Hydro	Oriental	8	Colotlipa	MEX0006566	17.4101	-99.2437
26	Gen46	Hydro	Occidental	2.5	CompaÃ±Ãa Electrica Carolina	MEX0006630	20.2048	-100.8865
36	Gen47	Biomass	Oriental	5.5	CompaÃ±Ãa Industrial Azucarera	MEX0006655	18.1612	-95.1866
34	Gen48	Hydro	Oriental	4	CompaÃ±Ãa Industrial Veracruzana	MEX0006632	18.803	-97.179
32	Gen49	Hydro	Oriental	36	CompaÃ±Ãa de EnergÃa Mexicana	MEX0006641	19.958	-97.4453
38	Gen50	Gas	Oriental	362.6	CompaÃ±Ãa de NitrÃ³geno de Cantarell	MEX0001813	18.61	-92.2647
36	Gen51	Biomass	Oriental	24.2	Cuenca del Papaloapan	MEX0006656	18.3734	-95.7425
28	Gen52	Hydro	Occidental	80	Cupatitzio	MEX0006590	19.2688	-102.0799
28	Gen53	Hydro	Occidental	60	CÃ³bano	MEX0006586	19.166	-102.0116
33	Gen54	Biomass	Oriental	8	DestilerÃa del Golfo	MEX0006713	18.9114	-96.7786
33	Gen55	Gas	Oriental	452	Dos Bocas	MEX0001805	19.0856	-96.1464
26	Gen56	Biomass	Occidental	1.7	Ecosys III	MEX0006657	21.0762	-101.7327
5	Gen57	Biomass	Noroeste	9.6	El Dorado	MEX0006658	24.3196	-107.3684
4	Gen58	Hydro	Noroeste	59.4	El Fuerte	MEX0006585	26.5073	-108.5756
30	Gen59	Gas	Occidental	591	El SÃ¡uz	MEX0001804	20.4575	-100.1206
18	Gen60	Hydro	Noreste	1.4	ElectroquÃmica	MEX0006554	22.1	-99.1524
40	Gen61	Wind	Oriental	67.5	ElÃ©ctrica del Valle de MÃ©xico	MEX0006706	16.5372	-94.9916
14	Gen62	Gas	Noreste	211.1	Emilio Portes Gil (RÃo Bravo) (CC)	MEX0001833	25.9821	-98.0627
14	Gen63	Gas	Noreste	300	Emilio Portes Gil (RÃo Bravo) (Vapor)	MEX0001820	25.9821	-98.0627

32	Gen64	Hydro	Oriental	10	Encanto	MEX0006570	19.9779	-97.1767
48	Gen65	Gas	Baja California	337.1	Energia de BC	MEX0001814	32.6009	-115.6275
30	Gen66	Gas	Occidental	131.1	EnergÃa Azteca VIII	MEX0001842	21.2452	-100.6111
48	Gen67	Gas	Baja California	298.6	EnergÃa Azteca X	MEX0001821	32.5982	-115.6297
7	Gen68	Biomass	Norte	6.4	EnergÃa ElÃ©ctrica de JuÃ¡rez	MEX0006701	31.5554	-106.486
24	Gen69	Biomass	Occidental	3.2	EnergÃa Verde de Aguascalientes	MEX0006698	21.9661	-102.2129
19	Gen70	Gas	Noreste	128	Enertek	MEX0001844	22.3739	-97.8913
40	Gen71	Wind	Oriental	164	Eoliatec del Istmo	MEX0001871	16.4406	-94.9912
40	Gen72	Wind	Oriental	250.5	Eurus	MEX0001866	16.4853	-94.9484
16	Gen73	Wind	Noreste	22	EÃ³lica Santa Catarina	MEX0006715	25.6907	-100.6221
40	Gen74	Wind	Oriental	70	EÃ³lica Zopiloapan (Bii Nee Stipa III)	MEX0006716	16.4448	-95.0588
40	Gen75	Wind	Oriental	28.8	EÃ³lica de Arriaga	MEX0006703	16.185	-93.9396
40	Gen76	Wind	Oriental	90	EÃ³licos Mexicanos de Oaxaca I	MEX0006705	16.546	-94.8285
13	Gen77	Hydro	Noreste	31.5	FalcÃ³n	MEX0006580	26.5584	-99.1694
42	Gen78	Gas	Peninsular	220	Felipe Carrillo Puerto (Valladolid)	MEX0001832	20.6971	-88.2659
20	Gen79	Hydro	Noreste	292	Fernando Hiriart Balderrama (ZimapÃ¡n)	MEX0001865	20.8468	-99.4584
19	Gen80	Biomass	Noreste	8	Fomento Azucarero del Golfo	MEX0006660	22.0179	-98.1801
41	Gen81	Oil	Peninsular	1605.6	Francisco PÃ©rez RÃos (Tula)	MEX0001767	20.0545	-99.2764
9	Gen82	Oil	Norte	300	Francisco Villa	MEX0001819	28.1662	-105.4435
40	Gen83	Wind	Oriental	80	Fuerza EÃ³lica del Istmo	MEX0006708	16.5863	-95.0016
1	Gen84	Gas	Noroeste	250	Fuerza y EnergÃa de Hermosillo	MEX0001828	29.0806	-111.025
28	Gen85	Hydro	Occidental	4.1	Gobierno del Estado	MEX0006633	19.0914	-102.0827
50	Gen86	Oil	Baja California Sur	104.1	Gral. AgustÃn Olachea A. (Puerto San Carlos)	MEX0001851	24.8147	-112.0916
11	Gen87	Oil	Norte	320	Guadalupe Victoria (Lerdo)	MEX0001815	25.4943	-103.5704
11	Gen88	Gas	Norte	239.8	GÃ³mez Palacio	MEX0001830	25.5934	-103.4772
1	Gen89	Gas	Noroeste	227	Hermosillo	MEX0001831	29.0331	-110.8351

27	Gen90	Hydro	Occidental	1.2	Hidroelectrica Cajon de PeÃ±a	MEX0006627	20.0171	-105.2216
33	Gen91	Hydro	Oriental	2.6	Hidroelectricas Virita	MEX0006631	18.8327	-97.1004
27	Gen92	Hydro	Occidental	9.2	Hidroelectricidad del Pacifico	MEX0006635	19.2541	-103.3701
33	Gen93	Hydro	Oriental	1.6	Hidrorizaba	MEX0006629	18.8455	-97.0684
33	Gen94	Hydro	Oriental	4.4	Hidrorizaba II	MEX0006634	18.8421	-97.071
16	Gen95	Gas	Noreste	377.7	HuinalÃ¡ (CC)	MEX0001788	25.718	-100.0962
16	Gen96	Gas	Noreste	150	HuinalÃ¡ (TurbogÃ¡s)	MEX0001789	25.7195	-100.1016
16	Gen97	Gas	Noreste	471.2	HuinalÃ¡ II	MEX0001806	25.7221	-100.1034
39	Gen98	Biomass	Oriental	12	Huixtla EnergÃa	MEX0006714	15.089	-92.4963
5	Gen99	Hydro	Noroeste	90	Humaya	MEX0006591	25.0971	-107.3913
16	Gen100	Gas	Noreste	659.2	Iberdrola EnergÃa Monterrey	MEX0001782	25.7403	-100.068
29	Gen101	Hydro	Central	1200	Infiernillo	MEX0001854	18.2711	-101.8939
36	Gen102	Biomass	Oriental	13.5	Ingenio Adolfo LÃ³pez Mateos	MEX0006642	18.0502	-96.1527
18	Gen103	Biomass	Noreste	6.4	Ingenio Alianza Popular	MEX0006661	21.9209	-99.3924
37	Gen104	Biomass	Oriental	14	Ingenio Benito JuÃ¡rez	MEX0006662	18.0053	-93.5875
41	Gen105	Biomass	Peninsular	3.4	Ingenio Casasano	MEX0006663	18.8499	-98.9633
33	Gen106	Biomass	Oriental	6.8	Ingenio El Carmen	MEX0006665	18.8727	-97.024
18	Gen107	Biomass	Noreste	21.8	Ingenio El Higo	MEX0006666	21.7739	-98.4543
18	Gen108	Biomass	Noreste	5.8	Ingenio El Mante	MEX0006667	22.7266	-98.98
33	Gen109	Thermal	Oriental	980	Ingenio El Modelo	MEX0006668	19.3772	-96.3704
22	Gen110	Biomass	Occidental	10	Ingenio El Molino	MEX0006669	21.5013	-104.8875
33	Gen111	Biomass	Oriental	10	Ingenio El Potrero	MEX0006670	18.8976	-96.7922
33	Gen112	Thermal	Oriental	480	Ingenio El Refugio	MEX0006671	18.5866	-96.6583
31	Gen113	Biomass	Central	8.6	Ingenio Emiliano Zapata	MEX0006659	18.6541	-99.1873
33	Gen114	Biomass	Oriental	21.5	Ingenio La Gloria	MEX0006672	19.4281	-96.4006
33	Gen115	Biomass	Oriental	7.3	Ingenio La Margarita	MEX0006673	18.5113	-96.5426
33	Gen116	Thermal	Oriental	700	Ingenio La Providencia	MEX0006674	18.7506	-96.7715
28	Gen117	Biomass	Occidental	5.5	Ingenio LÃ¡zaro CÃ¡rdenas	MEX0006675	19.3298	-101.9139
33	Gen118	Biomass	Oriental	3.3	Ingenio Mahuixtlan	MEX0006676	19.4549	-96.9586

27	Gen119	Biomass	Occidental	6.1	Ingenio Melchor Ocampo	MEX0006677	19.7854	-104.2372
33	Gen120	Biomass	Oriental	6.5	Ingenio Nuevo San Francisco	MEX0006678	18.6372	-95.5189
18	Gen121	Biomass	Noreste	16	Ingenio Plan De Ayala	MEX0006679	21.9861	-98.9587
18	Gen122	Biomass	Noreste	9	Ingenio Plan De San Luis	MEX0006680	21.9946	-99.0111
27	Gen123	Biomass	Occidental	5.5	Ingenio QueserÃa	MEX0006681	19.3883	-103.5731
23	Gen124	Thermal	Occidental	420	Ingenio San Francisco Ameca	MEX0006682	20.5442	-104.0531
33	Gen125	Biomass	Oriental	8	Ingenio San JosÃ© de Abajo	MEX0006683	18.7742	-96.7785
18	Gen126	Solar	Noreste	818	Ingenio San Miguel del Naranjo	MEX0006684	22.5322	-99.3354
33	Gen127	Biomass	Oriental	5.2	Ingenio San Miguelito	MEX0006685	18.864	-96.9168
37	Gen128	Biomass	Oriental	14	Ingenio San NicolÃ¡s	MEX0006686	17.9461	-94.2827
33	Gen129	Biomass	Oriental	10	Ingenio San Pedro	MEX0006687	18.6096	-95.5285
44	Gen130	Biomass	Peninsular	9	Ingenio San Rafael de Pucte	MEX0006688	18.2782	-88.683
28	Gen131	Biomass	Occidental	9.1	Ingenio Santa Clara	MEX0006689	19.6398	-102.492
23	Gen132	Biomass	Occidental	12	Ingenio Tala	MEX0006690	20.6693	-103.7183
33	Gen133	Biomass	Oriental	12	Ingenio Tres Valles	MEX0006691	18.2648	-96.1624
34	Gen134	Biomass	Oriental	15	Ingenio de Atencingo	MEX0006664	18.5113	-98.6078
40	Gen135	Wind	Oriental	5	Instituto de Investigaciones ElÃ©ctricas	MEX0006709	16.5456	-94.9634
33	Gen136	Hydro	Oriental	1.6	IxtaczoquitlÃ¡n	MEX0006555	18.9054	-97.0132
6	Gen137	Oil	Noroeste	616	JosÃ© Aceves Pozos (MazatlÃ¡n II)	MEX0001785	23.1901	-106.3558
39	Gen138	Hydro	Oriental	21	JosÃ© Cecilio del Valle	MEX0006577	14.9613	-92.2545
12	Gen139	Coal	Noreste	1200	JosÃ© LÃ³pez Portillo (RÃo Escondido)	MEX0001771	28.4844	-100.6897
4	Gen140	Oil	Noroeste	320	Juan de Dios BÃ¡tiz Paredes (Topolobampo)	MEX0001817	25.6079	-109.0515
22	Gen141	Hydro	Occidental	2.2	JumatÃ¡n	MEX0006557	21.6526	-105.0253
33	Gen142	Biomass	Oriental	10	Kimberly-Clark de MÃ©xico	MEX0006692	18.863	-97.0677
12	Gen143	Hydro	Noreste	66	La Amistad	MEX0006587	29.4485	-101.0602
11	Gen144	Gas	Norte	498	La Laguna II	MEX0001793	25.6017	-103.4672
40	Gen145	Wind	Oriental	102	La Mata	MEX0001879	16.539	-94.9993

40	Gen146	Wind	Oriental	84.2	La Venta	MEX0006620	16.5803	-94.8237
40	Gen147	Wind	Oriental	102.9	La Venta III	MEX0001874	16.5777	-94.8231
29	Gen148	Hydro	Central	320	La Villita	MEX0001864	18.0457	-102.1825
33	Gen149	Nuclear	Oriental	1510	Laguna Verde	MEX0001769	19.7208	-96.4064
53	Gen150	Geothermal	Mulege	10	Las Tres VÃrgenes	MEX0006615	27.5061	-112.5591
22	Gen151	Hydro	Occidental	750	Leonardo RodrÃguez Alcaine (El CajÃ³n)	MEX0001858	21.4279	-104.4507
42	Gen152	Oil	Peninsular	112.5	Lerma (Campeche)	MEX0001849	19.7956	-90.6128
30	Gen153	Hydro	Occidental	74	Lerma (Tepuxtepec)	MEX0006589	19.9825	-100.2524
30	Gen154	Geothermal	Occidental	225	Los Azufres	MEX0001870	19.791	-100.6669
32	Gen155	Geothermal	Oriental	68.6	Los Humeros	MEX0006617	19.6465	-97.4375
4	Gen156	Hydro	Noroeste	422	Luis Donaldo Colosio (Huites)	MEX0001861	26.8444	-108.3687
23	Gen157	Hydro	Occidental	5.3	Luis M. Rojas (Intermedia)	MEX0006564	20.6979	-103.27
37	Gen158	Hydro	Oriental	1080	Malpaso	MEX0001855	17.1806	-93.5973
23	Gen159	Hydro	Occidental	70	Manuel M. DiÃ©guez (Santa Rosa)	MEX0006588	20.9088	-103.7059
39	Gen160	Hydro	Oriental	2400	Manuel Moreno Torres (ChicoasÃ©n)	MEX0001853	16.9428	-93.1012
27	Gen161	Oil	Occidental	1300	Manuel Ã•lvarez Moreno (Manzanillo)	MEX0001770	19.0278	-104.3192
27	Gen162	Gas	Occidental	727	Manuel Ã•lvarez Moreno (Manzanillo) Paquete I	MEX0001778	19.0278	-104.3192
27	Gen163	Gas	Occidental	727	Manuel Ã•lvarez Moreno (Manzanillo) Paquete II	MEX0001779	19.0278	-104.3192
32	Gen164	Hydro	Oriental	220	Mazatepec	MEX0001869	20.0144	-97.4062
48	Gen165	Gas	Baja California	489	Mexicali	MEX0001800	32.5981	-115.6297
31	Gen166	Hydro	Central	30	Mexicana de Hidroelectricidad Mexhidro	MEX0006640	18.7015	-100.6699
32	Gen167	Hydro	Oriental	15	Minas	MEX0006573	19.6898	-97.1452
3	Gen168	Hydro	Noroeste	9.6	MocÃºzari	MEX0006569	27.2251	-109.1068
16	Gen169	Gas	Noreste	449	Monterrey III (Dulces Nombres)	MEX0001809	25.7192	-100.1017

48	Gen170	Wind	Baja California	10	Municipio de Mexicali	MEX0006710	32.4978	-116.0898
42	Gen171	Oil	Peninsular	168	MÃ©rida II	MEX0001836	20.927	-89.6878
42	Gen172	Gas	Peninsular	484	MÃ©rida III	MEX0001803	20.9336	-89.6992
2	Gen173	Gas	Noroeste	258	Naco Nogales	MEX0001826	31.2222	-109.6081
32	Gen174	Hydro	Oriental	109	Necaxa	MEX0001873	20.2171	-97.9872
41	Gen175	Gas	Peninsular	106	Nonoalco	MEX0001839	19.4503	-99.15
10	Gen176	Gas	Norte	450	Norte Durango (La Trinidad)	MEX0001807	24.2297	-104.4796
9	Gen177	Gas	Norte	433	Norte II	MEX0001810	28.4333	-105.9153
40	Gen178	Wind	Oriental	102	Oaxaca I	MEX0001875	16.5643	-94.7212
40	Gen179	Wind	Oriental	102	Oaxaca II	MEX0001876	16.5872	-94.7945
40	Gen180	Wind	Oriental	102	Oaxaca III	MEX0001877	16.5813	-94.7479
40	Gen181	Wind	Oriental	102	Oaxaca IV	MEX0001878	16.6123	-94.8105
3	Gen182	Hydro	Noroeste	19.2	OviÃ¡chic	MEX0006576	27.825	-109.8947
33	Gen183	Hydro	Oriental	1.3	Papelera Veracruzana	MEX0006628	18.8343	-97.103
32	Gen184	Hydro	Oriental	37	Patla	MEX0006582	20.2389	-97.8924
37	Gen185	Gas	Oriental	120.7	Pemex-Gas y PetroquÃmica BÃ¡sica Complejo Procesador de Gas Cactus	MEX0001846	17.8992	-93.1928
37	Gen186	Gas	Oriental	367.4	Pemex-Gas y PetroquÃmica BÃ¡sica Complejo Procesador de Gas Nuevo Pemex	MEX0001812	17.858	-93.123
37	Gen187	Gas	Oriental	163.5	Pemex-PetroquÃmica Complejo PetroquÃmico Cangrejera	MEX0001837	18.0929	-94.3591
37	Gen188	Gas	Oriental	172	Pemex-PetroquÃmica Complejo PetroquÃmico Morelos	MEX0001835	18.1405	-94.3665
26	Gen189	Gas	Occidental	142.8	Pemex-RefinaciÃ³n Ing. Antonio M. Amor	MEX0001840	20.5814	-101.1799
19	Gen190	Gas	Noreste	129	Pemex-RefinaciÃ³n RefinerÃa Francisco I. Madero	MEX0001843	22.2667	-97.8
40	Gen191	Gas	Oriental	115.2	Pemex-RefinaciÃ³n RefinerÃa Ing. Antonio DovalÃ Jaime	MEX0001848	16.211	-95.1721
41	Gen192	Gas	Peninsular	133.7	Pemex-RefinaciÃ³n RefinerÃa Miguel Hidalgo	MEX0001841	20.0489	-99.2802

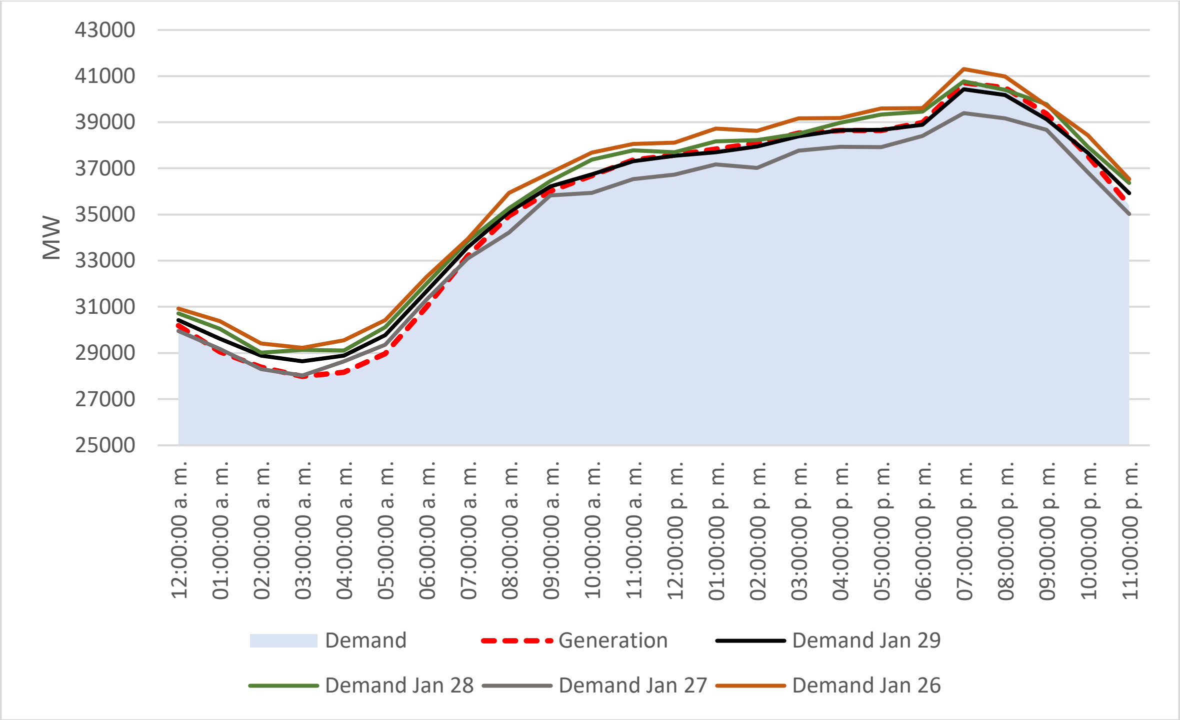
33	Gen193	Biomass	Oriental	40	Piasa Coogeneracion	MEX0006693	18.2583	-96.1546
16	Gen194	Biomass	Noreste	9.2	Planta Dulces Nombres	MEX0006694	25.739	-100.0675
16	Gen195	Biomass	Noreste	1.6	Planta Norte (Gob. de Nuevo LeÃ³n)	MEX0006695	25.7994	-100.2905
28	Gen196	Hydro	Occidental	12.6	Platanal	MEX0006571	19.9237	-102.2536
8	Gen197	Hydro	Norte	135	Plutarco ElÃas Calles (El Novillo)	MEX0001872	28.978	-109.642
29	Gen198	Coal	Central	2778.4	Plutarco ElÃas Calles (Petacalco)	MEX0001765	17.9837	-102.1154
34	Gen199	Hydro	Oriental	4.1	Portezuelos I y II	MEX0006562	18.9241	-98.3427
32	Gen200	Oil	Oriental	117	Poza Rica	MEX0001847	20.5264	-97.4903
46	Gen201	Gas	Baja California	773	Presidente JuÃ¡rez (Rosarito) (CC)	MEX0001777	32.3698	-117.0685
46	Gen202	Oil	Baja California	320	Presidente JuÃ¡rez (Rosarito) (Vapor)	MEX0001816	32.3698	-117.0685
6	Gen203	Hydro	Noroeste	14	Primero Empresa Minera	MEX0006638	24.4633	-105.975
33	Gen204	Hydro	Oriental	11.3	Procesamiento Energetico Mexicano	MEX0006637	18.8446	-97.0612
28	Gen205	Hydro	Occidental	19	Proveedora de Electricidad de Occidente	MEX0006639	19.291	-102.7738
5	Gen206	Biomass	Noroeste	7	Prozucar	MEX0006696	24.7657	-107.7018
23	Gen207	Hydro	Occidental	9	Puente Grande	MEX0006568	20.5769	-103.1462
1	Gen208	Oil	Noroeste	632	Puerto Libertad	MEX0001783	29.9068	-112.693
51	Gen209	Oil	Baja California Sur	112.5	Punta Prieta II	MEX0001850	24.2233	-110.3093
5	Gen210	Hydro	Noroeste	100	RaÃºl J. Marsal (Comedero)	MEX0001880	24.5707	-106.8084
15	Gen211	Gas	Noreste	495	RÃo Bravo II (AnÃ¡huac)	MEX0001796	25.7969	-97.7828
15	Gen212	Gas	Noreste	495	RÃo Bravo III	MEX0001797	25.7969	-97.7828
14	Gen213	Gas	Noreste	500	RÃo Bravo IV	MEX0001792	25.9821	-98.0627
26	Gen214	Oil	Occidental	550	Salamanca	MEX0001786	20.5694	-101.1712
17	Gen215	Gas	Noreste	247.5	Saltillo	MEX0001829	25.5939	-100.9164
5	Gen216	Hydro	Noroeste	14	Salvador Alvarado (Sanalona)	MEX0006572	24.8163	-107.1513
7	Gen217	Gas	Norte	521.8	Samalayuca II	MEX0001791	31.3276	-106.4841
34	Gen218	Gas	Oriental	382.1	San Lorenzo Potencia	MEX0001811	19.1194	-98.2412

28	Gen219	Hydro	Occidental	2.6	San Pedro PorÃºas	MEX0006560	19.4026	-101.3199
53	Gen220	Solar	Mulege	4	Santa RosalÃa	MEX0006618	27.4107	-112.5292
37	Gen221	Biomass	Oriental	25.2	Santa RosalÃa	MEX0006697	18.0899	-93.3562
39	Gen222	Hydro	Oriental	2.2	SchpoinÃ¡	MEX0006558	16.3145	-92.4261
40	Gen223	Wind	Oriental	74	Stipa Nayaa (Bii Nee Stipa II)	MEX0006712	16.496	-95
23	Gen224	Biomass	Occidental	25	Tala Electric	MEX0006699	20.667	-103.7224
23	Gen225	Biomass	Occidental	10.5	Tamazula	MEX0006700	19.6844	-103.2444
34	Gen226	Hydro	Oriental	2.5	Tamazulapan	MEX0006559	17.6868	-97.6178
20	Gen227	Gas	Noreste	1135	Tamazunchale	MEX0001772	21.3113	-98.7565
33	Gen228	Hydro	Oriental	354	Temascal	MEX0001863	18.2324	-96.4115
32	Gen229	Hydro	Oriental	39	Tepexic	MEX0006583	20.21	-97.9477
48	Gen230	Gas	Baja California	679.7	Termoelectrica de Mexicali	MEX0001781	32.6013	-115.6615
18	Gen231	Oil	Noreste	290	TermoelÃ©ctrica PeÃ±oles	MEX0001823	22.0694	-98.8469
18	Gen232	Oil	Noreste	290	TermoelÃ©ctrica del Golfo	MEX0001822	22.0694	-98.8469
33	Gen233	Hydro	Oriental	1.6	Texolo	MEX0006556	19.4023	-96.9936
46	Gen234	Gas	Baja California	345	Tijuana	MEX0001838	32.3685	-117.0694
26	Gen235	Hydro	Occidental	1.1	Tirio	MEX0006553	19.6297	-101.2589
16	Gen236	Gas	Noreste	284	Tractebel EnergÃa de Monterrey	MEX0001824	25.7674	-100.5482
38	Gen237	Gas	Oriental	252.4	Transalta Campeche	MEX0001827	17.9397	-91.7331
7	Gen238	Gas	Norte	259	Transalta Chihuahua III	MEX0001825	31.3308	-106.4865
41	Gen239	Gas	Peninsular	489	Tula	MEX0001801	20.0596	-99.2774
32	Gen240	Gas	Oriental	495	Tuxpan II	MEX0001798	20.839	-97.2534
32	Gen241	Gas	Oriental	983	Tuxpan III y IV	MEX0001775	20.8386	-97.2536
32	Gen242	Gas	Oriental	495	Tuxpan V	MEX0001799	20.8453	-97.2442
33	Gen243	Hydro	Oriental	36	Tuxpango	MEX0006581	18.8371	-97.0339
23	Gen244	Hydro	Occidental	240	ValentÃn GÃ³mez FarÃas (Agua Prieta)	MEX0001867	20.7008	-103.245
42	Gen245	Gas	Peninsular	525	Valladolid III	MEX0001790	20.6931	-88.2675
41	Gen246	Gas	Peninsular	549.3	Valle de MÃ©xico (CC)	MEX0001787	19.6183	-98.9764

41	Gen247	Gas	Peninsular	450	Valle de MÃ©xico (Vapor)	MEX0001808	19.6183	-98.9764
25	Gen248	Oil	Occidental	700	Villa de Reyes	MEX0001780	21.8322	-100.9344
43	Gen249	Wind	Peninsular	1.5	Yuumil'iik	MEX0006621	20.9761	-86.8621
28	Gen250	Hydro	Occidental	8.4	Zumpimito	MEX0006567	19.3607	-102.0697
37	Gen251	Hydro	Oriental	420	Ã•ngel Albino Corzo (PeÃ±itas)	MEX0001862	17.4463	-93.4628

8.3 Appendix D

Demand for similar days to representative day selected.



8.4 Appendix E

List of processes and components used for the Life Cycle Assessment of Sunamp's UNIQ.

Item	**Component**
C3003 - A	Lloyd 1S1 HX
C3001 - A	Grundfos UPM2 pump
C5030 - A	Copper tube, Seamless, 28mm Dia, BS en 1057, 4m
C1001 - D	PP cell case inc. lid
C3020 - A	Lamacell 32mm right side
C3021 - A	Lamacell 32mm right hand side elec
C3016 - A	Lamacell 19mm base
C3019 - A	Lamacell 19mm left side
C1008 - A	Cell lid support plate
C1027 - A	Body PV Case V2, 2.5mm Alu Sheet
C1029 - A	Front PV Case V2, 2.5mm Alu Sheet
C1030 - A	PCB Cover PV Case V2, 2.5mm Alu Sheet
C1026 - A	Lid PV Case V2, 2.5mm Alu Sheet
C3011 - A	20mm VIP - base + ends - 506mm x 273mm
C3012 - A	20mm VIP - front + back - 506mm x 466mm
C3013 - A	20mm VIP - lid - 450mm x 273mm
C5014 - A	Caleffi PRV @ 6 bar
C2020 - A	Blue crimp ring terminal for 5mm bolt
C2013 - A	Blue spade terminal
C5034 - A	500ml exp vessel - Altecnic
C5283 - A	1/2"BSP to 15mm comp
C5037 - A	TMV, Altecnic 35-65 Deg, ART: 5219
C1013 - A	PCB box - raw

C5281 - A	15mm comp WRAS check valve
C5279 - A	15mm Y strainer
C2023 - A	GSM antenna
C5026 - A	Copper tube, Seamless, 28mm Dia, BS en 1057, Various Lengths
C2094 - B	High temp cut out @ 85 deg
C3002 - B	HLP High Perf Cartridge Heater 2.8kW, 1/2", 250mm 16mm
C5033 - A	Speedfit 15mm straight
C5020 - A	Sensor Mounting Disc, 28mm Brass
C5035 - A	Copper Tube Seamless, 15mm Bend 4
C5019 - A	Copper tube, Seamless, 15mm Dia, BS en 1057, Various Lengths
C6001 - A	Grundfos Adapter Ring, 15mm ID, Brass
C6020 - A	Black rubber dome cable gland
C3015 - A	10mm Foamex spacer board - 490mm x 260mm
C2003 - A	Grundfos VFS flow + temp
C2021 - A	White coloured copper wire (approx 42cm)
C5021 - A	Copper 90 Deg Street Elbow, 15mm
C2012 - A	White coloured 4 core mains cable (130cm)
C3018 - A	Lamacell 19mm front and back
C3017 - B	Lamacell 32mm top
C2030 - A	103FT-7Y044 16mm pipe clip NTC sensor
C6026 - A	Black cable tie - small
C5036 - A	Y' Type Strainer, 15mm
C5023 - A	WRAS approved 1/2" washer
C5031 - A	WRAS approved 1" washer
C2026 - A	GSM SIM card
C3014 - A	4mm Correx board - 450mm x 220mm
C2014 - A	Blue heat shrink 10 cm (for black neutral cable)
C2015 - A	Brown heat shrink 10cm (for grey live cable)
A1014 - A	White cardboard outer case

C6022 - A	M2.5 washer
C6023 - A	M2.5 x 6mm panhead bolt
C6024 - A	M2.5 x 11mm PCB spacer
C6025 - A	M2.5 x 5mm PCB mounting post
C5001 - A	15mm Tectite classic straight comp coupling
C2001 - A	Control board
C2006 - A	GSM board
C2024 - A	LED Light pipe
C2025 - A	GSM cable
C5005 - A	28mm / 1/2" / 28mm Endex N29R FI RE Tree
C2008 - A	Yellow double size ring terminal
C2004_Flat	Thermostat, High Temp Cut Out, 85 Deg C, N/C
C5029 - A	1/2" brass flanged plug
C5003 - A	Kurt 424 15mm check valve
C2022 - A	Blue butt splice
C5008 - A	Endfeed reducer 28mm Internal to 15mm Copper
C5006 - A	1/2"BSP to 15mm comp
C2007 - A	Mains wiring gland and lockring
C5009- A	Endfeed Fitting reducer 28mm Internal to 15mm Copper
C5012- A	Endfeed 90 Deg Copper Elbow, 15mm
C5013- A	Endfeed Equal Tee, Copper, 15mm
C6029 - A	PTFE tape - thick single wrap
C5010- A	Endfeed Adaptor, 15mm Female to 1/2" Female Brass
C5016- A	1" Female Flat Face to 15mm Endfeed, Brass
C2011 - A	Red coloured copper wire (approx 42cm)
C2010 - A	Earth copper wire 2.5mm (approx 50cm)

C2002 - B	Clip on NTC temperature sensor - long assembly
C6012 - A	Panel grommet 15mm
C2018 - A	Earth copper wire 0.75mm (approx 13cm)
C1012 - A	LED and pipes labelling
C2005 - A	Earth clamp
C2002 - A	Clip on NTC temperature sensor - short assembly
C1009 - A	ErP large vinyl sticker
C6008 - A	M3 x 5mm A2 SS capscrew
C6019 - A	M5 flange nuts A2 SS
C6017 - A	M3 BZP nuts
C6021 - A	M4 x 5mm A2 SS capscrew
C6035 - A	M2.5 x 5mm bolt GSM mount
C6037 - B	M5 x 10mm A2 SS domehead capscrew
A1135 - A	SPV isolation warning sticker
C1010 - A	Sunamp small vinyl sticker
C4001 - A	PCM58
C6030 - A	Large 29mm panel grommet
A1017 - A	V2 hydraulic assembly
C2019 - A	M16 Cable Gland, plastic, comms, 50 .616 PA7035
C1007 - B	Outer enclosure
C1011 - A	Serial number silver vinyl sticker
A1005 - A	HB5 8 Red Cell Assembly

Item	**Component**	**#**	**Weight (gr)**	**Weight (Ton)**

C3003 - A	Lloyd 1S1 HX	1	5700	0.0057
C3001 - A	Grundfos UPM2 pump	1	1800	0.0018
C5030 - A	Copper tube, Seamless, 28mm Dia, BS en 1057, 4m	1	1100	0.0011
C1001 - D	PP cell case inc. lid	1	3563	0.003563
C3020 - A	Lamacell 32mm right side	1	700	0.0007
C3021 - A	Lamacell 32mm right hand side elec	1	700	0.0007
C3016 - A	Lamacell 19mm base	1	650	0.00065
C3019 - A	Lamacell 19mm left side	1	650	0.00065
C1008 - A	Cell lid support plate	1	154	0.000154
C1027 - A	Body PV Case V2, 2.5mm Alu Sheet	1	900	0.0009
C1029 - A	Front PV Case V2, 2.5mm Alu Sheet	1	900	0.0009
C1030 - A	PCB Cover PV Case V2, 2.5mm Alu Sheet	1	800	0.0008
C1026 - A	Lid PV Case V2, 2.5mm Alu Sheet	1	750	0.00075
C3011 - A	20mm VIP - base + ends - 506mm x 273mm	3	70	0.00007
C3012 - A	20mm VIP - front + back - 506mm x 466mm	2	70	0.00007
C3013 - A	20mm VIP - lid - 450mm x 273mm	1	60	0.00006
C5014 - A	Caleffi PRV @ 6 bar	1	70	0.00007
C2020 - A	Blue crimp ring terminal for 5mm bolt	1	90	0.00009
C2013 - A	Blue spade terminal	2	80	0.00008
C5034 - A	500ml exp vessel - Altecnic	1	60	0.00006
C5283 - A	1/2"BSP to 15mm comp	4	40	0.00004
C5037 - A	TMV, Altecnic 35-65 Deg, ART: 5219	1	55	0.000055

C1013 - A	PCB box - raw	1	40	0.00004
C5281 - A	15mm comp WRAS check valve	2	50	0.00005
C5279 - A	15mm Y strainer	1	50	0.00005
C2023 - A	GSM antenna	1	55	0.000055
C5026 - A	Copper tube, Seamless, 28mm Dia, BS en 1057, Various Lengths	1	45	0.000045
C2094 - B	High temp cut out @ 85 deg	1	30	0.00003
C3002 - B	HLP High Perf Cartridge Heater 2.8kW, 1/2", 250mm 16mm	1	57	0.000057
C5033 - A	Speedfit 15mm straight	6	25	0.000025
C5020 - A	Sensor Mounting Disc, 28mm Brass	1	35	0.000035
C5035 - A	Copper Tube Seamless, 15mm Bend 4	2	34	0.000034
C5019 - A	Copper tube, Seamless, 15mm Dia, BS en 1057, Various Lengths	35	30	0.00003
C6001 - A	Grundfos Adapter Ring, 15mm ID, Brass	2	28	0.000028
C6020 - A	Black rubber dome cable gland	4	25	0.000025
C3015 - A	10mm Foamex spacer board - 490mm x 260mm	1	35	0.000035
C2003 - A	Grundfos VFS flow + temp	1	30	0.00003
C2021 - A	White coloured copper wire (approx 42cm)	1	100	0.0001
C5021 - A	Copper 90 Deg Street Elbow, 15mm	7	22	0.000022
C2012 - A	White coloured 4 core mains cable (130cm)	1	15	0.000015
C3018 - A	Lamacell 19mm front and back	2	60	0.00006
C3017 - B	Lamacell 32mm top	1	60	0.00006
C2030 - A	103FT-7Y044 16mm pipe clip NTC sensor	2	25	0.000025
C6026 - A	Black cable tie - small	7	25	0.000025

C5036 - A	Y' Type Strainer, 15mm	1	18	0.000018
C5023 - A	WRAS approved 1/2" washer	3	16	0.000016
C5031 - A	WRAS approved 1" washer	2	16	0.000016
C2026 - A	GSM SIM card	1	10	0.00001
C3014 - A	4mm Correx board - 450mm x 220mm	2	40	0.00004
C2014 - A	Blue heat shrink 10 cm (for black neutral cable)	1	18	0.000018
C2015 - A	Brown heat shrink 10cm (for grey live cable)	1	18	0.000018
A1014 - A	White cardboard outer case	1	60	0.00006
C6022 - A	M2.5 washer	10	15	0.000015
C6023 - A	M2.5 x 6mm panhead bolt	6	15	0.000015
C6024 - A	M2.5 x 11mm PCB spacer	4	15	0.000015
C6025 - A	M2.5 x 5mm PCB mounting post	2	15	0.000015
C5001 - A	15mm Tectite classic straight comp coupling	1	25	0.000025
C2001 - A	Control board	1	50	0.00005
C2006 - A	GSM board	1	50	0.00005
C2024 - A	LED Light pipe	4	40	0.00004
C2025 - A	GSM cable	1	10	0.00001
C5005 - A	28mm / 1/2" / 28mm Endex N29R FI RE Tree	1	20	0.00002
C2008 - A	Yellow double size ring terminal	1	10	0.00001
C2004_Flat	Thermostat, High Temp Cut Out, 85 Deg C, N/C	1	28.00	0.000028
C5029 - A	1/2" brass flanged plug	1	32	0.000032
C5003 - A	Kurt 424 15mm check valve	1	28	0.000028

C2022 - A	Blue butt splice	1	25	0.000025
C5008 - A	Endfeed reducer 28mm Internal to 15mm Copper	1	25	0.000025
C5006 - A	1/2"BSP to 15mm comp	2	24	0.000024
C2007 - A	Mains wiring gland and lockring	1	80	0.00008
C5009-A	Endfeed Fitting reducer 28mm Internal to 15mm Copper	1	22	0.000022
C5012-A	Endfeed 90 Deg Copper Elbow, 15mm	1	22	0.000022
C5013-A	Endfeed Equal Tee, Copper, 15mm	1	22	0.000022
C6029 - A	PTFE tape - thick single wrap	1	20	0.00002
C5010-A	Endfeed Adaptor, 15mm Female to 1/2" Female Brass	1	18	0.000018
C5016-A	1" Female Flat Face to 15mm Endfeed, Brass	1	18	0.000018
C2011 - A	Red coloured copper wire (approx 42cm)	1	16	0.000016
C2010 - A	Earth copper wire 2.5mm (approx 50cm)	2	14	0.000014
C2002 - B	Clip on NTC temperature sensor - long assembly	1	16	0.000016
C6012 - A	Panel grommet 15mm	2	12	0.000012
C2018 - A	Earth copper wire 0.75mm (approx 13cm)	1	12	0.000012
C1012 - A	LED and pipes labelling	1	20	0.00002
C2005 - A	Earth clamp	1	8	0.000008
C2002 - A	Clip on NTC temperature sensor - short assembly	1	8	0.000008
C1009 - A	ErP large vinyl sticker	1	10	0.00001
C6008 - A	M3 x 5mm A2 SS capscrew	2	15	0.000015
C6019 - A	M5 flange nuts A2 SS	13	15	0.000015
C6017 - A	M3 BZP nuts	4	15	0.000015

C6021 - A	M4 x 5mm A2 SS capscrew	2	15	0.000015
C6035 - A	M2.5 x 5mm bolt GSM mount	2	15	0.000015
C6037 - B	M5 x 10mm A2 SS domehead capscrew	2	15	0.000015
A1135 - A	SPV isolation warning sticker	2	6	0.000006
C1010 - A	Sunamp small vinyl sticker	1	6	0.000006
C4001 - A	PCM58	1	22000	0.022
C6030 - A	Large 29mm panel grommet	2		0
A1017 - A	V2 hydraulic assembly	1		0
C2019 - A	M16 Cable Gland, plastic, comms, 50 .616 PA7035	1	25	0.000025
C1007 - B	Outer enclosure	1		0
C1011 - A	Serial number silver vinyl sticker	1	6	0.000006
A1005 - A	HB5 8 Red Cell Assembly	2		
				0.047726
			kgs	47.726

Item	**Component**	**Supplier**	**Adress**	**Distance to Sunamp**	**Distance in km**	**Tkm**
C3003 - A	Lloyd 1S1 HX	Lloyd Coils	55 Spinney Hill, Melbourne, Derby DE73 8LX	282	453.8	2.587
C3001 - A	Grundfos UPM2 pump	Grundfos	Beswick House, Greenfold Way, Leigh WN7 3XJ	224	360.5	0.649
C5030 - A	Copper tube, Seamless, 28mm Dia, BS en 1057, 4m	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.483

C1001 - D	PP cell case inc. lid	Wydedale	91 Vermont St, Glasgow G41	62.9	101.2	0.361
C3020 - A	Lamacell 32mm right side	Jet Cut	NA	100	160.9	0.113
C3021 - A	Lamacell 32mm right hand side elec	Jet Cut	NA	100	160.9	0.113
C3016 - A	Lamacell 19mm base	Jet Cut	NA	100	160.9	0.105
C3019 - A	Lamacell 19mm left side	Jet Cut	NA	100	160.9	0.105
C1008 - A	Cell lid support plate	Pentland Tech	Middlesex, UK, UB7 8JL	391	629.3	0.097
C1027 - A	Body PV Case V2, 2.5mm Alu Sheet	SAA	Bothwell, Glasgow G71 8DA	53.5	86.1	0.077
C1029 - A	Front PV Case V2, 2.5mm Alu Sheet	SAA	Bothwell, Glasgow G71 8DA	53.5	86.1	0.077
C1030 - A	PCB Cover PV Case V2, 2.5mm Alu Sheet	SAA	Bothwell, Glasgow G71 8DA	53.5	86.1	0.069
C1026 - A	Lid PV Case V2, 2.5mm Alu Sheet	SAA	Bothwell, Glasgow G71 8DA	53.5	86.1	0.065
C3011 - A	20mm VIP - base + ends - 506mm x 273mm	Kevothermal	The Factory Rectory Lane, Ludlow SY8 4NX	328	527.9	0.037
C3012 - A	20mm VIP - front + back - 506mm x 466mm	Kevothermal	The Factory Rectory Lane, Ludlow SY8 4NX	328	527.9	0.037

C3013 - A	20mm VIP - lid - 450mm x 273mm	Kevothermal	The Factory Rectory Lane, Ludlow SY8 4NX	328	527.9	0.032
C5014 - A	Caleffi PRV @ 6 bar	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.031
C2020 - A	Blue crimp ring terminal for 5mm bolt	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.031
C2013 - A	Blue spade terminal	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.027
C5034 - A	500ml exp vessel - Altecnic	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.026
C5283 - A	1/2"BSP to 15mm comp	Pentland Tech	Middlesex, UK, UB7 8JL	391	629.3	0.025
C5037 - A	TMV, Altecnic 35-65 Deg, ART: 5219	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.024
C1013 - A	PCB box - raw	Trend	Unit 6/Odhams Trading Est/St. Albans Rd, Watford WD24 7TR	372	598.7	0.024
C5281 - A	15mm comp WRAS check valve	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.022
C5279 - A	15mm Y strainer	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.022
C2023 - A	GSM antenna	Sabre	Golf Rd, Hale, Altrincham WA15 8AH	233	375.0	0.021
C5026 - A	Copper tube, Seamless, 28mm Dia, BS en 1057, Various Lengths	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.020
C2094 - B	High temp cut out @ 85 deg	Sinolec	Guildford GU4 7WA	409	658.2	0.020
C3002 - B	HLP High Perf Cartridge Heater	Clariant	Unit 2 Rawdon Park, Green Lawe, Yeadon, Leeds LS19 7BA	201	323.5	0.018

	2.8kW, 1/2", 250mm 16mm					
C5033 - A	Speedfit 15mm straight	John Guest	Horton Rd, West Drayton, Middlesex, UK UB7 8JL	391	629.3	0.016
C5020 - A	Sensor Mounting Disc, 28mm Brass	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.015
C5035 - A	Copper Tube Seamless, 15mm Bend 4	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.015
C5019 - A	Copper tube, Seamless, 15mm Dia, BS en 1057, Various Lengths	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.013
C6001 - A	Grundfos Adapter Ring, 15mm ID, Brass	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.012
C6020 - A	Black rubber dome cable gland	Spelsberg	TF1 6AL, Hadley, Telford	288	463.5	0.012
C3015 - A	10mm Foamex spacer board - 490mm x 260mm	PAR Group	Preston, Bridge House, Chorley North Industrial Park, Drumhead Rd, Chorley PR6 7BX	204	328.3	0.011
C2003 - A	Grundfos VFS flow + temp	Grundfos	Beswick House, Greenfold Way, Leigh WN7 3XJ	224	360.5	0.011
C2021 - A	White coloured copper wire (approx 42cm)	RS	38 Baird St, Glasgow G4 0ED	61.4	98.8	0.010
C5021 - A	Copper 90 Deg Street Elbow, 15mm	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.010
C2012 - A	White coloured 4 core mains cable (130cm)	Electrolyte	2 Stafford Place, Weston-Super-Mare, Somerset, BS23 2QZ	400	643.7	0.010
C3018 - A	Lamacell 19mm front and back	Jet Cut	NA	100	160.9	0.010
C3017 - B	Lamacell 32mm top	Jet Cut	NA	100	160.9	0.010

C2030 - A	103FT-7Y044 16mm pipe clip NTC sensor	ATC Semitec	Daisy Bank Ln, Anderton, Northwich CW9 6FY	238	383.0	0.010
C6026 - A	Black cable tie - small	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.009
C5036 - A	Y' Type Strainer, 15mm	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.008
C5023 - A	WRAS approved 1/2" washer	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.007
C5031 - A	WRAS approved 1" washer	Altecnic	Mustang Dr, Stafford ST16 1GW	273	439.3	0.007
C2026 - A	GSM SIM card	Wireless Logic	Maidenhead SL6 6RJ	401	645.3	0.006
C3014 - A	4mm Correx board - 450mm x 220mm	Jet Cut	NA	100	160.9	0.006
C2014 - A	Blue heat shrink 10 cm (for black neutral cable)	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.006
C2015 - A	Brown heat shrink 10cm (for grey live cable)	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.006
A1014 - A	White cardboard outer case	Weston packaging	Unit 1A Clyde Industrial Estate, Cunninghame Road, Rutherglen G73 1PP	59.7	96.1	0.006
C6022 - A	M2.5 washer	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.005
C6023 - A	M2.5 x 6mm panhead bolt	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.005
C6024 - A	M2.5 x 11mm PCB spacer	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.005
C6025 - A	M2.5 x 5mm PCB mounting post	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.005

C5001 - A	15mm Tectite classic straight comp coupling	William Williamson	Newcastle upon Tyne NE12 9UP	106	170.6	0.004
C2001 - A	Control board	Bay Solutions	Unit 5 Buko Business Centre, Ashley Rd, Glenrothes KY6 2SE	51.3	82.6	0.004
C2006 - A	GSM board	Bay Solutions	Unit 5 Buko Business Centre, Ashley Rd, Glenrothes KY6 2SE	51.3	82.6	0.004
C2024 - A	LED Light pipe	Multitron	RS, 38 Baird St, Glasgow G4 0ED	61.4	98.8	0.004
C2025 - A	GSM cable	Sabre	Golf Rd, Hale, Altrincham WA15 8AH	233	375.0	0.004
C5005 - A	28mm / 1/2" / 28mm Endex N29R FI RE Tree	William Williamson	Newcastle upon Tyne NE12 9UP	106	170.6	0.003
C2008 - A	Yellow double size ring terminal	Farnell	150 Armley Road, Leeds, LS12 2QQ	212	341.2	0.003
C2004_Flat	Thermostat, High Temp Cut Out, 85 Deg C, N/C				118.0	0.003
C5029 - A	1/2" brass flanged plug	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.003
C5003 - A	Kurt 424 15mm check valve	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.003
C2022 - A	Blue butt splice	RS	38 Baird St, Glasgow G4 0ED	61.4	98.8	0.002
C5008 - A	Endfeed reducer 28mm Internal to 15mm Copper	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.002

C5006 - A	1/2"BSP to 15mm comp	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.002
C2007 - A	Mains wiring gland and lockring	Hylec	Dalry Road, Edinburgh, EH11 2EZ.	16.4	26.4	0.002
C5009-A	Endfeed Fitting reducer 28mm Internal to 15mm Copper	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.002
C5012-A	Endfeed 90 Deg Copper Elbow, 15mm	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.002
C5013-A	Endfeed Equal Tee, Copper, 15mm	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.002
C6029 - A	PTFE tape - thick single wrap	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.002
C5010-A	Endfeed Adaptor, 15mm Female to 1/2" Female Brass	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.002
C5016-A	1" Female Flat Face to 15mm Endfeed, Brass	Primaflow	16 Clydesmill Pl, Glasgow G32 8RE	57.4	92.4	0.002
C2011 - A	Red coloured copper wire (approx 42cm)	RS	38 Baird St, Glasgow G4 0ED	61.4	98.8	0.002
C2010 - A	Earth copper wire 2.5mm (approx 50cm)	RS	38 Baird St, Glasgow G4 0ED	61.4	98.8	0.001
C2002 - B	Clip on NTC temperature sensor - long assembly	Bay Solutions	Unit 5 Buko Business Centre, Ashley Rd, Glenrothes KY6 2SE	51.3	82.6	0.001

C6012 - A	Panel grommet 15mm	RS	38 Baird St, Glasgow G4 0ED	61.4	98.8	0.001
C2018 - A	Earth copper wire 0.75mm (approx 13cm)	RS	38 Baird St, Glasgow G4 0ED	61.4	98.8	0.001
C1012 - A	LED and pipes labelling	CCA Signs	Unit 5, Silverbirch Studios, Cavalry Park, Peebles EH45 9BU	34.2	55.0	0.001
C2005 - A	Earth clamp	RS	38 Baird St, Glasgow G4 0ED	61.4	98.8	0.001
C2002 - A	Clip on NTC temperature sensor - short assembly	Bay Solutions	Unit 5 Buko Business Centre, Ashley Rd, Glenrothes KY6 2SE	51.3	82.6	0.001
C1009 - A	ErP large vinyl sticker	CCA Signs	Unit 5, Silverbirch Studios, Cavalry Park, Peebles EH45 9BU	34.2	55.0	0.001
C6008 - A	M3 x 5mm A2 SS capscrew	MEF	10 Dryden Loan, Edinburgh EH20 9LZ	15.2	24.5	0.0004
C6019 - A	M5 flange nuts A2 SS	MEF	10 Dryden Loan, Edinburgh EH20 9LZ	15.2	24.5	0.000
C6017 - A	M3 BZP nuts	MEF	10 Dryden Loan, Edinburgh EH20 9LZ	15.2	24.5	0.000
C6021 - A	M4 x 5mm A2 SS capscrew	MEF	10 Dryden Loan, Edinburgh EH20 9LZ	15.2	24.5	0.000
C6035 - A	M2.5 x 5mm bolt GSM mount	MEF	10 Dryden Loan, Edinburgh EH20 9LZ	15.2	24.5	0.000
C6037 - B	M5 x 10mm A2 SS domehead capscrew	MEF	10 Dryden Loan, Edinburgh EH20 9LZ	15.2	24.5	0.000
A1135 - A	SPV isolation warning sticker	CCA Signs	Unit 5, Silverbirch Studios, Cavalry Park, Peebles EH45 9BU	34.2	55.0	0.000
C1010 - A	Sunamp small vinyl sticker	CCA Signs	Unit 5, Silverbirch Studios, Cavalry Park, Peebles EH45 9BU	34.2	55.0	0.000
C4001 - A	PCM58	Sunamp	Macmerry	0	0.0	0.000

C6030 - A	Large 29mm panel grommet	Reevite	16 Murdock Rd, Bicester OX26 4PP	365	587.4	0.000
A1017 - A	V2 hydraulic assembly	SAA	Bothwell, Glasgow G71 8DA	53.5	86.1	0.000
C2019 - A	M16 Cable Gland, plastic, comms, 50 .616 PA7035				0.0	0.000
C1007 - B	Outer enclosure				0.0	0.000
C1011 - A	Serial number silver vinyl sticker	Sunamp	Macmerry	0	0.0	0.000
A1005 - A	HB5 8 Red Cell Assembly					

SimaPro 8.0.3.14	product stages	Date:	15/08/2017	Time:	11:55
Project	UniQ				
Name	Project	Assembly	Status	Type	Category
0 00000 UniQ	UniQ		None	Assembly	Others
1 A0000 2 Red Cell Assembly	UniQ		None	Assembly	Others
2 B0000 Hydraulic Assembly	UniQ		None	Assembly	Others
3 C0000 Red Heat Exchanger Assembly	UniQ		None	Assembly	Others
4 E0000 Grey Outer Case	UniQ		None	Assembly	Others

A A1007 Outer Cover Component, SPV	UniQ		None	Assembly	Others
Aluminium, primary, ingot {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Metals\Nonferro\Market
B C1012 LED and pipes labelling	UniQ		None	Assembly	Others
B C2003 Grundfos VFS flow + temp	UniQ		None	Assembly	Others
B C2004 Thermostat, High Temp Cut Out, 85 Deg	UniQ		None	Assembly	Others
B C2011 Earth copper wire 2.5mm (approx 50cm)	UniQ		None	Assembly	Others
B C2011 Red coloured copper wire (approx 42cm)	UniQ		None	Assembly	Others
B C2012 White coloured 4 core mains cable (130cm)	UniQ		None	Assembly	Others
B C2013 Blue spade terminal	UniQ		None	Assembly	Others
B C2014 Blue heat shrink 10 cm	UniQ		None	Assembly	Others
B C2015 Brown heat shrink 10cm	UniQ		None	Assembly	Others
B C2018 Earth copper wire 0.75mm (approx 13cm)	UniQ		None	Assembly	Others
B C2020 Blue crimp ring terminal for 5mm bolt	UniQ		None	Assembly	Others
B C2021 White coloured copper wire (approx 42cm)	UniQ		None	Assembly	Others

B C2022 Blue butt spice	UniQ		None	Assembly	Others
B C2023 GSM Antenna	UniQ		None	Assembly	Others
B C2024 LED Light pipe	UniQ		None	Assembly	Others
B C2025 GSM Cable	UniQ		None	Assembly	Others
B C2026 GSM SIM card	UniQ		None	Assembly	Others
B C2030 103FT-7Y044 16mm pipe clip NTC sensor	UniQ		None	Assembly	Others
B C2094 High temp cut out @ 85 deg	UniQ		None	Assembly	Others
B C3001 Grundfos UPM2 pump	UniQ		None	Assembly	Others
B C3014 4mm Correx board - 450mm x 220mm	UniQ		None	Assembly	Others
B C3015 10mm Foamex spacer board - 490mm x 260mm	UniQ		None	Assembly	Others
B C3016 Lamacell 19mm base	UniQ		None	Assembly	Others
B C3019 Lamacell 19mm left side	UniQ		None	Assembly	Others
B C3020 Lamacell 32mm right side	UniQ		None	Assembly	Others
B C3021 Lamacell 32mm right hand side elec	UniQ		None	Assembly	Others
B C5001 15mm Tectite classic straight comp	UniQ		None	Assembly	Others

B C5005 28mm Endex N29R FI RE Tree	UniQ		None	Assembly	Others
B C5008 Endfeed reducer 28mm Internal to 15mm	UniQ		None	Assembly	Others
B C5009 Endfeed Fitting reducer 28mm	UniQ		None	Assembly	Others
B C5010 Endfeed Adaptor, 15mm Female to 1/2" Femal	UniQ		None	Assembly	Others
B C5012 Endfeed 90 Deg Copper Elbow, 15mm	UniQ		None	Assembly	Others
B C5013 Endfeed Equal Tee, Copper, 15mm	UniQ		None	Assembly	Others
B C5014 Caleffi PRV @ 6 bar	UniQ		None	Assembly	Others
B C5016 1" Female Flat Face to 15mm Endfeed, Brass	UniQ		None	Assembly	Others
B C5019 Copper tube,Seamless, 15mm Dia, BS en 1057	UniQ		None	Assembly	Others
B C5020 Sensor Mounting Disc, 28mm Brass	UniQ		None	Assembly	Others
B C5021 Copper 90 Deg Street Elbow, 15mm	UniQ		None	Assembly	Others
B C5023 WRAS approved 1/2" washer	UniQ		None	Assembly	Others
B C5026 Copper tube, Seamless, 28mm Dia, BS en 105	UniQ		None	Assembly	Others
B C5031 WRAS approved 1" washer	UniQ		None	Assembly	Others
B C5033 Speedfit 15mm straight	UniQ		None	Assembly	Others

B C5034 500ml exp vessel - Altecnic	UniQ		None	Assembly	Others
B C5035 Copper Tube Seamless, 15mm Bend 4	UniQ		None	Assembly	Others
B C5036 Y' Type Strainer, 15mm	UniQ		None	Assembly	Others
B C5037 TMV, Altecnic 35-65 Deg, ART: 5219	UniQ		None	Assembly	Others
B C5279 15mm Y strainer	UniQ		None	Assembly	Others
B C5281 15mm comp WRAS check valve	UniQ		None	Assembly	Others
B C5283 1/2"BSP to 15mm comp	UniQ		None	Assembly	Others
B C6001 Grundfos Adapter Ring, 15mm ID, Brass	UniQ		None	Assembly	Others
B C6008 M3 x 5mm A2 SS capscrew	UniQ		None	Assembly	Others
B C6012 Panel grommet 15mm	UniQ		None	Assembly	Others
B C6020 Black rubber dome cable gland	UniQ		None	Assembly	Others
B C6026 Black cable tie - small	UniQ		None	Assembly	Others
B C6029 PTFE tape - thick single wrap	UniQ		None	Assembly	Others
B HLP High Perf Cartridge Heater 2.8kW	UniQ		None	Assembly	Others
Bitumen, at refinery/kg/US	USLCI		None	Material	Construction\Bitumen

Bituminous coal, at mine/US	USLCI		None	Material	Fuels\Coal\Produced coal\Mined coal
Bituminous coal, combusted in industrial boiler/US	USLCI		None	Energy	Heat\Coal
Blow moulding {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Plastics\Market
Brass {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Metals\Nonferro\Market
C C1001 PP cell case inc. lid	UniQ		None	Assembly	Others
C C1008 Cell lid support plate	UniQ		None	Assembly	Others
C C3003 Lloyd 1S1 HX	UniQ		None	Assembly	Others
C C4001 PCM Phase Change Material	UniQ		None	Assembly	Others
C C5003 Kurt 424 15mm check valve	UniQ		None	Assembly	Others
C C5006 1/2"BSP to 15mm comp	UniQ		None	Assembly	Others
C C5029 1/2" brass flanged plug	UniQ		None	Assembly	Others
C C5030 Copper Tube, Seamless 28mm Dia, 4 m	UniQ		None	Assembly	Others
Calendering, rigid sheets {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Plastics\Market

Copper {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Metals\Nonferro\Market
Corrugated board box {GLO}| market for corrugated board box | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Paper+ Board\Corrugated board\Market
Crude oil, at production/RNA	USLCI		None	Material	Fuels\Oil\Crude oil\Production
De-icer {GLO}| sodium chloride to generic market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Chemicals\ Inorganic\ Transformation
Diesel, at refinery/l/US	USLCI		None	Material	Fuels\Oil\ Diesel
Diesel, combusted in industrial boiler/US	USLCI		None	Energy	Heat\Oil
Disposal of UniQ	UniQ	0 00000 UniQ	None	Disposal scenario	Others
Dissassembly of UniQ	UniQ	0 00000 UniQ	None	Disassembly	Others
Dummy_Disposal, ash and flue gas desulfurization sludge, to unspecified reuse/US	USLCI		None	Waste treatment	Others\Dummy processes
Dummy_Disposal, lignite coal combustion byproducts, to unspecified reuse/US	USLCI		None	Waste treatment	Others\Dummy processes

Dummy_Disposal, solid waste, unspecified, to sanitary landfill/US	USLCI		None	Waste treatment	Others\Dummy processes
Dummy_Disposal, solid waste, unspecified, to underground deposit/US	USLCI		None	Waste treatment	Others\Dummy processes
Dummy_Disposal, solid waste, unspecified, to unspecified treatment/US	USLCI		None	Waste treatment	Others\Dummy processes
Dummy_Electricity, at wind power plant, unspecified/US	USLCI		None	Energy	Others\Dummy processes
Dummy_Electricity, fossil, unspecified, at power plant/US	USLCI		None	Energy	Others\Dummy processes
Dummy_Electricity, geothermal, unspecified/US	USLCI		None	Energy	Others\Dummy processes
Dummy_Electricity, hydropower, at power plant, unspecified/kWh/RNA	USLCI		None	Energy	Others\Dummy processes
Dummy_Electricity, hydropower, at power plant, unspecified/US	USLCI		None	Energy	Others\Dummy processes
Dummy_Electricity, photovoltaic, unspecified/US	USLCI		None	Energy	Others\Dummy processes
Dummy_Transport, pipeline, coal slurry/US	USLCI		None	Transport	Others\Dummy processes
Dummy_Transport, pipeline, unspecified/tkm/US	USLCI		None	Processing	Others\Dummy processes
Dummy_Transport, pipeline, unspecified/US	USLCI		None	Transport	Others\Dummy processes

E A1014 White cardboard outer case	UniQ		None	Assembly	Others
E A1135 SPV isolation warning sticker	UniQ		None	Assembly	Others
E C1009 ErP large vinyl sticker	UniQ		None	Assembly	Others
E C1010 Sunamp small vinyl sticker	UniQ		None	Assembly	Others
E C1011 Serial number silver vinyl sticker	UniQ		None	Assembly	Others
E C1013 PCB box - raw	UniQ		None	Assembly	Others
E C1026 Lid PV Case V2, 2.5mm Alu Sheet	UniQ		None	Assembly	Others
E C1029 Body PV Case V2, 2.5mm Alu Sheet	UniQ		None	Assembly	Others
E C1029 Front PV Case V2, 2.5mm Alu Sheet	UniQ		None	Assembly	Others
E C1030 PCB Cover PV Case V2, 2.5mm Alu Sheet	UniQ		None	Assembly	Others
E C2001 Control board	UniQ		None	Assembly	Others
E C2002 Clip on NTC temperature sensor	UniQ		None	Assembly	Others
E C2002 Clip on NTC temperature sensor - long asse	UniQ		None	Assembly	Others
E C2005 Earth Clamp	UniQ		None	Assembly	Others
E C2006 GSM board	UniQ		None	Assembly	Others

E C2007 Mains wiring gland and lockring	UniQ		None	Assembly	Others
E C2008 Yellow double size ring terminal	UniQ		None	Assembly	Others
E C2019 M16 Cable Gland	UniQ		None	Assembly	Others
E C3017 Lamacell 32mm top	UniQ		None	Assembly	Others
E C3018 Lamacell 19mm front and back	UniQ		None	Assembly	Others
E C6017 M3 BZP nuts	UniQ		None	Assembly	Others
E C6019 M5 flange nuts A2 SS	UniQ		None	Assembly	Others
E C6021 M4 x 5mm A2 SS capscrew	UniQ		None	Assembly	Others
E C6022 M2.5 washer	UniQ		None	Assembly	Others
E C6023 M2.5 x 6mm panhead bolt	UniQ		None	Assembly	Others
E C6024 M2.5 x 11mm PCB spacer	UniQ		None	Assembly	Others
E C6025 M2.5 x 5mm PCB mounting post	UniQ		None	Assembly	Others
E C6035 M2.5 x 5mm bolt GSM mount	UniQ		None	Assembly	Others
E C6037 M5 x 10mm A2 SS domehead capscrew	UniQ		None	Assembly	Others
Electricity, at eGrid, AKGD, 2008/RNA U	USLCI		None	Energy	Electricity country

					mix\Low Voltage
Electricity, at grid, US/US	USLCI		None	Energy	Electricity country mix\Low Voltage
Electricity, biomass, at power plant/US	USLCI		None	Energy	Electricity by fuel\Biomass
Electricity, bituminous coal, at power plant/US	USLCI		None	Energy	Electricity by fuel\Coal
Electricity, diesel, at power plant/US U	USLCI		None	Energy	Electricity by fuel\Oil
Electricity, lignite coal, at power plant/US	USLCI		None	Energy	Electricity by fuel\Coal
Electricity, natural gas, at power plant/US	USLCI		None	Energy	Electricity by fuel\Gas
Electricity, nuclear, at power plant/US	USLCI		None	Energy	Electricity by fuel\Nuclear
Electricity, residual fuel oil, at power plant/US	USLCI		None	Energy	Electricity by fuel\Oil
Ethylene vinyl acetate copolymer {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Thermoplasts\Market
Fuel grade uranium, at regional storage/US	USLCI		None	Material	Fuels\Uranium\Fuel element
Full Life Cycle UniQ	UniQ	0 00000 UniQ	None	Life cycle	Others
Gasoline, at refinery/l/US	USLCI		None	Material	Fuels\Oil\Petrol
Gasoline, combusted in equipment/US	USLCI		None	Energy	Heat\Oil
Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocatio		None	Material	Plastics\Thermoplasts\Market

	n, default - system				
Heat, central or small-scale, other than natural gas {CH}| treatment of biogas, burned in micro gas turbine 100kWe | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Heat\Biofuel\Transformation
Injection moulding {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Plastics\Market
Injection moulding {RER}| processing | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Plastics\Transformation
Installation at Case Study W-S-M	UniQ	C C5030 Copper Tube, Seamless 28mm Dia, 4 m	None	Life cycle	Others
Kerosene, at refinery/l/US	USLCI		None	Material	Fuels\Oil\Kerosene
Lignite coal, at surface mine/US	USLCI		None	Material	Fuels\Coal\Produced coal\Mined coal
Lignite coal, combusted in industrial boiler/US	USLCI		None	Energy	Heat\Lignite
Liquefied petroleum gas, at refinery/l/US	USLCI		None	Material	Fuels\Oil\Propane/butane
Liquefied petroleum gas, combusted in industrial boiler/US	USLCI		None	Energy	Heat\Oil
Manufacturing at Sunamp	UniQ	0 00000 UniQ	None	Life cycle	Others
Metal working, average for aluminium product manufacturing {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocatio		None	Processing	Metals\General manufacturing\Market

	n, default - system				
Metal working, average for copper product manufacturing {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Metals\General manufacturing\Market
Metal working, average for metal product manufacturing {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Metals\General manufacturing\Market
Metal working, average for steel product manufacturing {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Metals\General manufacturing\Market
Municipal solid waste (waste scenario) {CH}| Treatment of municipal solid waste, landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste scenario	Landfill
Municipal solid waste (waste treatment) {CH}| treatment of municipal solid waste, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Natural gas, at extraction site/US	USLCI		None	Material	Fuels\Natural gas\Produced gas
Natural gas, combusted in industrial boiler/US	USLCI		None	Energy	Heat\Gas
Natural gas, processed, at plant/US	USLCI		None	Material	Fuels\Natural gas\Produced gas
Nylon 66/glass fibre composite E	Industry data 2.0		None	Material	Plastics\Thermoplasts
Paper, newsprint {Europe without Switzerland}| paper production, newsprint, recycled | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Paper+ Board\Graphic paper\Market

Petroleum coke, at refinery/kg/US	USLCI		None	Material	Fuels\Oil\Coke
Petroleum refining coproduct, unspecified, at refinery/kg/US	USLCI		None	Material	Fuels\Oil\Crude oil\Production
Plaster mixing {CH}| processing | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Others\Transformation
Polycarbonate {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Thermoplasts\Market
Polyester-complexed starch biopolymer {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Biopolymers\Market
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Thermoplasts\Market
Polyethylene, high density, granulate {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Thermoplasts\Market
Polyethylene, linear low density, granulate {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Thermoplasts\Market
Polymer foaming {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Plastics\Market
Polypropylene, granulate {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocatio		None	Material	Plastics\Thermoplasts\Market

	n, default - system				
Polystyrene foam slab {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Construction\Insulation\Market
Polystyrene, high impact {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Thermoplasts\Market
Polyvinylchloride, bulk polymerised {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Thermoplasts\Market
Polyvinylchloride, emulsion polymerised {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Thermoplasts\Market
Refinery gas, at refinery/m3/US	USLCI		None	Material	Fuels\Oil\Refinery gas
Residual fuel oil, at refinery/l/US	USLCI		None	Material	Fuels\Oil\Fuel oil
Residual fuel oil, combusted in industrial boiler/US	USLCI		None	Energy	Heat\Oil
Scrap steel (waste treatment) {CH}| treatment of scrap steel, inert material landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Inert material landfill
Scrap tin sheet (waste treatment) {CH}| treatment of scrap tin sheet, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Sodium borates {RoW}| production | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Chemicals\Inorganic\Transformation

Sodium phenolate {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Chemicals\Organic\Market
Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Metals\Ferro\Market
Steel, low-alloyed {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Metals\Ferro\Market
Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Metals\Ferro\Market
Stretch blow moulding {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Plastics\Market
Synthetic rubber {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Plastics\Rubbers\Market
Tap water, at user {CH}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Material	Water\Drinking water\Market
Thermoforming, with calendering {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Plastics\Market
Thermoforming, with calendering {RER}| production | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Processing	Plastics\Transformation

Transport Musselburgh to W-S-M	UniQ		None	Life cycle	Others
Transport, barge, average fuel mix/US	USLCI		None	Transport	Water
Transport, barge, diesel powered/US	USLCI		None	Transport	Water
Transport, barge, residual fuel oil powered/US	USLCI		None	Transport	Water
Transport, combination truck, average fuel mix/US	USLCI		None	Transport	Road
Transport, combination truck, diesel powered/US	USLCI		None	Transport	Road
Transport, freight, light commercial vehicle {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Transport	Road\Market
Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Transport	Road\Market
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {GLO}| market for | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Transport	Road\Market
Transport, ocean freighter, average fuel mix/US	USLCI		None	Transport	Water
Transport, ocean freighter, diesel powered/US	USLCI		None	Transport	Water
Transport, ocean freighter, residual fuel oil powered/US	USLCI		None	Transport	Water
Transport, train, diesel powered/US	USLCI		None	Transport	Rail

Use at W-S-M	UniQ		None	Life cycle	Others
Waste aluminium (waste treatment) {CH}| treatment of waste aluminium, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste glass (waste treatment) {CH}| treatment of waste glass, inert material landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Inert material landfill
Waste graphical paper (waste treatment) {CH}| treatment of waste graphical paper, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste paint (waste treatment) {CH}| treatment of waste paint, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste paperboard (waste treatment) {CH}| treatment of waste paperboard, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste plastic, mixture (waste treatment) {CH}| treatment of waste plastic, mixture, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste polyethylene (waste treatment) {CH}| treatment of waste polyethylene, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste polyethylene terephtalate (waste treatment) {CH}| treatment of waste polyethylene terephtalate, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste polypropylene (waste treatment) {CH}| treatment of	Ecoinvent 3 -		None	Waste	Transformation\Landfi

waste polypropylene, sanitary landfill | Alloc Def, S	allocation, default - system			treatment	ll\Sanitary landfill
Waste polystyrene (waste treatment) {CH}| treatment of waste polystyrene, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste polyurethane (waste treatment) {CH}| treatment of waste polyurethane, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste polyvinylchloride (waste treatment) {CH}| treatment of waste polyvinylchloride, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill
Waste wood, untreated (waste treatment) {CH}| treatment of waste wood, untreated, sanitary landfill | Alloc Def, S	Ecoinvent 3 - allocation, default - system		None	Waste treatment	Transformation\Landfill\Sanitary landfill