UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

OFFICIAL MASTER'S DEGREE IN THE
ELECTRIC POWER INDUSTRY

Master's Thesis

Planning of generation mix and system costs in the Canary Islands

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Supervisor: Javier Revuelta Alonso

Madrid, August 2024

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PLANNING OF GENERATION MIX AND SYSTEM COSTS IN THE CANARY ISLANDS

Author: Pérez de Guzmán Bermúdez Coronel, Fátima.
Supervisor: Revuelta Alonso, Javier.

ABSTRACT

The current electricity sector is undergoing constant change towards a more sustainable and low-emission model. Ambitious energy and climate objectives have been established at the European level through European Union policies. In this context, Spain has also demonstrated its significant commitments regarding energy and climate matters on the last version of National Energy and Climate Plan.

This master thesis seeks to contribute to the decarbonisation of the Canary Islands, specifically Tenerife, taking into consideration the key challenges these isolated systems propose, efficient curtailment and the regulatory framework in place for the development of the system.

The core of the study revolves around the development of a generation mix and system cost model for the Canary Island Tenerife, projecting towards a 2040 scenario with significant increase in renewable energy integration. The model includes demand projections considering key variables such as energy efficiency measures, GDP and population growth, as well as new demand drivers as the electric vehicle. There are three main scenarios compared in the study: government plans, BAU scenario and Author-AFRY scenario. These generation mix scenarios are studied and analysed based on their final renewable share in contrast with the share of curtailment entailed. Within each scenario, the study analysis the impact of storage facilities used for renewable integration.

Key findings suggest that while integrating renewable energy is essential for decarbonisation, there is a saturation point beyond which the extra benefit is close to zero in absence of abundant storage. This emphasises the need for careful strategic planning in the generation mix, particularly in isolated systems like Tenerife, where land and resources are constrained. Additionally, the study highlights the critical role of storage facilities in managing the intermittency of renewable generation. It also reveals that, due to the regulatory framework governing non-mainland systems, these storage facilities must operate as regulated assets to ensure optimal system performance.

Foreword

To my family and friends for their constant support,

To the AFRY team for their unconditional willingness to help, especially Javier for his guidance and trust,

And my MEPI colleagues and professors for making this journey into the electric sector unforgettable.

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Chapter 1. INTRODUCTION

The current electricity sector is undergoing constant change towards a more sustainable and low-emission model. Ambitious energy and climate objectives have been established at the European level through European Union policies. Among the latest legislative packages, one can find the Fit for 55 packages [1], in which member states are required to reduce greenhouse gas emissions by 55% by 2030.

In this context, Spain has also demonstrated its significant commitments regarding energy and climate matters. In the latest revision of the National Energy and Climate Plan (NECP) [2], at the time of writing in draft form, it sets a target of 42 GW of installed wind power capacity and 76 GW of installed photovoltaic solar power capacity by 2025.

Parque de generación del Escenario. Potencia bruta (MW)				
Años	**2019**	**2020**	**2025**	**2030**
Eólica*	25.083	26.754	42.144	62.044
Solar fotovoltaica**	8.306	11.004	56.737	76.387
Solar termoeléctrica	2.300	2.300	2.300	4.800
Hidráulica	14.006	14.011	14.261	14.511
Biogás	203	210	240	440
Otras renovables	0	0	25	80
Biomasa	413	609	1.009	1.409
Carbón	10.159	10.159	0	0
Ciclo combinado	26.612	26.612	26.612	26.612
Cogeneración	5.446	5.276	4.068	3.784
Fuel y Fuel/Gas (Territorios No Peninsulares)	3.660	3.660	2.847	1.830
Residuos y otros	600	609	470	342
Nuclear	7.399	7.399	7.399	3.181
Almacenamiento*	6.413	6.413	8.828	18.543
Total	**111.101**	**115.015**	**166.939**	**213.963**

Figure 1. Generation capacity mix scenario 2023-2030. Source: NECP

Moreover, since late 2020, prices in the daily market started to soar due to high gas prices. In Europe, clearing is carried out at the European level through a marginalist market. This means that the last unit to enter the hourly clearing will set the price for each MWh consumed in that hour. Frequently in Spain, the marginal units are gas combined cycle plants, which were major importers of Russian gas. With the outbreak of the war in Ukraine, and gas reserves at a minimum, Spain faced an energy crisis while still recovering from the Covid crisis, which led to the closure of large, medium, and small industries.

In this context, the European Union pushed forward several policies to promote renewable energy penetration, notably the REPowerEU program [3]The objectives of this program are to promote energy savings, boost clean energy production, and diversify energy supply. Following spot market maximum prices that reached 700 €/MWh in March 2022 [4], Spain, in line with the goals of the REPowerEU program, has been promoting renewable energy sources to reduce dependence on Russian gas.

1.1 MOTIVATION

Focusing on the subject of this master's thesis, in the current situation of the Canary Islands, the majority of energy demand is being met by fossil fuels. Considering the significant negative impacts this entails on the environment, as well as European policies promoting the use of indigenous energy sources in the country and Spain's potential to become a leader in sustainable energy sources, the Canary Islands will be modelled toward a decarbonized scenario.

The National Energy and Climate Plan (NECP) empowers the Canary Islands to lead their own energy transition and commits to promote a sustainable energy strategy in collaboration with regional and island governments. The plan aims to reduce energy costs and integrate renewables effectively, while addressing the challenges posed by the insular electrical system. Key measures include reducing fossil fuel dependency by at least 50% by 2030 and investing in unique projects to drive innovation and tackle specific challenges.

Additionally, the last version of NECP 23-30, still in draft, mentions Canary's Sustainable Energy Strategy based on NECP which aims at reducing the energy dependence of the islands and promote renewable penetration to guarantee the stability of the electric system.

The strategy pretends to mobilize 466.67 M€ skyrocketing the decarbonization of the islands by 2040 as contemplated in the Emergency Climate Statement of Canary Islands approved by its government in 2019 and ratified by its Parliament in 2020 [5]. To this means, and aligning with the Spanish Recovery, Transformation, and Resilience Plan [6], in 2022 it was published Royal Decree 451/2022 to regulate the concession of incentives for the Balearic and Canary energy strategies financials [7]This Royal Decree transfers an amount of 301.7 M€ for the following actions in the Canary Islands:

a) Funding for the administrative costs that agents must incur including permitting, engineering, construction or even events needed for the projects.
b) Programs for grants for new power installations that help integrate renewables, give technical support to the network, stability and frequency services.
c) Promote projects that help develop “smart islands”.
d) Investment Promotion Programs “Clean Energy for EU Islands”.
e) Programs that promote storage and contribute to renewable development.
f) Initial Boost for Energy Communities Promotion, supporting the establishment of new communities and developing transition agendas for each island.

This master thesis seeks to contribute to the decarbonisation of the Canary Islands, specifically Tenerife, taking into account the key challenges these isolated systems propose, efficient curtailment and the regulatory framework in place for the development of the system.

1.2 MASTER’S THESIS OBJECTIVES

Following the description made in the introduction, the main focus of this piece of work will be the development of a planning of generation mix and system costs in the Canary Islands for 2040 outlook.

1. Understanding and analysing the functioning of the electricity regulation in the Canary Islands.

2. Build iteratively a scenario of demand and generation capacity mix in Tenerife out until year 2040, consistent with security of supply as well as with RES integration constraints.
3. This scenario will be used to project total annual system costs, both fixed investment costs and variable fuel costs. In turn, these costs will be used to project the extra-costs of the Canary Islands to be socialized in national electricity grid tariffs.

Chapter 2. STATE OF ART

This chapter focuses on understanding the current regulation of the electricity sector in the non-mainland territories and specifically in the Canary Island Tenerife.

2.1 CANARY ISLANDS' ELECTRICITY REGULATION

The Canary Islands' electricity system is broken down into six small-sized and electrically isolated subsystems: Gran Canaria, Tenerife, Lanzarote-Fuerteventura, La Palma, La Gomera and El Hierro.

Before 1997, UNELCO-Endesa was the local vertically integrated company responsible for managing the system, generating most of the electricity and having exclusive control over the transmission, distribution and supply of the electricity. After market liberalisation, UNELCO was split in generation, distribution and transmission companies. Since then, Canary Islands generation is governed by a central dispatching of audited costs system.

Law 17/2013 [8] and Law 24/2013 [9] are the fundamental pieces of legislation for electricity regulation in the Canary Islands as well as for the mainland territories. Law 17/2013 includes the possibility to further subsidy renewable energy in isolated systems, such as the Canary Islands, as far as economical savings are achieved.

The Canary Islands, due to their insularity has got specificities that can be summarised as:

- Standard generation assets are remunerated under an audited cost scheme.
- Dispatch procedure based in audited costs except for renewables as they are dispatched based on an instrumental price of 10€/MWh.
- Market price is established under a specific mechanism for each island system.
- Consumers in the Canary Islands pay no extra costs for their specificities compared with mainland Spain. Extra costs both on the supply and generation side are to be paid by the electricity System and the National Budget.

2.1.1 ROYAL DECREE 738/2015

RD 738/2015, of 31st of July, regulates the production activity and dispatch procedure in non-peninsular electricity systems [10]. Non-mainland territories include the Balearic Islands, the Canary Islands, and the towns of Ceuta and Melilla located in the north coast of Africa. RD 738/2015 develops some specific aspects for those systems, introduced in:

- RD-Law 13/2012 [11]on criteria for the remuneration of generation in the non-peninsular systems.
- RD-Law 20/2012 [12] revising the financial remuneration of regulated activities.
- Law 17/2013 [8] on supply and competition in the non-mainland systems.
- Law 24/2013 [9] which repeals the sector Law 54/1997 [13] promoting renewables in the mainland systems as well as introducing market criteria in the mainland systems.

In addition, Order TEC/1172/2018 [14] modified Royal Decree 738/2015 by redefining the Balearic Islands as a single market system and introducing a new methodology for calculating demand acquisition prices and energy sale prices in the non-mainland territories.

2.1.1.1 General framework

In non-mainland systems, non-renewable generators and large hydro power plants are remunerated according to their audited costs, both the operational and the capital expenditures. These costs are much higher than in mainland Spain given the small size and less efficient technology of the generators, and their lack of access to gas.

Spain has a political commitment with all isolated territories to give them access to similar prices as the mainland despite much higher production costs. In the non-mainland systems, it is found the hourly ‘fabricated prices’ for which energy is traded in every subsystem. The difference between the ‘fabricated price’ which is aligned with the mainland spot market, and the real audited costs of the generation in the islands, is calculated by the regulating authority (CNMC). It is half paid by the State General Budget and half by all Spanish consumers through their bills. The total annual extra cost of all non-mainland systems amounts around 1.5billion € [15].

Hourly prices for the Canary Islands are different for each island system (Gran Canaria, Tenerife, La Palma, La Gomera, El Hierro and Lanzarote-Fuerteventura), but linked to the Spanish mainland pool price and calculated according to the operating guidelines established in RD 738/2015. These prices are 'fabricated', with an annual average equal to the mainland average price but affected by hourly demand coefficients which aim to provide local cost signals to foster a more efficient system. In these subsystems it can be found two different prices: demand acquisition prices and generation sale prices:

1. The hourly price $Ph_{demand}(j)$ at which retailers, direct consumers, self-generators with net balance as buyer and market representatives, is calculated as:

   $$Ph_{demand}(j) = Ppenin_D * Ah(z)$$

   Where:

   $Ppenin_D$ is the average final daily price in the peninsular market, expressed in €/MWh, for suppliers and direct consumers purchasing energy in the mainland production market, as published by the system operator. This price is adjusted by excluding capacity mechanisms costs, deviation costs, costs from unfulfilled international exchanges by market participants, and costs related to the interruptibility demand management service, as well as any other costs that may be established.

   $Ah(z)$ is an hourly adjustment factor based on the expected captured demand in each non-mainland territory z. It is calculated as:

   $$Ah(z) = \frac{Dh(z)}{DD(z)}$$

   Where:

   $Dh(z)$ is the hourly demand forecasted by the system operator in the non-mainland territory z, expressed in MWh.

$DD(z)$ is the daily average of the hourly demand forecasted by the system operator in the non-mainland territory z, expressed in MWh.

2. The hourly price Ph(j) at which merchant renewables are remunerated in system ‘j’, is calculated as:

$$Ph_{sale}(j) = PMDI_D * Ah(z)$$

Where:

$PMDI_D$ is the average daily price of the mainland daily and intraday market, in €/MWh. It is obtained from the weighted average of the hourly prices of the daily and intraday market on day D.

2.1.1.2 Dispatching

There are three dispatch procedures done by the system operator in place. The first is a purely economic dispatch, which will be explained in detail later. The second incorporates both economic and security of supply criteria. Finally, the third procedure, building upon the second, includes network constraints.

A minimising centralised dispatch is performed by the system operator REE. In order to obtain an economic merit order dispatch, different variable costs are considered depending on the allowed remuneration scheme for the different generation plants.

Firstly, for the power plants recognised with the so-called Additional Regime Retribution, mainly thermal and non-flowing hydro generation, variable costs are metered and regulated through audited cost curves as a function of the hourly plant output. The hourly cost curves are determined in Annex XIII of RD 738/2015, by parameters A (th/h)[1], B (th/h.MW) and C

1 ‘th’ is a therm, or 1000 kCal.

(th/h.MW^2), such that the hourly generation fuel cost at output power P, measured in therms per hour (th/h), is:

$$Chtherm(P) = A + B * P + C * P^2$$

Start-up costs are regulated through parameters D (€/start-up), A'(th), and B'(h), where A' and B' are parameters of an exponential curve that determine start-up costs as a function of time.

Emission costs are also regulated and calculated based on the power injected (P), the monthly average price from the emission rights auction (PCO_2), and the specific emission factors per technology established by the National Plan for the Allocation of GHG Emission Rights (fie). The calculation of emission costs also includes two correlation factors related to the efficiency of the energy produced (Corp), detailed in Annex XVII of R.D. 738/2015, as well as the actual emission level of each group (CoreD), as specified in the aforementioned National Plan.

$$C_{CO2}[€] = P * P_{CO2} * fie * Cor_p * Cor_{e_D}$$

Finally, there are regulation band costs calculated as 1% generation fuel cost as well as a variable cost of O&M determined by the regulator for each plant.

Secondly, for renewable energy sources recognised with the so-called Special Regime Retribution, production is considered for the dispatching at an instrumental cost of 10€/MWh, therefore getting priority of dispatch by being the first in the merit order.

Thirdly, the rest of power generation plants that do not have recognised the additional Remuneration scheme, such as any merchant renewable generator, will be dispatched through the variable costs that each plant communicates to the system operator.

2.2 CANARY ISLANDS' CURRENT ELECTRICITY SECTOR

The electrical sector in the Canary Islands relies heavily on conventional thermal power generation, which includes Steam Turbines (TV), Gas Turbines (TG), Diesel Engines (MD), and Combined Cycles (CC) as it can be seen on Figure 2. These technologies play a crucial role in meeting the energy demands of the archipelago, but their usage and importance vary across the different islands. Gran Canaria and Tenerife are the primary locations for steam turbines and combined cycle plants. While these units are less flexible, they provide more cost-effective energy compared to other conventional thermal technologies. They primarily cover the base demand, operating efficiently at full load. Flexibility in these systems is achieved using diesel and gas units, which can quickly adjust to real-time demand fluctuations.

On the islands of La Palma, Lanzarote, and Fuerteventura, the power generation primarily relies on diesel engines and gas turbines. These technologies offer rapid response capabilities, essential for meeting the dynamic demand on these islands. Historically, La Gomera and El Hierro have depended on diesel engines. However, these islands are seeing a shift due to the Gorona del Viento hydro-wind power plant in El Hierro, which reduces the reliance on conventional generators. The planned electrical interconnection between Tenerife and La Gomera, expected to be operational by 2025, will further decrease the need for conventional thermal generation on these islands.

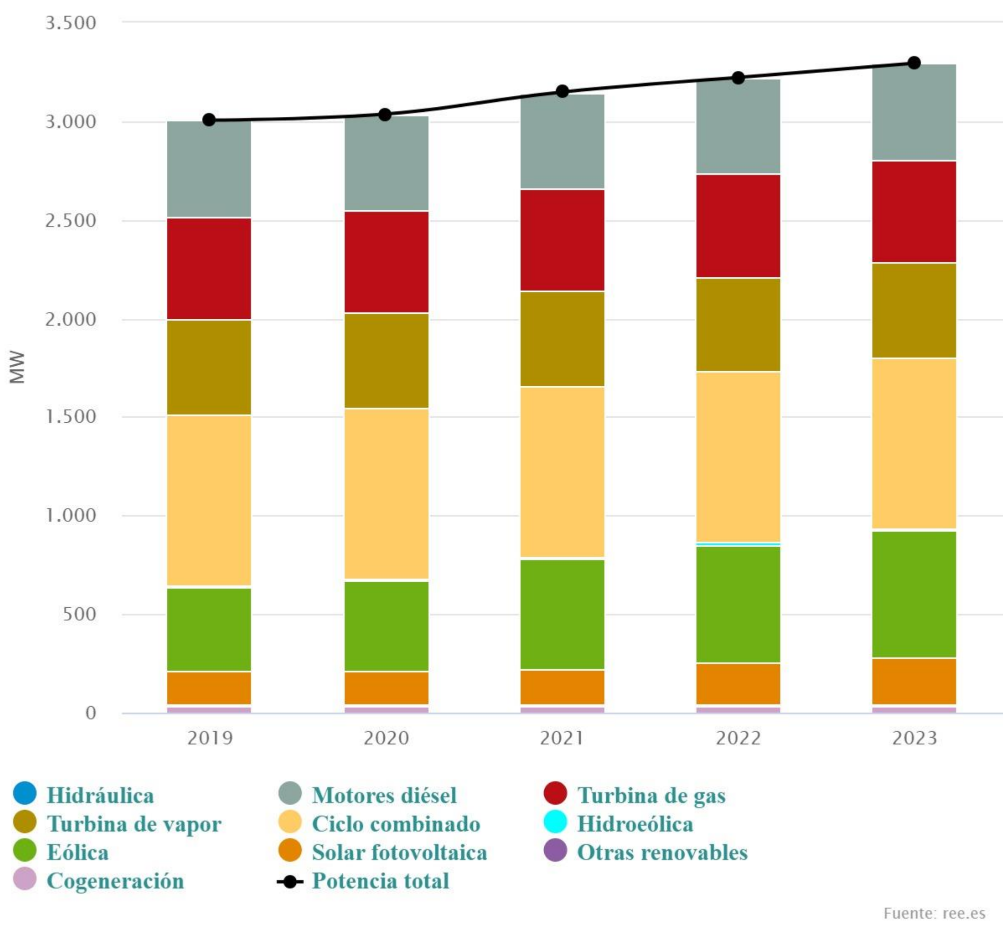

Figure 2. Canary Island's capacity mix. Source: ree.es

The share of renewable energy increased from about 10% coverage of demand in 2018 to approximately 24% in 2023. Despite this growth, conventional thermal generation remains vital to ensure a stable and reliable power supply due to the current limitations in renewable generation and storage technologies.

Conventional thermal power plants currently provide most of the regulatory services required to maintain grid stability. These plants must operate above their technical minimums to stay connected and offer ancillary services. The sector aims to increase the share of renewable energy, using more flexible and manageable renewable sources. The transition to renewable energy is ongoing, with significant efforts to increase its penetration in the coming years.

2.3 TENERIFE'S CURRENT ELECTRICITY MIX SITUATION

Tenerife's current installed capacity is dominated by fossil fuel power plants, with low participation of renewable generation (19% in 2023, according to REE[16]). The total installed capacity reached 1.4 GW in 2023. In Figure 3, it can be seen the capacity mix per technology of the past four years from 2019-2022.

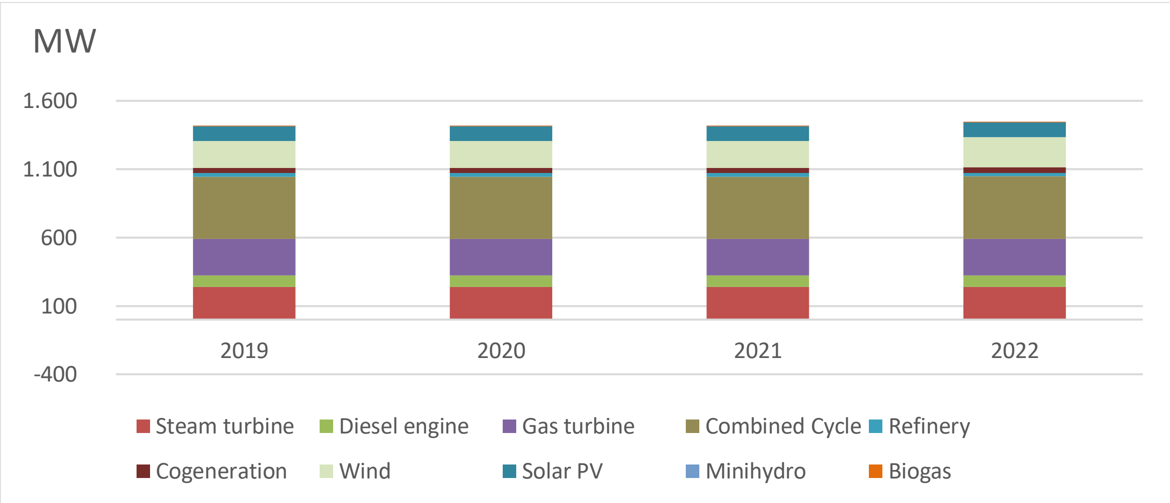

Figure 3. Capacity mix in Tenerife. Source: Canary Energy Journals [17]

Regarding generation, Figure 4 shows the very low penetration of renewables in the Tenerife amounting to 19%, which compares to around 40% in the mainland, and the national target of 81% by 2030 on the last version of NPEC, still in draft.

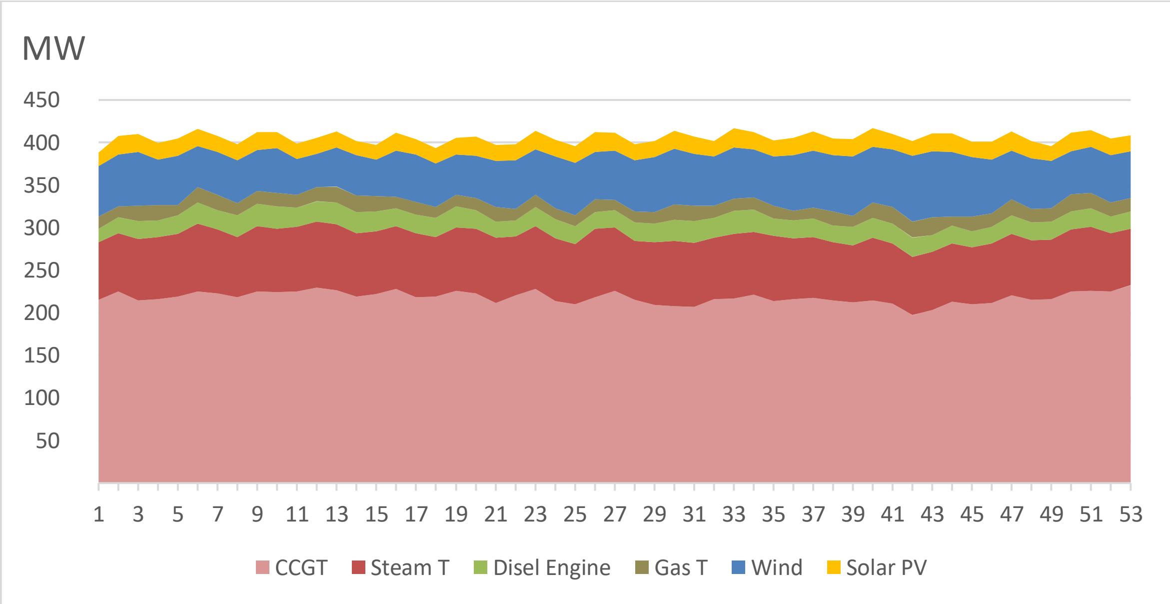

Figure 4. Weekly generation mix in Tenerife 2023. Source: esios.es

In addition, as it can be appreciated in Figure 4 combined cycles and steam turbines are used as base generation and represented 72% of annual demand coverage in 2023. Solar and wind energy still account for a small percentage of total coverage. Nevertheless, as it was previously mentioned, Spain's goal to achieve Net Zero goals by 2050 added to the Climate Emergency situation established in the Canary Islands due to their dependence on fossil fuel, impulses this master thesis to provide the capacity mix scenarios for 2030 and 2040 leading towards a more sustainable situation.

Chapter 3. PROPOSED METHODOLOGY

This chapter includes the different methodologies used for demand forecast and the hourly modelled built for comparing curtailment and renewable penetration with different capacity mix scenarios.

3.1 GENERAL ELECTRICITY DEMAND FORECAST

In this study, the general electricity demand in Tenerife has been modelled using a multiple regression approach, incorporating key variables such as Gross Domestic Product (GDP), population, and energy efficiency. This model aims to provide an accurate forecast of future electric demand in Tenerife, leveraging both historical data and reliable projections from esteemed institutions.

3.1.1 MODEL DESCRIPTION

The multiple regression model employed in this study includes three primary variables:

- GDP: Representing the economic activity and overall wealth.
- Population: Indicating the number of potential consumers.
- Energy Efficiency: Reflecting the technological advancements and adoption of energy-saving practices.

3.1.1.1 Initial Correlation Analysis

Before developing the multiple regression model, a preliminary analysis of correlations between the electricity demand and each of the three variables (population, GDP and energy efficiency) has been caried out using historical data. The results of this analysis can be seen in Table 1.

GDP	*0,87*
Population	*0,86*
Energy efficiency	-0,69

Table 1. Historical correlations with Demand in Tenerife. Source: created by the author

These correlation coefficients indicate a strong positive relationship between GDP and electricity demand, as well as between population and electricity demand. In addition, the negative value for energy efficiency correlation, was expected as the more energy efficient measures are taken, less energy is necessary for the same purpose.

3.1.1.2 GDP Projections

To project future GDP, data from several credible sources such as the Bank of Spain [18], the International Monetary Fund (IMF) [19], and the Organisation for Economic Co-operation and Development (OECD) [20] were consulted. Among these, the OECD projections were chosen for implementation. The decision to use OECD projections was based on their comprehensive methodology, which includes a detailed analysis of global economic trends, as well as their reputation for providing reliable and widely accepted economic forecasts. Although these projections are available at a national level for Spain, historical data shows that they are applicable to the Canary Islands, including Tenerife, due to similar economic behaviours and trends.

A study of correlations between the GDP growth of Spain and Tenerife over the past 23 years was conducted, resulting in a coefficient of 0.982268. This high correlation indicates a very strong positive relationship between the GDP growth patterns of Spain and Tenerife, reinforcing the applicability of national-level projections to regional forecasts for Tenerife as it can be seen on Figure 5.

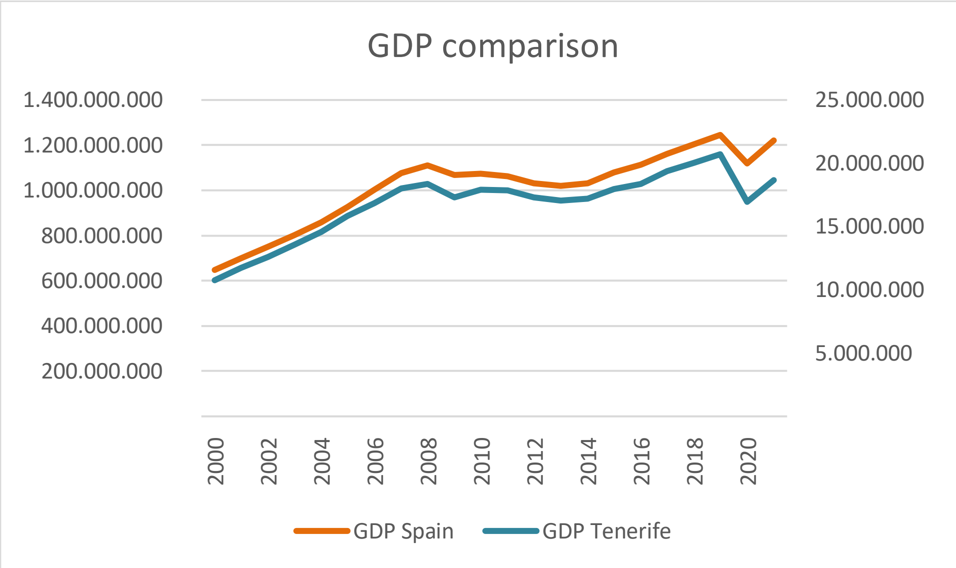

Figure 5. GDP correlations. Source: created by the author

Also, in Figure 6 it can be seen the GDP projections for Tenerife based on OECD information. It can be appreciated that in 2023 and 2024 the economy is still recovering from the energy crisis but from 2025 onwards a steady cyclical economic growth is expected.

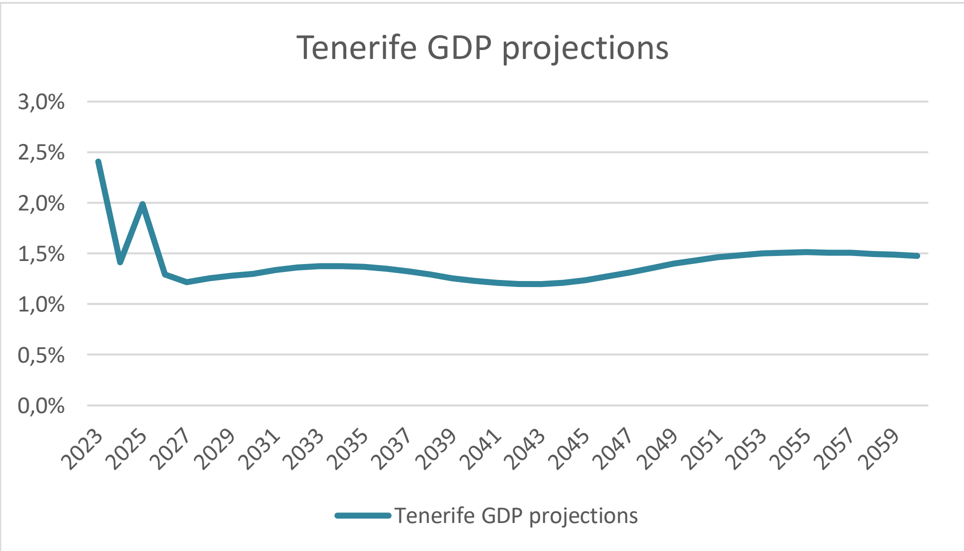

Figure 6. GDP projections. Source: OECD

3.1.1.3 Population Projections

Population projections were developed using a linear regression model based on historical data from the year 2000 onwards as it can be seen in Figure 7. This approach was validated by conducting a benchmark with forecasts from the National Institute of Statistics (INE) [21]. The similar results obtained from the proposed model's results and a renounced source as INE, validates the population projections used in the demand model.

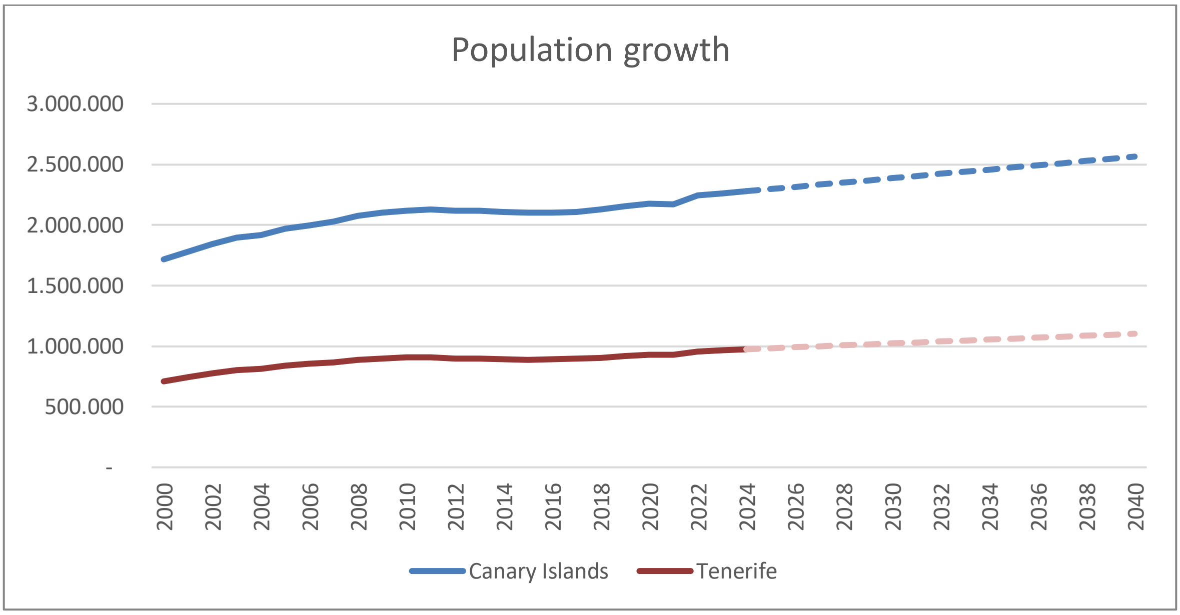

Figure 7. Population growth projections. Source: created by the author

3.1.1.4 Energy Efficiency

The impact of energy efficiency on demand was included in order to consider advancements in technology and increased adoption of energy-saving measures. It was also considered a linear approach based on passed data since 2015. Although it is known energy saving measures saturate, the linear approach is considered to be valid as the efficiency electricity measures in Tenerife are still on its early stages.

3.1.2 REGRESSION ANALYSIS

Following the initial correlation analysis, a multiple regression analysis was conducted to study in depth the impact of GDP, population, and energy efficiency on electricity demand. The results are summarized in the following table:

Statistic	***Value***
Multiple R	*0.966*
R Square	0.934
Adjusted R Square	0.923
Standard Error	225.206

Table 2. Main results of the Multivariable regression model

The multiple regression analysis yielded a Multiple R value of 0.9662, as it can be seen in Table 2, indicating a very strong positive correlation between the observed and predicted values of electricity demand, which suggests that the model's predictions are highly accurate. The R Square value shows that approximately 93.35% of the variance in electricity demand can be explained by the model, indicating a high level of explanatory power.

On the other hand, the low Standard Error reinforces that the model's predictions are very close to the actual observed values. Lastly, in Table 3 it can be seen the high t-statistics and low p-values for the different variables indicate that they are statistically significant and have a strong impact on electricity demand.

Variable	*Coefficient*	*Standard Error*	*t-Stat*	*P-value*
Intercept	-14768,8	2977,229	-4,9606	0,000111
GDP	9,37E-05	2,16E-05	4,331	0,000402
Population	0,004397	0,001066	4,1269	0,000633
Energy Efficiency	75655,6	12184,43	6,2092	7,36E-06

Table 3. Summary of multiple regression analysis. Source: created by the author

Once the results are validated, the hourly demand has been modelled by applying the annual increase derived from the 2023 regression model to the hourly demand data from 2023. This enables to maintain the general demand profile. In Figure 8 it can be seen the annual results of the model.

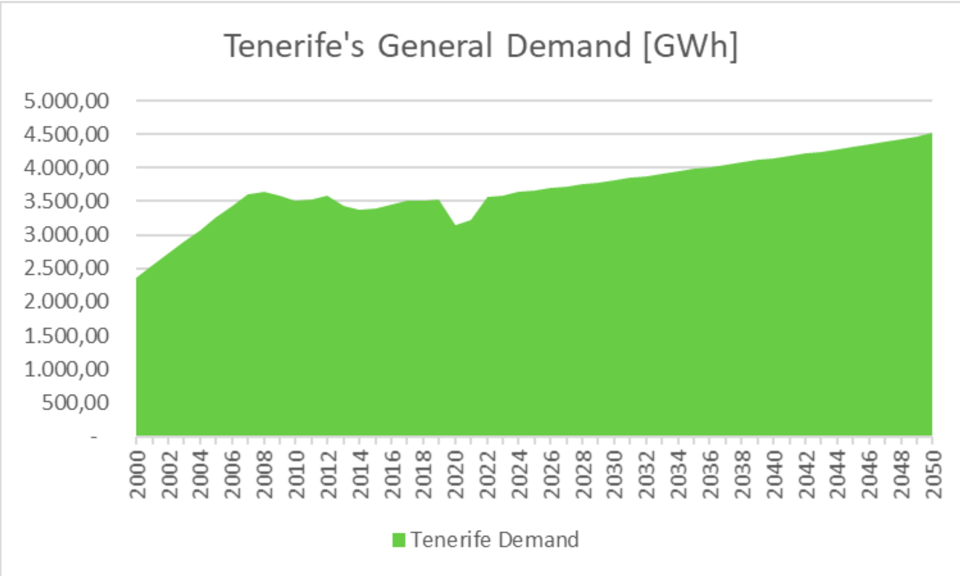

Figure 8. Annual Tenerife's general demand forecast

3.2 ELECTRIC VEHICLE ENERGY DEMAND

In addition to the general demand, it has been modelled the electric vehicle future demand in Tenerife. This study has been carried out using passed data on vehicle registrations in Tenerife using data from the Statistic Institute of Canarias [22] and assumptions based on policy announcements such as the Climate Emergency Declaration in 2019 [23].

3.2.1 MODEL

A preliminary analysis of the passed registrations per type of vehicle have been done. In Figure 9 it can be appreciated the most popular vector for electric vehicles are passenger cars and derivatives such as vans and pickups.

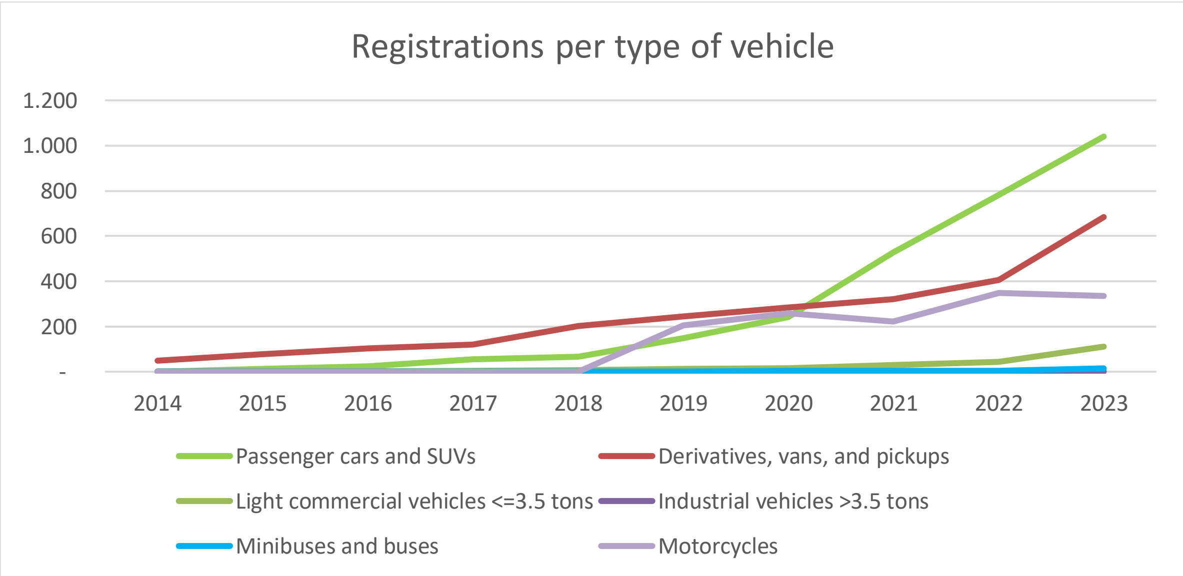

Figure 9. Registrations per type of fuel. Source: ISTAC [22]

For this reason, the study has estimated an amount of 16 kW/100 km for all vehicles assuming most of them are these two similar consumptive type vehicles.

On the other hand, in order to estimate the total electric vehicle fleet in 2030 and 2040 historical data on registrations per fuel type has been used. A regression BAU model has been implemented introducing policy factors based on the International Energy Agency forecasts on the Global EV Outlook 2023 [24]as well as local regulation as Climate Emergency Declaration in 2019 [5], Canary Energy Transition Plan and regional government announcements [25].

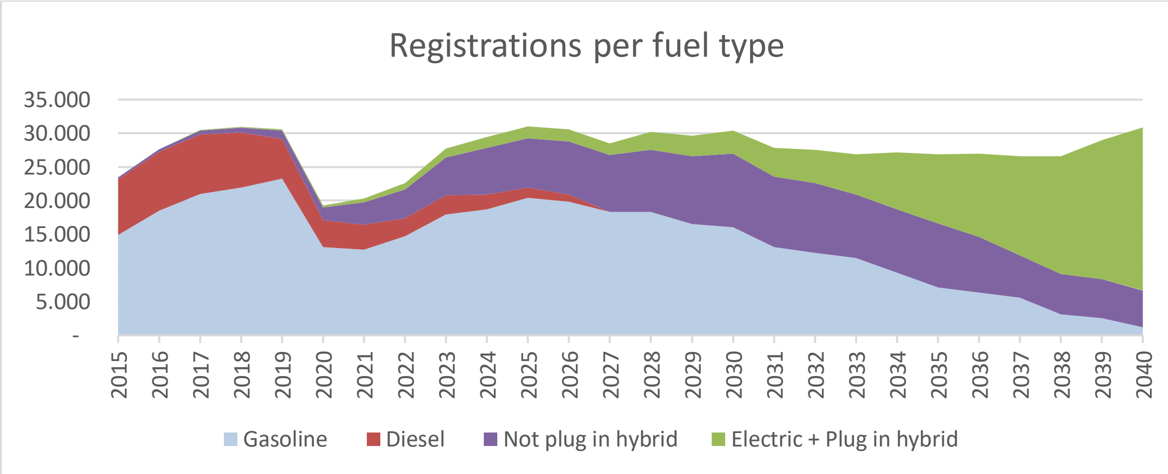

Figure 10. Registrations per fuel type. Source: Executed by author

As it can be seen in Figure 10, the BAU scenario is the main character until 2030. Small incentives have been considered since 2025 on EV, nevertheless, the transition plan skyrockets from 2030-2040 as its regional government has suggested on their Energy Transition Plan. Gasoline vehicles registrations decrease as electric vehicles registration increase. In addition, Not plug in hybrid diesel and gasoline vehicles have been considered to increase first half of the period but decrease the second half. This is because this technology is seen as a transition technology as it is not completely emission free. In Table 4 it can be the total fleet expected by 2030 and 2040.

Number of electric vehicles 2030	*19,807*
Number of electric vehicles 2040	*143,345*

Table 4. Total number of electric vehicle 2030 and 2040

Having estimated the expected EV registrations, it can be obtained the future energy demand for electricity vehicles. As it was mentioned before, it has been assumed 16 kW/100 km and according to the National Statistic Institute in the non-mainland territories the average distance rises 12,000 km per vehicle. Considering these figures, the following results are obtained in Table 5.

Electric Vehicle demand 2030 [MWh]	*38.028,82*
Electric Vehicle demand 2040 [MWh]	*275.221,78*

Table 5. Annual electric vehicle expected demand

In order to consider the electric demand on the hourly model, hourly values must be provided. Electric vehicle consumption patterns have been divided in two types: price responsive and non-responsive price profiles. The non-responsive profile has been provided by AFRY Management consulting following human behaviour prediction consumption similar to the mainland profile. However, price-responsive profile has been designed by the author in order to contemplate the high peak prices in Tenerife, which coincide with peak demand values as it was previously mentioned.

It has been studied the different profile the demand presents along the year using 2023 data from REE [26]. Four different clusters have been done: Summer Business Day (BD), Summer Non-Business Day (NBD), Winter BD and Winter NBD. Summer represents April to September months and winter the rest. The study has shown some difference along the year on energy magnitude consumptions; however, it can be concluded that low demand hours are constant along the year as it can be seen Figure 11.

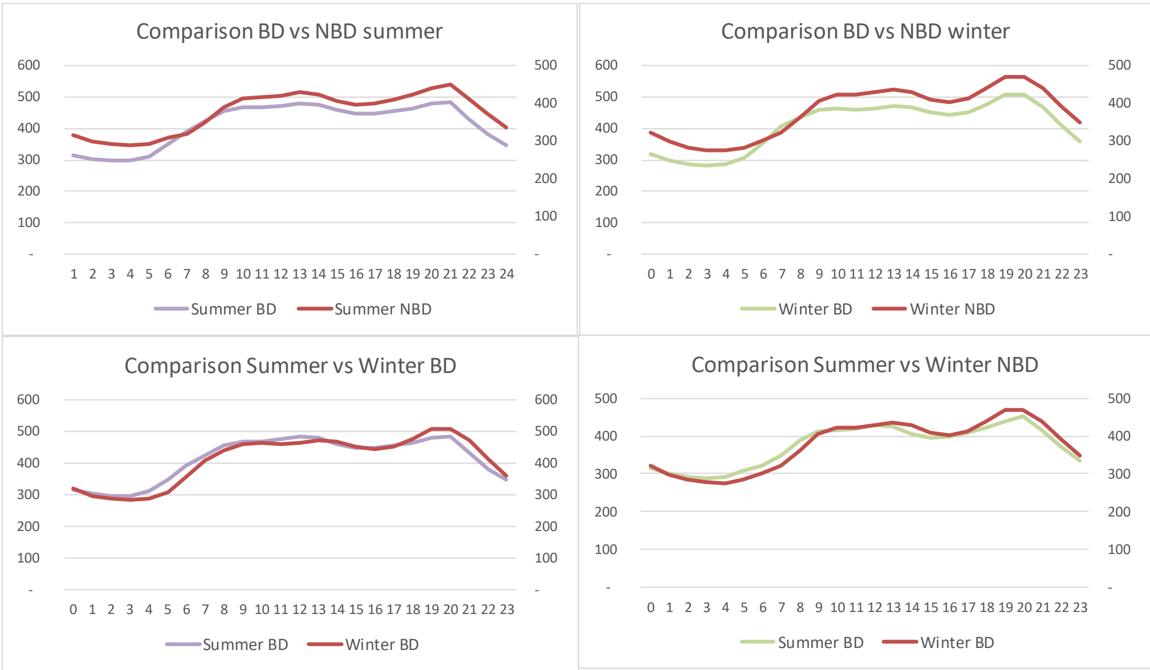

Figure 11. Demand fluctuations along the day in each month for 2023

Considering the findings from the research, the profile was designed to charge 50% of the time between 2-7am and 20% between 16-19 pm. The result can be seen in Figure 12.

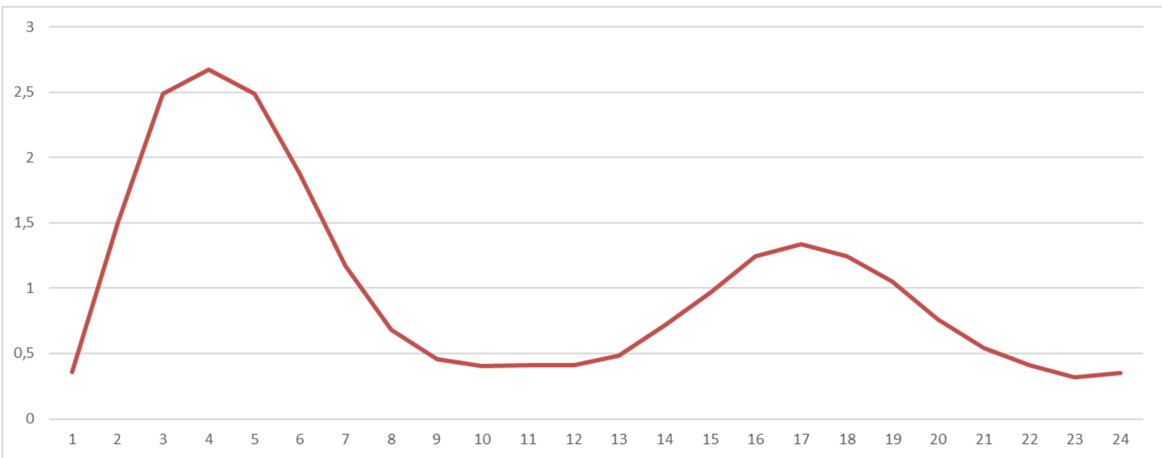

Figure 12. EV price-responsive profile. Source: Created by the author

In addition, in Figure 13 it can be seen the non-responsive profile provided by AFRY Management Consulting.

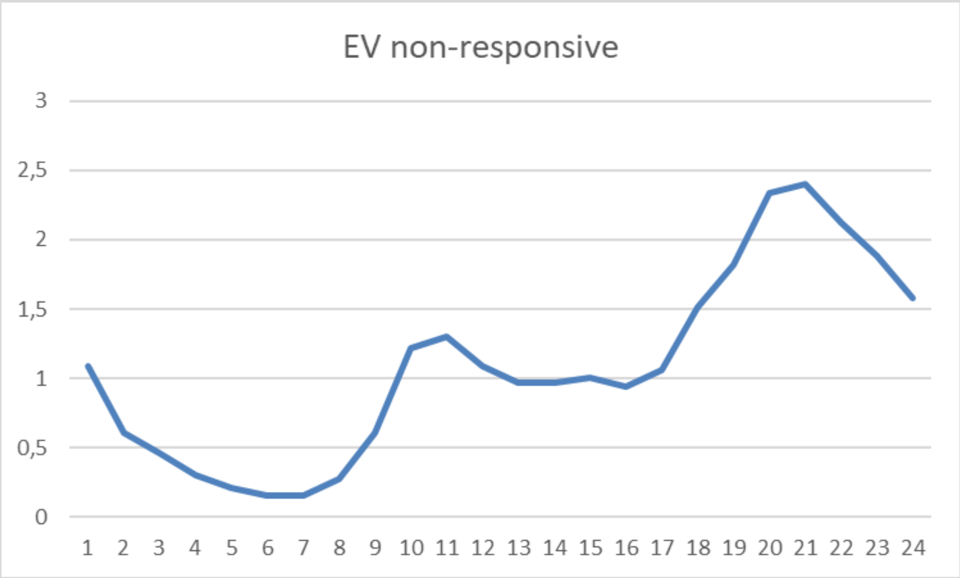

Figure 13. Non-price responsive profile. Source: AFRY

3.3 GENERATION MIX

System planning requires several complex and interrelated inputs. The so-called 'energy trilemma' seeks to design power systems at the best trade-off between high security of supply, high sustainability and low cost. The generation mix in Tenerife has been modelled using an hourly-based approach that ensures both security of supply and integration of renewable energy sources. This model takes into account the minimum thermal generation required in the island due to frequency and voltage control reasons as well as historical series for wind and solar energy.

The model's scenario-based approach allows for a robust analysis of how increased renewable energy sources should not only seek a lower emission generation mix but also a trade off with the potential curtailment it would bring. This model also incorporates batteries maximization usage for res penetration in order to maximise renewable penetration.

Overall, this hourly-based generation mix model serves as a vital tool in planning and optimizing Tenerife's future energy landscape ensuring a secure and efficient integration of renewable energy the island's transition towards a more sustainable and resilient power system.

3.3.1 UTILIZATION FACTORS

The study has been carried out using historical data on the hourly generation of the different technologies: solar PV, wind, diesel engines, gas turbines, combined cycles and steam turbines that represent the main generation units on the island. Red Eléctrica, the Spanish System Operator, provides the hourly generation for each one of these technologies on their website [26].

Wind series and solar series have been obtained dividing the hourly generation by the capacity installed each year, obtaining a utilization factor for each hour of the year. This has been calculated for the past four years obtaining a reliable generation scenario. In Figure 14 it can be seen part of the annual hourly wind profile obtained as an example with a 3-day profile in May.

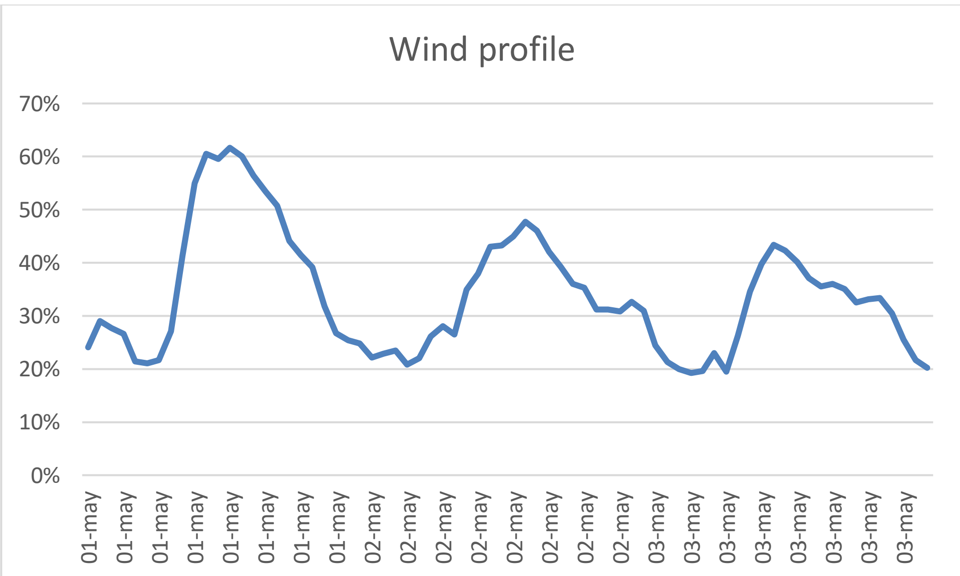

Figure 14. Wind series for 3 days in May. Source: created by the author

In the end, only one wind series and one solar series have been modelled using the average of the hourly utilization factor in order to obtain a solar and wind hourly profile. This has been one of the simplifications of the series acquisitions as well as assuming that no spillage has already been occurring as the model divides the generation by the installed capacity, assuming no curtailment in the past four years. In Figure 15 it can be seen that there are hours where there might have been spillage or maybe just clouds in that moment. The Canary Islands are known for their tropical weather and also, the little renewable generation these past four years support the weather assumption, even though due to security of supply issues there could have been exceptions.

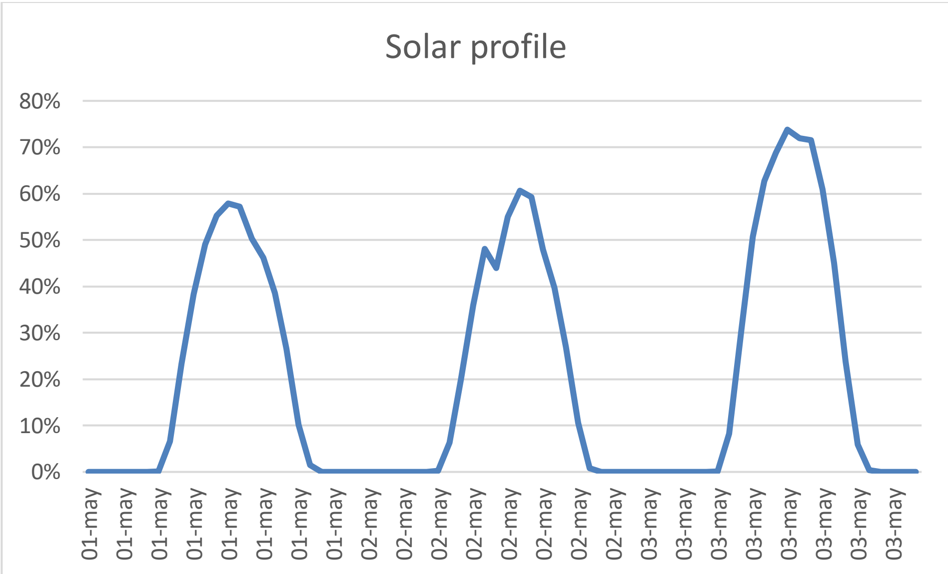

Figure 15. Solar series for 3 days in May. Source: created by the author

In order to maximize renewable penetration while ensuring security of supply requirements, the model implements a minimum must run thermal generation in order to couple with frequency and voltage control. Obtaining the minimum generation needed has been done using historical data on the four thermal generation founded in the island. Combined cycles and steam turbines have historically been used to cover base load as they are the cheapest but less flexible technologies, while gas turbines and diesel engines were used to follow the demand as they provide a more flexible response.

Historically, Tenerife Island has had maximum thermal generation reaching 578 MW in 2023 and minimum 146 MW of thermal generation. On 2023, the thermal distribution has been 66% covered by CCGT, 22% by steam turbine, 7% by diesel engine and 5% % by gas turbine. In Figure 16 it can be seen the thermal generation distribution along the year, highlighting the island's fossil fuel dependence.

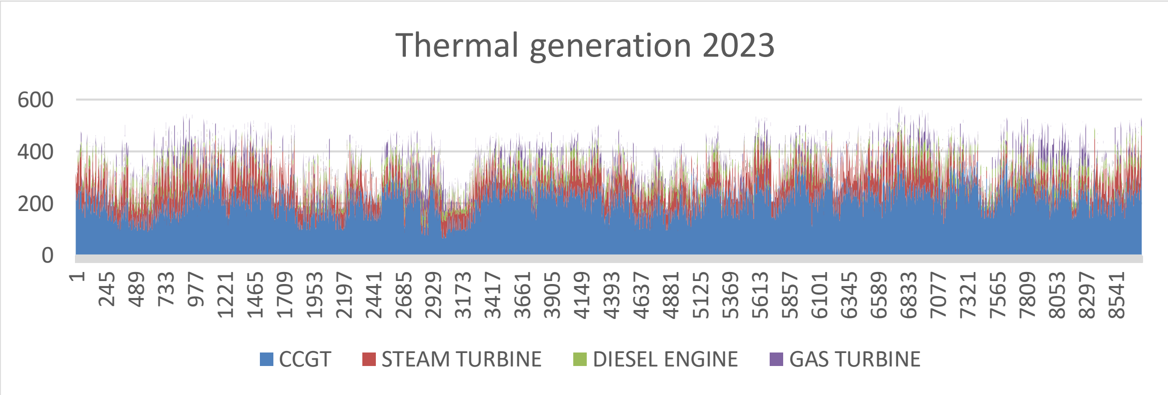

Figure 16. Thermal generation distribution in 2023. Source: REE

In the model, it has been studied the thermal generation for the last two years, and stablished the minimum thermal generation needed in 146 MW according to historical data. In Figure 17 it can be seen the thermal generation fluctuations along the year and it can be appreciated that the annual average generation is around 320 MW.

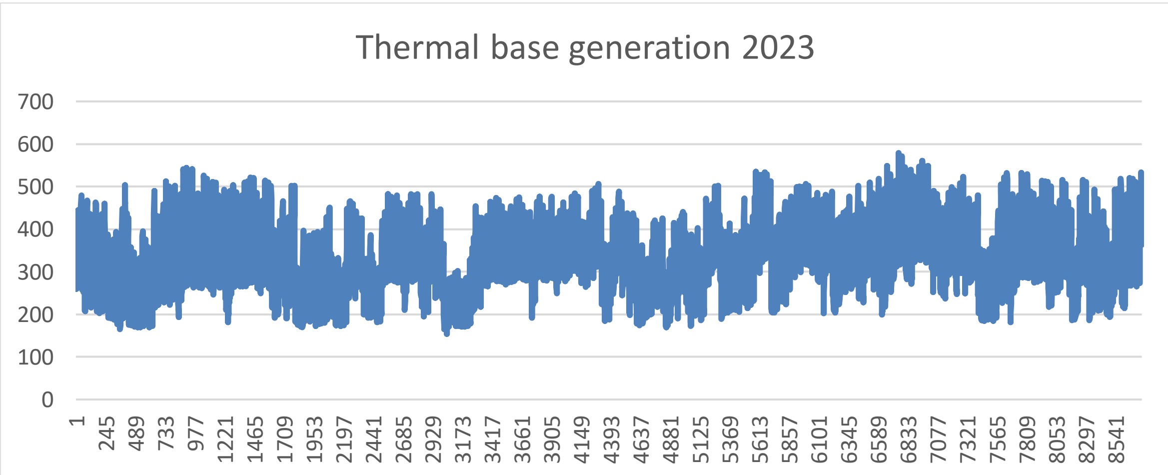

Figure 17. Thermal generation in Tenerife. Source: REE

The model assumes a minimum must run thermal generation of 146 MW by 2030 covered 48% by combined cycle, 41% by steam turbine and 11% by diesel engine. Nevertheless, by

2040 the new renewable generation derated has been taken into account to reduce the minimum thermal generation requirement. In order to consider renewable generation for each of the firm capacity the thermal generation provided, derating factors have been considered. In Table 6 it can be appreciated the different derating factors considered, obtained from a benchmark with capacity market rules in Belgium, UK and a study carried out on security of supply in Spain.

	Derating Factors
Geothermal	80%
Mini-hydro	45%
Biogas	87%
Onshore Wind	10%
Solar PV	0%
Offshore Wind	10%

Table 6. Renewable generation derating factors

In addition, the actual Tenerife generation mix also incorporates biogas and mini-hydro technologies. However, due to their small size and little participation in the generation mix REE does not provide their hourly production. Nevertheless, the Island Canary yearbooks [17]provide the equivalent hours for both technologies for the past years.

Year	*Equivalent hours*
2010	*5257*
2011	5507
2012	4784
2013	4853
2014	5076
2015	4539
2016	5713
2017	5871
2018	5322
2019	5296
2020	5503
2021	5000
2022	5547
Average	**5251**

Table 7. Biogas equivalent hours. Source: Canary Island yearbooks

Year	*Equivalent hours*
2014	7514
2015	7746
2016	7498
2017	7087
2018	7084
2019	7610
2020	7528
2021	6582
2022	7411
Average	**7340**

Table 8. Mini-hydro equivalent hours. Source: Canary Island yearbooks

As it can be seen, mini-hydro technology produces mostly at all hours of the year while biogas produces 60% of the hours of a year at rated capacity. In order to include these two technologies in the model it has been assumed a constant hourly production for the 8760 hours of the year. It is a simplification, however, due to the lack of information and the negligible generation it has been considered appropriate.

3.3.2 BATTERY OPTIMIZATION

Having revised the remuneration scheme for generators in the non-mainland system, in order to appropriately model the optimisation of the battery, it has been concluded it must be a regulated asset. Due to the nature of the 'fabricated price', price-signals are distortional and do not represent the actual cost of generation. In addition, as it was shown on previous

Figures, solar hours are usual peak demand values, translating into high market prices. Battery arbitrage would not be incentivised to charge in curtailment usual hours which would decrease the efficiency of the system. For this reason, the battery optimization has been modelled as a regulated asset by the system operator and with the goal of maximising the renewable production in the island.

This model implements different battery deployment scenarios in order to maximize renewable energy penetration and minimize resource curtailment, taking qualitative analysis on the development of this technology given its ongoing development and future potential.

In Tenerife, the shift towards renewable energy sources is vital due to the island's geographic and environmental constraints as it has been stated earlier. The island's isolation from the mainland grid means that energy stability must be maintained locally. Until now, this service has been provided by diesel engines and gas turbine, nevertheless, storage appears to be a perfect substitutive. Implementing large-scale battery systems, such as a 100 MW battery by 2030 and a 300 MW battery by 2040, is essential to address the intermittent nature of renewable energy sources like wind and solar [27].

The model proposes 4-hour duration batteries with 100 MW installed by 2030 and 300 MW installed by 2040. These proposed battery capacities are part of a broader strategy that aligns with Spain's national energy goals, which include a significant increase in storage capacity across the country by 2030. Spain's government has recognized the critical role of battery storage in integrating renewables, with plans to expand storage to 22 GW by 2030 [2]. This expansion supports the goal of a sustainable and reliable energy system, especially in regions like Tenerife where renewable energy plays an increasingly important role.

Moreover, the strategic deployment of these batteries not only supports renewable energy integration but also enhances grid stability by providing quick response times to balance supply and demand fluctuations. A 4-hour duration battery allows the System Operator to follow the demand when instability problems arise, giving time to other resources with higher ramp values to be operatively available. This capability is also particularly valuable as the island increases its renewable energy share, which can otherwise lead to instability in the grid due to the variability of renewable sources. Additionally, 4-hour batteries are economically viable, offering a balance between cost and functionality. They are generally more cost-effective compared to longer-duration batteries, making them an attractive option [28].

By gradually increasing battery storage capacity, the model ensures a scalable approach that accommodates technological advancements and optimizes investment over time. This approach not only supports Tenerife's energy transition but also aligns with global efforts to reduce reliance on fossil fuels and enhance energy resilience through innovative storage solutions.

The model assumes 89% of roundtrip efficiency, which has been taken into account on the discharge. As an example, assuming 100 MW scenario, the maximum charge on an hour rises 100 MW while the maximum output rises 89 MW and 11 MW on losses.

In order to optimise renewable penetration, the battery will charge whenever there is curtailment and the battery capacity is not at its maximum. On the other hand, for 2030 scenario, the battery will discharge on the 8 hours of the day with highest demand, in order to cover peak demand values, if there is missing generation and if there is capacity available on the battery. However, for 2040 scenario, as battery capacity increases, the 8-hour condition is changed for a 24-hour condition in order to maximise renewable penetration.

As the aim of the master thesis is the maximization of the usage of renewable resources installed, the damage in the useful life of the battery by charging and discharging not at its rated power has not been considered. This work is left outside of the project’s scope but could be developed on future works. On Figure 18 it can be seen an example of the functioning of the battery.

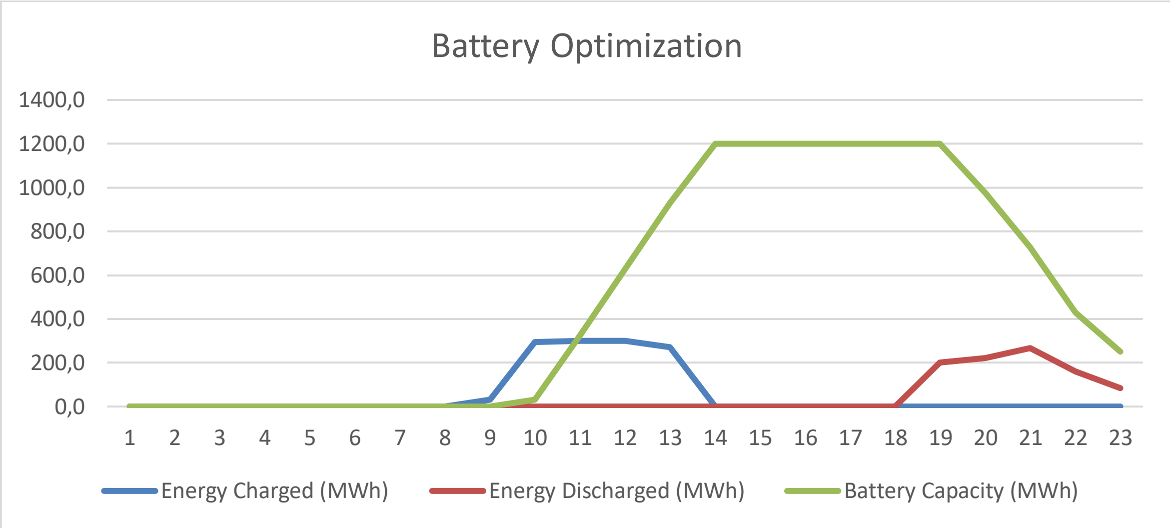

Figure 18. Battery optimization example

3.3.3 CAPACITY MIX SCENARIOS

Once it has been stablished the hourly generation profile for each technology and the battery optimization model, the capacity mix scenarios will be analysed. The objective of this master thesis is to provide a generation mix that meets integration of renewable resources in the Canary Island Tenerife with sufficient security of supply while considering efficient decisions according to curtailment.

In this study, there will be 3 main scenarios to be compared: government scenario, Business As Usual (BAU) scenario and Author-AFRY scenario. The Author-AFRY scenario arises from a qualitative analysis to provide a 50% renewable scenario mix for 2030 and an 80% renewable scenario by 2040 taking into account actual Tenerife's situation, technology developments, efficient renewable curtailment, security of supply and renewable penetration goals. In addition, there will be different sub-scenarios according to storage capacity installed.

The following scenarios will be analysed based on their renewable generation penetration and the level of expected curtailment:

1. Government Scenario

1.1. Results 2030
    1.1.1. No batteries installed
    1.1.2. 100 MW batteries installed
1.2. Results 2040
    1.2.1. No batteries installed
    1.2.2. 100 MW batteries installed

2. BAU Scenario
    2.1. Results 2030
        2.1.1. No batteries installed
        2.1.2. 100 MW batteries installed
    2.2. Results 2040
        2.2.1. No batteries installed
        2.2.2. 100 MW batteries installed
3. Author-AFRY Scenario
    3.1. Results 2030
        3.1.1. No batteries installed
        3.1.2. 100 MW batteries installed
    3.2. Results 2040
        3.2.1. No batteries installed
        3.2.2. 100 MW batteries installed

The Author-AFRY scenario has been stablished to look for a 50% res penetration by 2030 and 80 % res penetration by 2040. Both scenarios will be the result of a qualitative analysis on the development of certain emerging technologies such as high geothermal enthalpy and offshore wind, as well as the increase in the already developed technologies onshore wind and solar wind. The potential increase has been set keeping the installed capacity ratio of this two technologies constant.

Chapter 4. RESULTS AND FINDINGS

This chapter includes the different capacity mix scenarios and the percentage of renewable generation and curtailment obtained. For visual purposes, each scenario includes a Figure that captures a 2-day mix in September, instead of the 8760 hours of the year.

4.1 GOVERNMENT SCENARIO

As it was mentioned earlier, the government has the commitment of achieving 50% res penetration by 2030 and has announced a total renewable capacity mix by 2040. The government scenario is based on the announcements and plans the regional government from the Canary Island has stated. The Canary Energy Transition Plans [25]and the Dispatchable Generation Strategy [29] provide the expected generation mix scenarios.

	2023	***2030***	***2040***
Geothermal	0	20	20
Mini-hydro	0,46	2,6	2,6
Biogas	1,6	7	17,8
Onshore Wind	245,6	568	1700
Solar PV	107,6	719	2506
Offshore Wind	0	130	505
Minimum thermal	146	146	0

Table 9. Installed Capacity Mix Government's scenario in MW

4.1.1 GOVERNMENT SCENARIO RESULTS 2030

By incorporating the capacity mix into the model, the following values for renewable penetration and curtailment have been obtained for the different scenarios, both with and without batteries.

	Government Scenario 2030	
Storage capacity installed [MW]	100	0
% RES in Generation Mix	59%	55%
% Curtailment	33%	36%
Net Energy stored in batteries [MWh]	76,848.14	0

Table 10. Results Government Scenario 2030

As it can be seen in Table 10, government plans fulfil the objective of 50% demand covered by renewable generation by 2030. However, there is a 29% of curtailment on the best scenario of renewable penetration and a 31% not considering storage. It can be appreciated that renewable penetration increases 4% due to batteries installation. Nevertheless, a 29% of curtailment significantly impacts the Levelized Cost of Energy (LCOE) of the different technologies.

$$LCOE = \frac{Total\ Costs}{Total\ Energy\ Output}$$

From the previous equation it could be thought that the higher the energy output the lower the LCOE. However, that is not correct when introducing curtailment. When curtailment is introduced, the energy output that is actually utilized (aka dispatched) decreases, thereby increasing the LCOE proportionally.

To illustrate the impact of a 29% curtailment on the LCOE, consider the following example:

Assume a wind plant is designed to produce 100,000 MWh of energy annually at a total cost of 5,000,000 €. Without any curtailment, the LCOE would be:

$$LCOE = \frac{5{,}000{,}000\ €}{100{,}000\ MWh} = 50\ {}^{€}/_{MWh}$$

However, if 29% of the generated energy is curtailed, only 71,000 MWh (71% of the total generation) is effectively utilized. In this case, the LCOE increases as follows:

$$LCOE = \frac{5{,}000{,}000\ €}{71{,}000\ MWh} = 70{,}42\ {}^{€}/_{MWh}$$

This example demonstrates that a 29% curtailment results in a 41% increase in the LCOE, from 50 €/MWh to 70 €/MWh. This significant rise in LCOE underscores the importance of minimizing curtailment in order to keep the cost of renewable energy competitive.

To address these issues, it is essential to consider additional strategies beyond the constant installation of renewable assets to increase res penetration. By planning a more optimized generation mix alongside other measures such as storage facilities, enhanced grid flexibility and improved demand-side management.

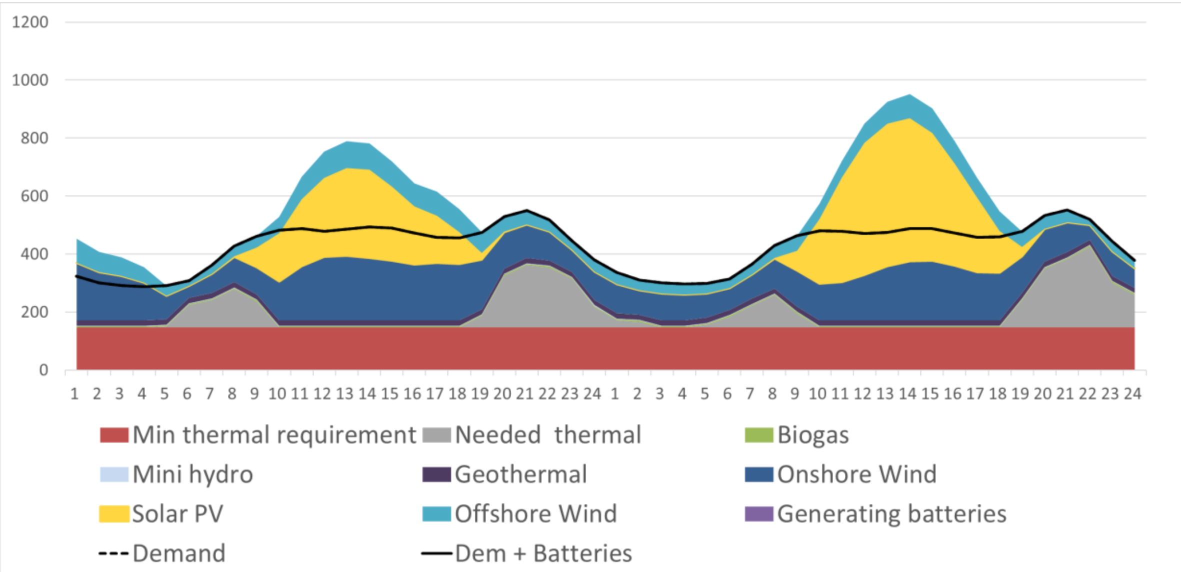

Figure 19. Generation mix Government scenario 2030 with 0 MW storage capacity

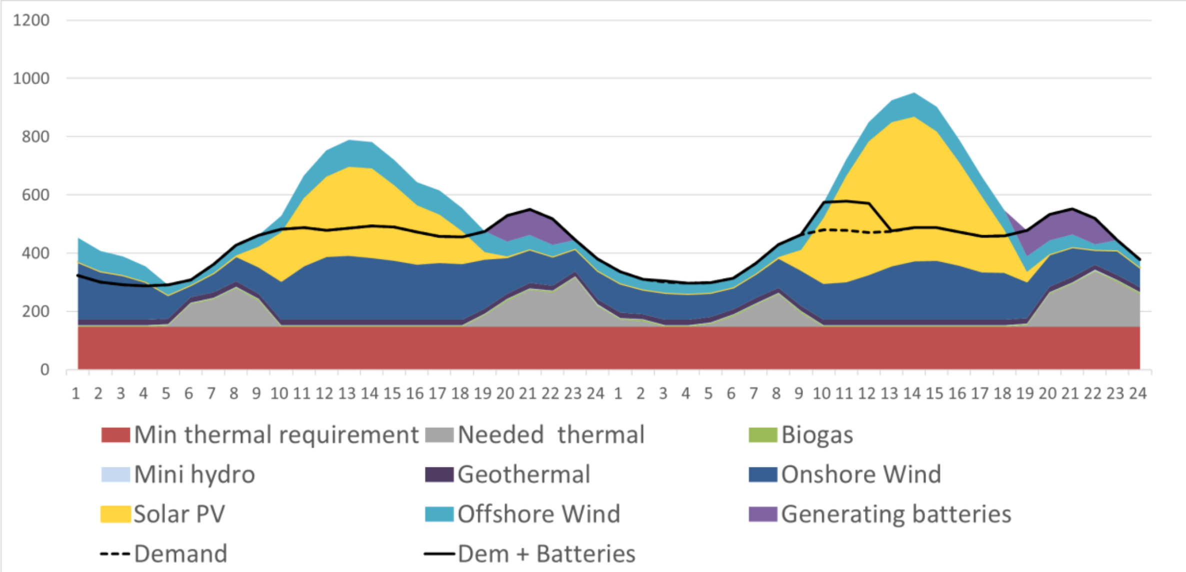

Figure 20. Generation mix Government scenario 2030 with 100 MW storage capacity

4.1.2 GOVERNMENT SCENARIO RESULTS 2040

The outlook for 2040 on the government scenario provides a generation mix almost fully decarbonised with a 96% renewable penetration in batteries' scenario. However, curtailment presents unprecedented figures as it can be seen in Table 11.

	Government Scenario 2040	
Storage capacity installed [MW]	300	0
% RES in Generation Mix	96%	92%
% Curtailment	60%	62%
Net Energy stored in batteries [MWh]	143,157.2	0

Table 11. Results Government Scenario 2040

From the results and from Figure 21 Figure 22 it can be seen that most of curtailment occurs during solar hours. It is important to underline that peak demand for 2040 rises up to 925

MW while maximum solar PV production expected on one hour reaches 2080 MW, resulting on 1155 MW of curtailment on best scenario, just accounting for solar PV production. Actually, curtailment maximum figure reaches 3400 MW on one hour.

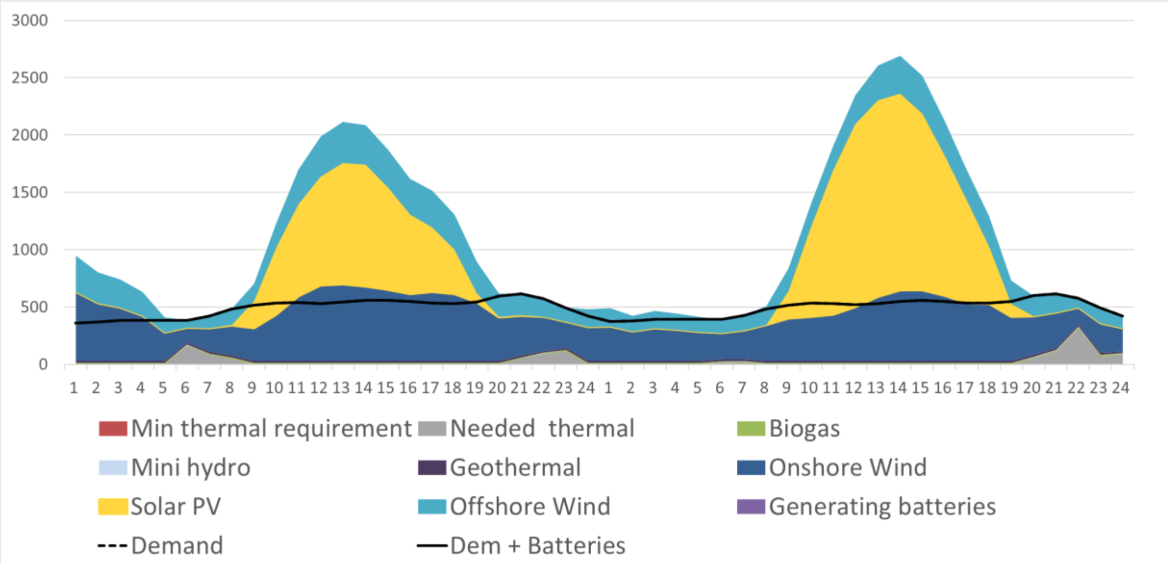

Figure 21. Generation mix Government scenario 2040 with 0 MW storage capacity

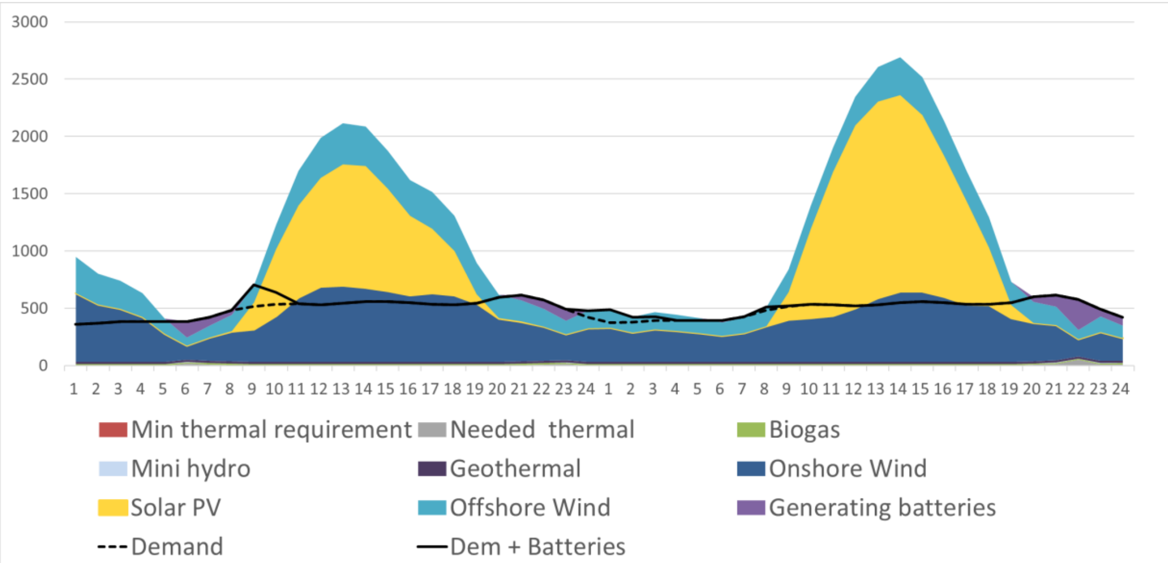

Figure 22. Generation mix Government scenario 2040 with 300 MW storage capacity

For comparison reasons, it has been modelled the same scenario except for the solar PV installed capacity. Solar PV installed capacity has been decreased from 2506 MW to 1400

MW, keeping the percentage of RES penetration constant. The results can be seen on Table 12 and Figure 23.

	Government PV Solar Scenario 2040
Storage capacity installed [MW]	300
% RES in Generation Mix	96%
% Curtailment	52%
Net Energy stored in batteries [MWh]	144,696.88

Table 12. Results Government PV Solar Extra scenario 2040

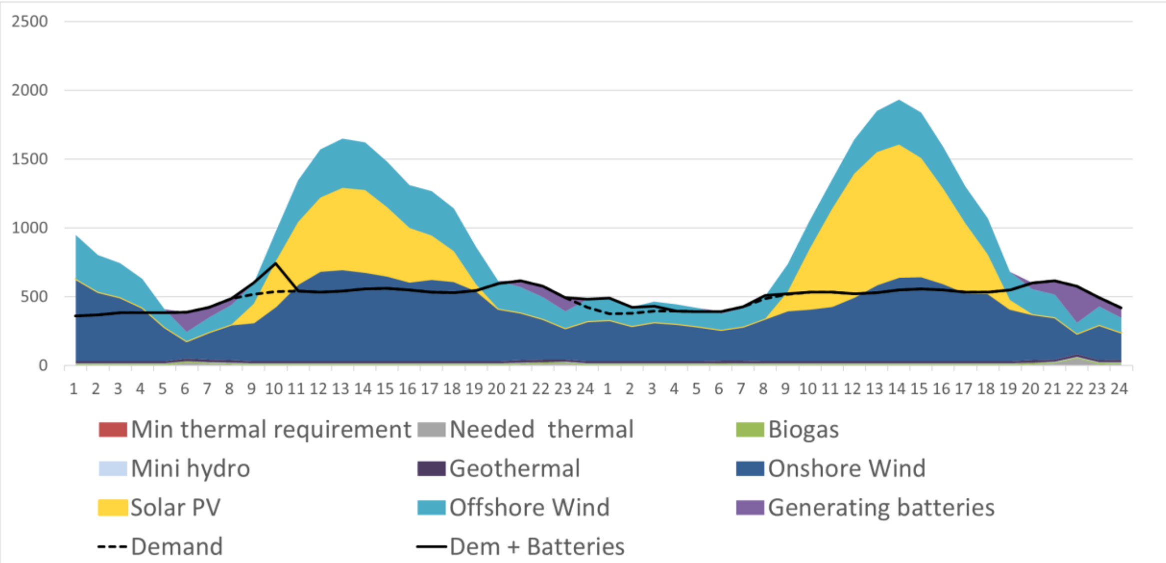

Figure 23. Generation mix Government PV Solar scenario 2040 with 300 MW storage capacity

As illustrated in Table 12, there has been a 6% reduction in curtailment, while the level of renewable energy penetration has remained constant. This highlights a critical insight: there are inherent limitations to renewable energy installations, particularly for solar PV, due to its restricted production hours compared to other technologies. Simply increasing the installed capacity does not necessarily contribute to further decarbonise the energy system. In this context, the concept of marginal benefit becomes relevant. Specifically, the question arises: what additional value does one extra MW of installed solar PV capacity provide? As shown, the addition of 1106 MW does not translate into increased renewable energy output within the system, indicating that the marginal benefit, in this case, would be zero.

4.2 BAU SCENARIO

The Canary Islands Yearbooks provide the installed capacity of each technology over the years. The Business As Usual scenario represents a linear regression of the renewable energy installed capacity over the years.

MW	***2023***	***2030***	***2040***
Geothermal	0	0	0
Mini-hydro	0,46	0,46	0,46
Biogas	1,6	1,6	1,6
Onshore Wind	245,6	485	784
Solar PV	107,6	147	214
Offshore Wind	0	0	0
Minimum thermal	146	146	103

Table 13. Installed Capacity Mix BAU scenario in MW

4.2.1 RESULTS BAU SCENARIO 2030

On Table 14 it can be appreciated the results for the BAU scenario for 2030. If the renewable sources kept growing at the same pace that are growing today, green goals would not be achieved. This reflects the need of incentive regulation in order to attract investors in the renewable sector in Tenerife. In addition, it can be stated that batteries, for RES penetration purposes, would not be efficient on this scenario as nearly no curtailment is seen.

	BAU Scenario 2030	
Storage capacity installed [MW]	100	0
% RES in Generation Mix	36%	36%
% Curtailment	1%	2%
Net Energy stored in batteries [MWh]	14296,95	0

Table 14. Results BAU Scenario 2030

In addition, Figure 24 Figure 25 reflect a two-day outcome of the capacity mix with and without batteries. It is remarkable the amount of extra thermal needed in order to fulfil electric demand needs.

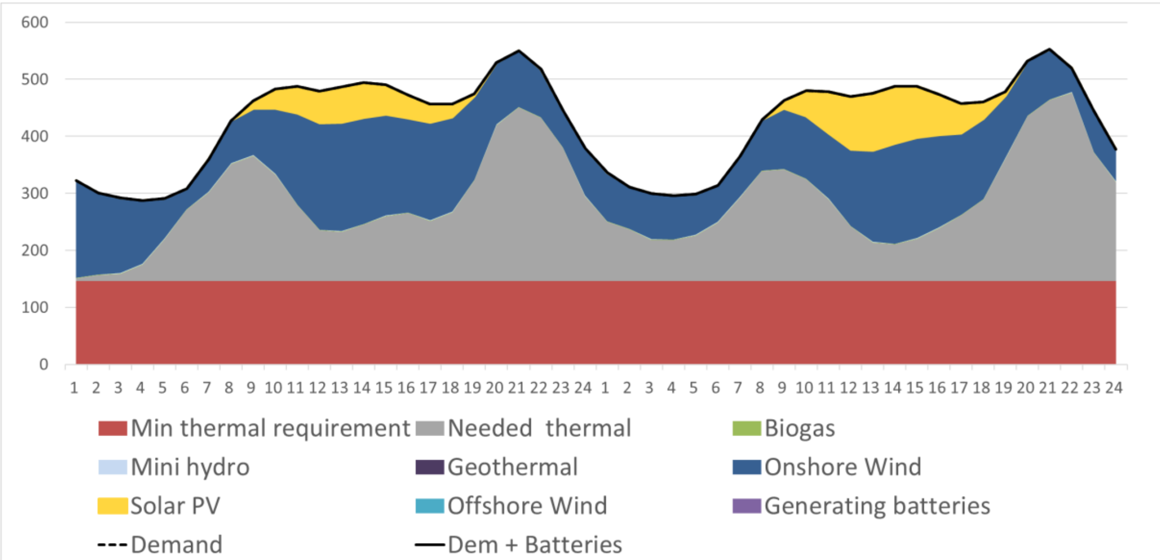

Figure 24. Generation mix BAU Scenario 2030 with 0 MW storage capacity

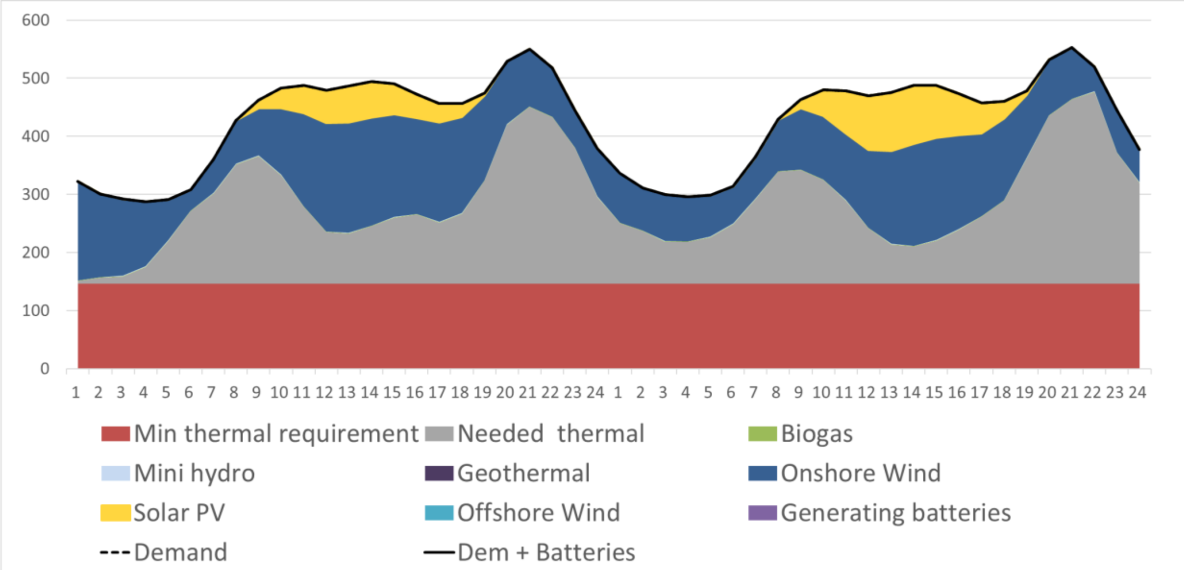

Figure 25. Generation mix BAU Scenario 2030 with 100 MW storage capacity

4.2.2 RESULTS BAU SCENARIO 2040

It can be observed in Table 15 that using storage capacity would avoid 3,34% of curtailment while achieving a 50 % renewable generation on Tenerife's system. Nevertheless, as it was stated before, the Canary Islands are under a Climate emergency and this scenario would not satisfy the renewable penetration goals.

	BAU Scenario 2040	
Storage capacity installed [MW]	300	0
% RES in Generation Mix	50%	48%
% Curtailment	1%	5%
Net Energy stored in batteries [MWh]	65905,64	0

Table 15. Results BAU Scenario 2040

As shown in Figure 26Figure 27 thermal generation is one of the main players in this scenario and storage capacity is still underused compared to the other scenarios.

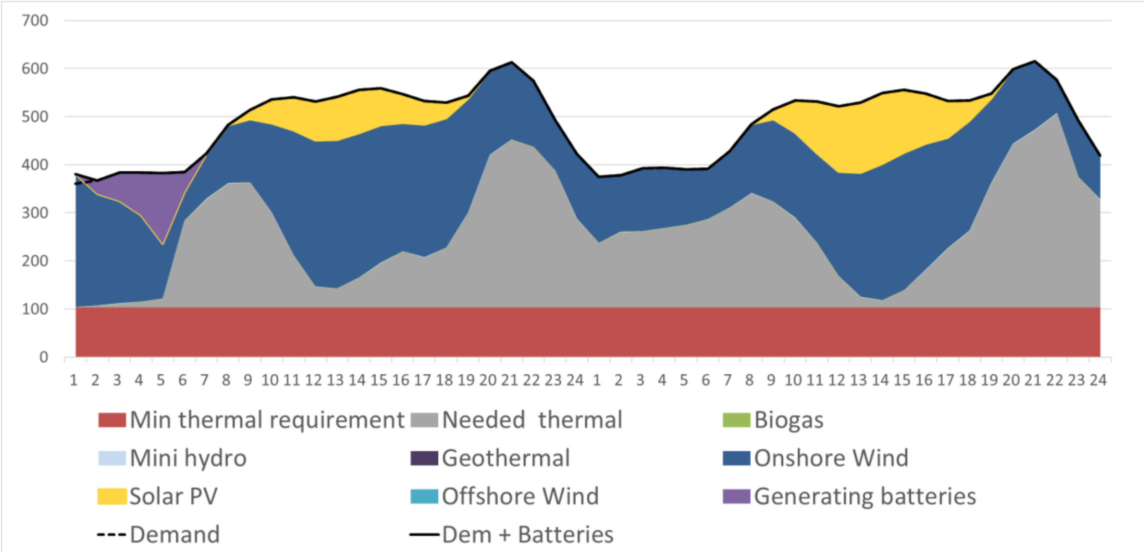

Figure 26. Generation mix BAU Scenario 2040 with 300 MW storage capacity

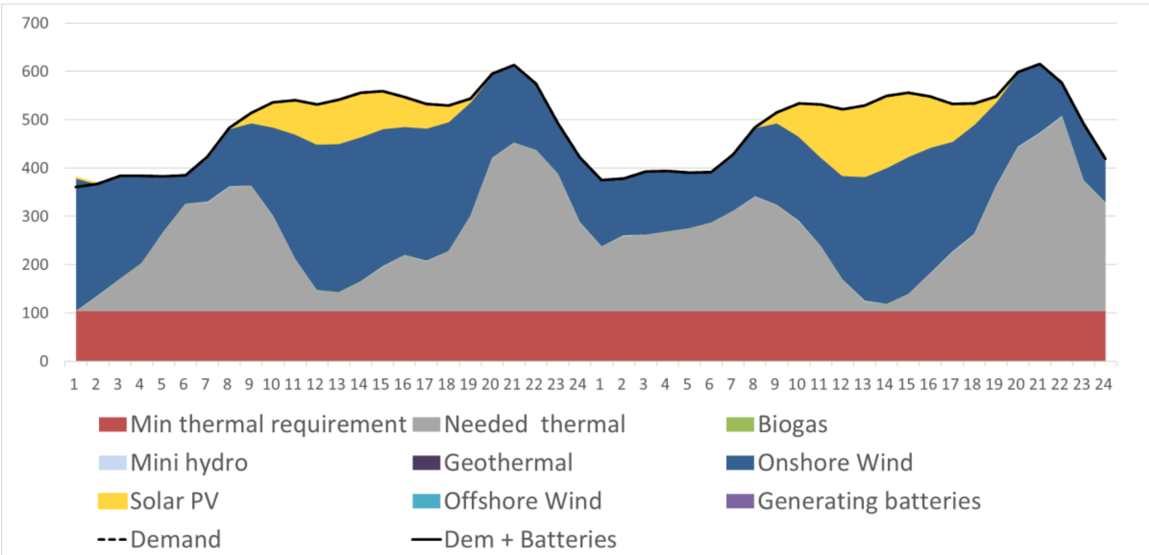

Figure 27. Generation mix BAU Scenario 2040 with 0 MW storage capacity

4.3 AUTHOR-AFRY SCENARIO

The author- AFRY scenario mix is the result of an iterative process in which the author has sought to achieve both renewable targets of 50% and 80% on the generation mix. Through a qualitative analysis and announcements made by energy sector companies the following generation mix were finally obtained. In addition, both scenarios were conditioned by a maximum curtailment of 20% in order to maximise renewable capacity utilization, in addition to not increasing the LCOE more than 25% which would decrease significantly the financial viability.

MW	***2023***	***2030***	***2040***
Geothermal	0	0	10
Mini-hydro	0,46	0,46	2,6
Biogas	1,6	1,6	15
Onshore Wind	245,6	620	1180
Solar PV	107,6	250	500
Offshore Wind	0	50	150
Minimum thermal	146	146	36

Table 16. Installed Capacity Mix Author-AFRY scenario in MW

4.3.1 RESULTS AUTHOR-AFRY SCENARIO 2030

As it can be observed in Table 17, renewable penetration goals are achieved in batteries storage scenario. Curtailment is under control and the storage facility enables to capture 3 % of the total curtailment.

	Author-AFRY Scenario 2030	
Storage capacity installed [MW]	100	0
% RES in Generation Mix	50%	47%
% Curtailment	10%	13%
Net Energy stored in batteries [MWh]	55,697.87	0

Table 17. Results Author-AFRY Scenario 2030

On Figure 28 Figure 29 it can be seen the generation mix on both situations. Batteries substitute thermal generation such as diesel engines and gas turbines which are usually used in Tenerife to follow demand fluctuations.

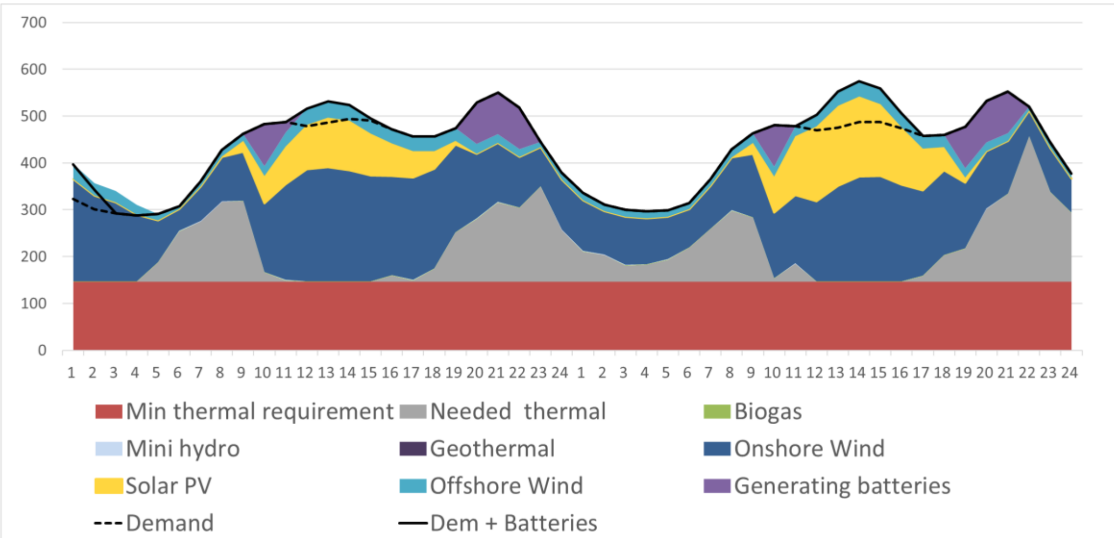

Figure 28. Generation mix Author-AFRY Scenario 2030 with 100 MW storage capacity

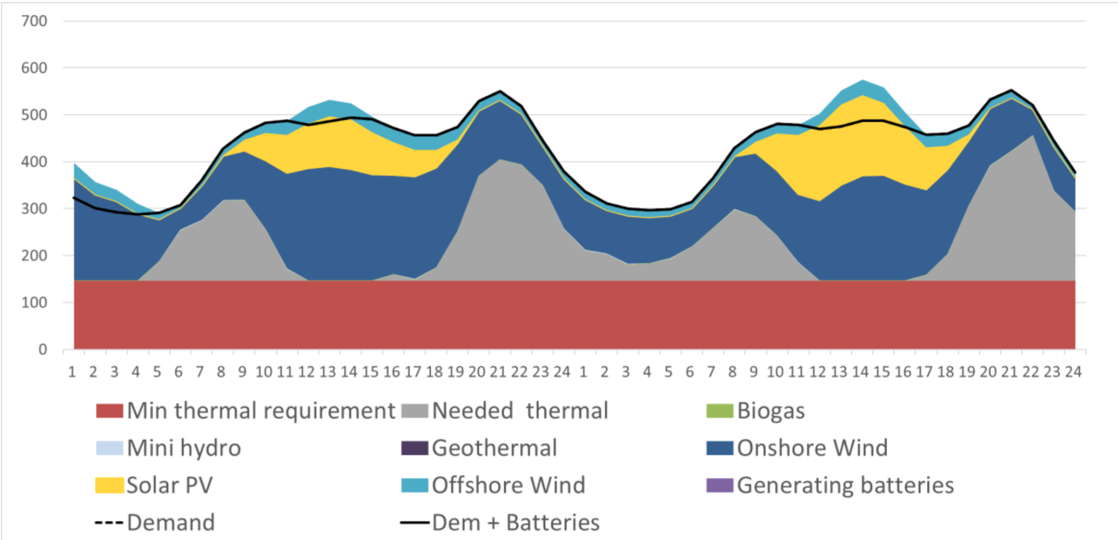

Figure 29. Generation mix Author-AFRY Scenario 2030 with 0 MW storage capacity

4.3.2 RESULTS AUTHOR-AFRY SCENARIO 2040

It is found in Table 18 the results for Author-AFRY scenario 2040. As it can be appreciated, the 80% renewable goal is achieved and the total curtailment is 20% of the total resource.

	Author-AFRY Scenario 2040	
Storage capacity installed [MW]	300	0
% RES in Generation Mix	80%	75%
% Curtailment	20%	25%
Net Energy stored in batteries [MWh]	195,893.56	0

Table 18. Results Author-AFRY Scenario 2040

It is also seen in Figure 30 and Figure 31 the different generation mix obtained with and without batteries. Curtailment represents a high figure which could be dropped introducing more storage facilities into the system.

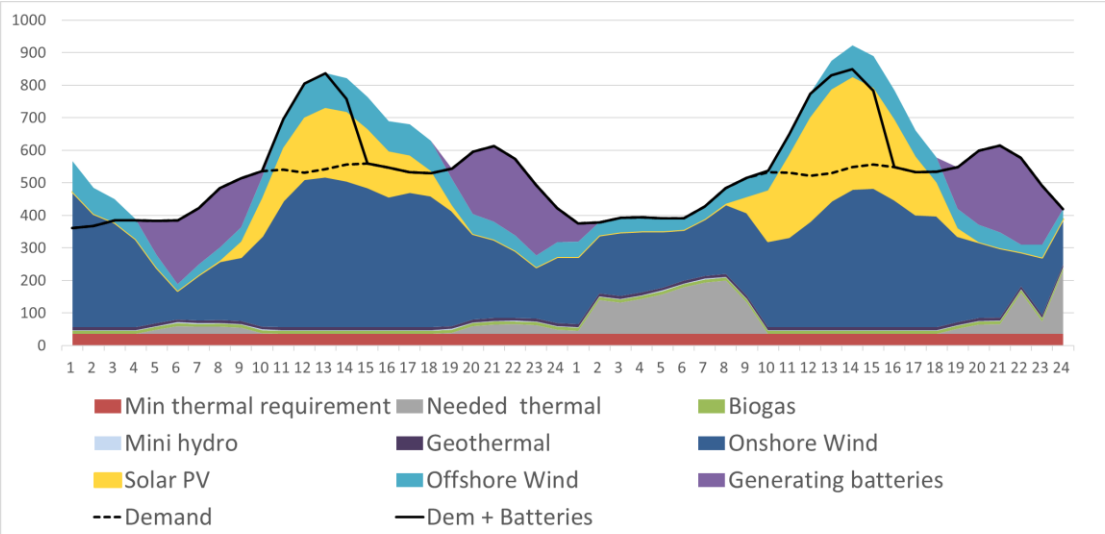

Figure 30. Generation mix Author-AFRY Scenario 2040 with 300 MW storage capacity

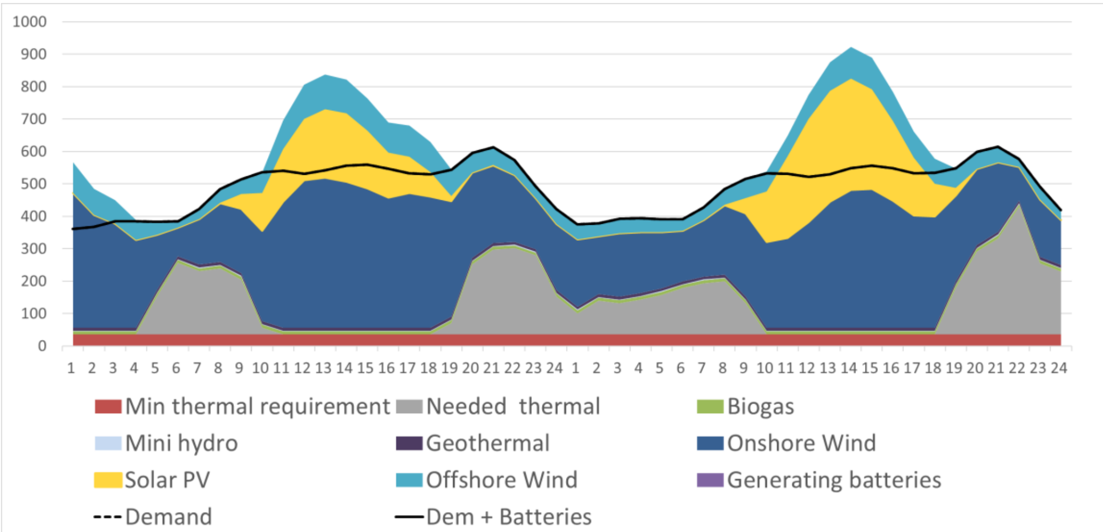

Figure 31. Generation mix Author-AFRY Scenario 2040 with 0 MW storage capacity

4.4 FINAL COMPARISON

As it was seen, each scenario has its own advantages and disadvantages. The BAU scenario could be said to be the cheapest one as it does not implement extra measures nor investments. However, net zero goals would not be met by this scenario.

On the other hand, government plans achieve renewable penetration goals. Nevertheless, it could be said to be optimistic and not efficient. As it was demonstrated, government plan for 2040 entails a curtailment percentage over 60%. These figures make the investment at high risk of no payback and so, no investments made. Or else, if the government were to pay them, they would just entail a very inefficient measure to make using state budget.

Finally, the proposed mix capacity scenarios have shown to optimise renewable penetration while keeping curtailment in low levels. These scenarios could yet be more optimised maybe by different storage capacity facilities and considering the useful life of them. Nevertheless, this study could take place as a continuity of this work as it escapes the scope of this project.

Chapter 5. ECONOMIC STUDY 80 % RES SCENARIO

In this chapter, it will be assessed the total system costs associated with achieving an 80% renewable energy share in Tenerife's electricity generation mix by 2040. This analysis includes both capital expenditures (CAPEX) and operational expenditures (OPEX) for each energy technology. The aim of this study is to understand the financial implications of transitioning to a predominantly renewable energy system while maintaining grid stability and meeting energy demands.

The technologies analysed include onshore and offshore wind, solar PV, geothermal, mini-hydro, biogas, and battery storage. The data for the different technologies' costs were obtained from renounced sources such as the National Renewable Energy Laboratory [30], Global Wind Energy Council Report [31] and World Biogas Association [32]. In addition, conventional thermal power generation will continue to play a role, with contributions from diesel engines, steam turbines, and combined cycle plants covering 11%, 41%, and 48% of thermal generation, respectively. The costs for these technologies have been estimated and annualized to provide a clear picture of the system's economic demands in 2040.

Table 19 presents the assumed CAPEX (in millions of euros per MW) and OPEX (in euros per MW per year) for the technologies considered in this scenario.

Technology	CAPEX [m€/MW]	OPEX [€/MW]
Onshore Wind [33]	1.2	30,000
Solar PV [33]	0.8	2,000
Offshore Wind [31], [34]	5.6-3.5	90,000
Geothermal [35]	4	75,000
Mini-Hydro [30]	2.25	30,000
Biogas [32]	3.75	75,000
Battery Storage Ion-Lithium [36], [37]	0.634-0.340	10,000

Table 19. CAPEX and OPEX renewable technologies

These values are based on current market trends and industry benchmarks, adjusted for expected conditions in 2040. Solar PV, Onshore Wind, Mini-hydro and biogas have been considered mature and prices would not change between 2030 and 2040 installations. However, offshore wind is still an immature technology in Spain which justifies the higher prices for the first decade of the scenario and a lower cost for the second half of the scenario timeline.

In order to obtain the expected extra generation cost in the non-mainland territory Tenerife, investments have been annualised considering lineal depreciation and an 8% interest on the capital return. In real life investments would take place progressively, however, as this is a simplification on the calculation of the total costs, investments have been considered to start their regulatory life on 2030 the first scenario for achieving 50% res penetration and on 2040 the second scenario which is the rest of installed capacity missing to achieve the 80% res penetration. The useful life of the technologies has been set on 25 years, except for batteries which they present 15 years of useful life.

In addition, as it was stated in previous chapters, the thermal generation used would be covered 48% by combined cycle, 41% by steam turbine and 11% by diesel engine. The study on Canary Island's regulation enabled to extract the annualised audited costs for the different technologies which depend on the CO_2 prices and the fuel prices. Based on U.S. Energy Information Administration (EIA) [38] the following prices have been considered in Table 20.

Fueloil BIA 1%	744
Fueloil BIA 0,3%	683
Fueloil BIA 0,73%	683
Gasoil 0,1 % S	859
Dieseloil	953
Natural Gas	688

Table 20. Fuel projections costs for 2040 in €/ton. Source: eia

In addition, prices for CO2 have been considered from renounced sources such as Enerdata [39] which projects a cost of 130 €/ton CO2 by 2040. After 2040 they expect an extremely high rise on prices as it can be seen on Figure 32.

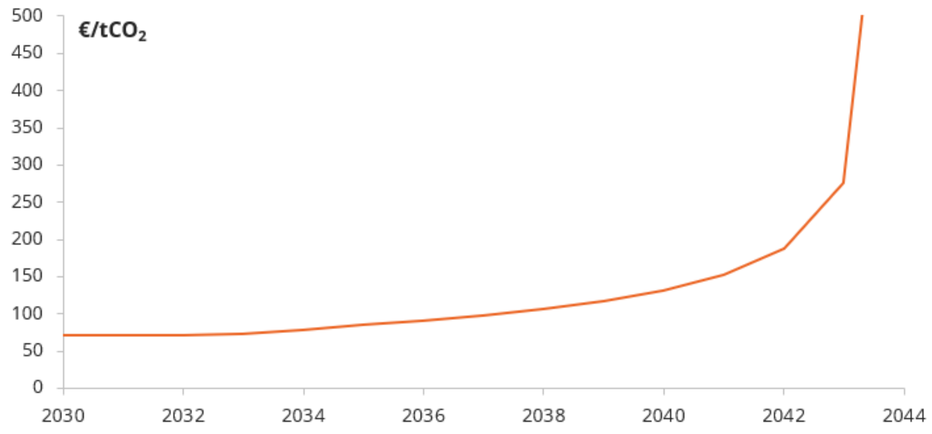

Figure 32. CO2 price projections. Source: Enerdata

Considering the abovementioned values and the audited costs for Tenerife's thermal plants, the annualised variable and investment costs can be seen in

Technology	Annualised CAPEX [m€]	OPEX [€/MWh]
Combined Cycle	4.234	301.36
Steam Turbine	3.128	318.70
Diesel Engine	0.354	299.97

Table 21. Thermal plants audited costs

Finally, considering the production per technology obtained on 80% RES scenario and the previously mentioned costs, the total system costs amount 400,053,957.66 €.

In order to obtain the production costs, it is divided by the total 2040 demand as follows:

$$Average\ production\ cost = \frac{400{,}053{,}957.66}{4{,}332{,}463.02} = 92.34 \frac{€}{MWh}$$

Comparing this value with actual average production cost in 2023 being 226,33 €/MWh in the Canary Islands, represents a significant decrease due to the independence on fossil fuels which have significantly higher variable costs and are more dependent on global political decisions.

To calculate the additional cost that Spanish consumers will bear, it is assumed an annual average daily price reaching 45 €/MWh. Consumers are expected to cover half of this extra cost through their bills, with the other half being subsidized by the state budget, as previously mentioned.

$$Extra\ cost\ [€] = \left(Generation_{price} - \ Penin_{price}\right) * Demand$$

$$Extra\ cost\ = (92{,}34 - \ 45) * 4{,}332{,}463 = \ 205{,}1\ m€$$

As mentioned, the state budget would subsidize half of the extra cost resulting in 102,55 m€ to pay by Spanish electricity consumers.

Chapter 6. CONCLUSIONS

This master thesis has studied different aspects of the energy sector in Spain and specifically in the non-mainland territory Tenerife. An isolated system with particularities not only on regulatory affairs but on security of supply issues as it does not have the back up of a European network as the mainland does.

One of the main findings from this master thesis affects regulation in the non-mainland territories on storage facilities. The current practice of aligning prices between mainland and isolated systems can lead to inefficiencies, particularly in how prices are set for merchant generation. As discussed in the regulatory chapter, these fabricated price signals are heavily influenced by daily demand fluctuations. This could result in inefficient incentives for battery storage, as peak demand periods often coincide with solar production hours. During these times, the actual cost of generation is minimal, especially given the expected curtailment from increased renewable energy capacity.

Because of these conflicting signals, storage facilities must be utilized under a regulated scheme where the system operator can optimize their usage. This approach would allow the operator to take advantage of energy curtailment and optimising overall system efficiency. In addition, it can be seen how Chira Soria, a hydro pumped facility in Gran Canaria, owns its on regulatory scheme, which reinstate how storage facilities are expected to work under regulatory schemes in non-mainland territories.

In addition, as it has been exposed in the results and findings chapter, it can be seen how renewable penetration in order to decarbonise the system is important, however, curtailment is an important factor in the decision-making process due to its impact on the Levelized Cost of Energy.

As demonstrated in the extra scenario for government projections, there is a saturation point in installed capacity where increasing renewable energy no longer leads to further decarbonization of the system. This saturation can be seen in Figure 33. The marginal benefit, previously defined, is significantly higher in the BAU and Author-AFRY scenarios and close to cero on the Governments scenario.

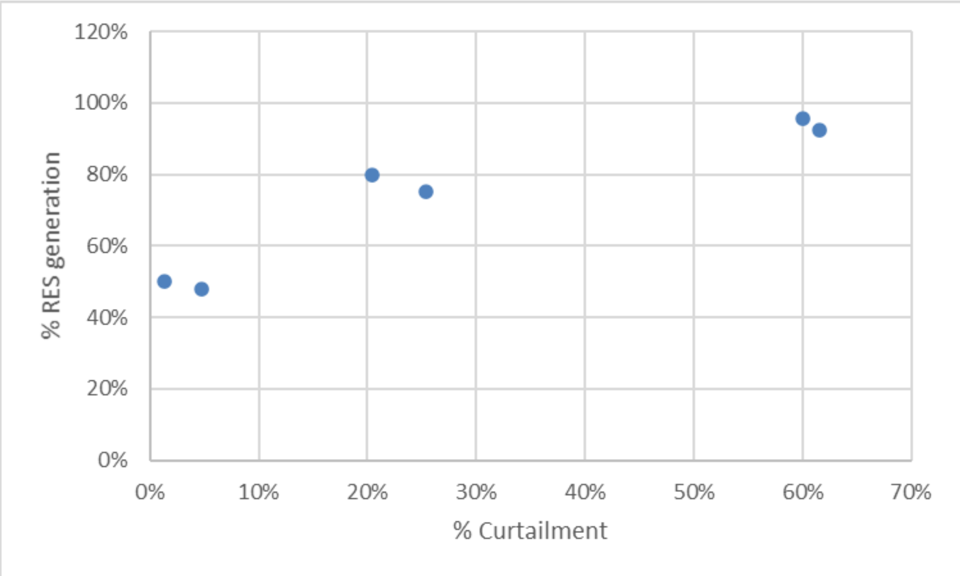

Figure 33. Comparison % Curtailment VS % res generation on the three scenarios

This is a critical consideration when planning the generation mix for an isolated system, especially where land availability is limited, environmental constraints are significant, and the associated costs are high.

All in all, this thesis underscores the unique challenges and opportunities that come with managing energy systems in non-mainland territories like Tenerife. The insights gained from this research highlight the importance of tailored regulatory frameworks that can effectively integrate renewable energy while addressing the specific needs of isolated systems. By carefully considering the impact of storage facilities, curtailment, and the optimal generation mix, the way for a more sustainable and resilient energy future can be paved for these regions.

The findings also emphasize the critical role of strategic planning in ensuring that the transition to renewable energy is both economically viable and environmentally sound. As the world moves towards decarbonization, the lessons learned from Tenerife's energy landscape can serve as a valuable model for other isolated systems facing similar challenges.

In conclusion, this work not only contributes to the understanding of energy management in non-mainland territories but also offers practical recommendations that can support Spain's broader goals of sustainability and energy security of supply.

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