Nuevo León

Carbon Emissions Analysis

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Nomenclature

Abbreviations

CFE: *Comisión Federal de Electricidad* - Federal Electricity Commission

CO_2: Carbon Dioxide

CO_2e: Equivalent Carbon Dioxide

DAC: Direct Air Capture

DOF: *Diario Oficial de la Federación* - Official Journal of the Federation

GHG: Greenhouse Gas

GWP: Global Warming Potential

IEA: International Energy Agency

IMAI: *Indicador Mensual de la Actividad Industrial* - Monthly Indicator of Industrial Activity

INECC: *Instituto Nacional de Ecología y Cambio Climático* - National Institute for Climate Change

INEGI: *Instituto Nacional de Estadística y Geografía* - National Institute of Statistics and Geography

INEGYCEI: *Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero* - The National Inventory of Greenhouse Gases and Compounds Emissions

LGCC: *Ley General de Cambio Climático* - General Law on Climate Change

MSW: Municipal Solid Waste

RENE: *Registro Nacional de Emisiones* - National Emissions Registry

RETC: *Registro de Emisiones y Transferencias de Contaminantes* - Pollutant Release and Transfer Registry

Units

TW: Terawatt, unit of power equivalent to $1x10^{12}$ Watts.

GW: Gigawatt, unit of power equivalent to $1x10^{9}$ Watts.

MW: Megawatt, unit of power equivalent to $1x10^{6}$ Watts.

GWh: Gigawatt-hour, unit of energy equivalent to $1x10^{9}$ Watts-h or $3.6x10^{12}$ Joules.

MWh: Megawatt-hour, unit of energy equivalent to $1x10^{6}$ Watts-h or $3.6x10^{9}$ Joules.

KWh: Kilowatt-hour, unit of energy equivalent to $1x10^{3}$ Watts-h or $3.6x10^{6}$ Joules.

Context of Key Industries

CFE (Federal Electricity Commission)**:** It is the State-owned electric utility. In Mexico, the government is responsible for the control of the national electric industry as stated in the Mexican constitution.

Compañía de Electricidad Los Ramones: Cogeneration Power Station in *Nuevo León* that began commercial operations in 2020.

IBERDROLA: It is a Spanish industry and global leader in clean energy, grids and storage. Iberdrola Mexico is a subholding industry from Iberdrola, which has an installed capacity of more than 11 GW by 17 combined cycle and cogeneration plants, 693 MW in seven eolic parks and 470 MW in three solar farms with presence in 15 states in the country.

PEMCORP: Industry that operates mainly in the electric sector with a gas-fired power station in *Nuevo León*.

Abstract

One of the fastest industrial growing regions in the country, Nuevo León, has a harsh problem regarding pollutant emissions, being the electrical energy generation industry liable for most of them. An analysis over several years is presented, which involves evaluating emissions and proposing mitigation techniques. The study focuses on specific industries in the electric power generation sector and their carbon dioxide emissions. Furthermore, diverse technological and non-technological options for emissions reduction are provided, along with corresponding cost and carbon benefit evaluations.

After analyzing various emission reduction options, this study identifies the most effective strategy for implementation in the selected region. Using a decision matrix, seven categories (initial investment, viability, annual CO_2e emission reduction, annual energy production, marginal cost, law approval) were used to compare and classify the effectiveness of the proposals. Because of its availability, cost and energy production it was able to pinpoint "policy and regulations" and "solar panels" as the most competent options.

I. Introduction

<u>Nuevo León as a point of interest for Analysis</u>

Nuevo León, located in the northeast of Mexico, is known as the industrial capital of the country, as it is one of the most important industrial regions and contributor to the total real industrial variation in the country (INEGI, 2021). Industrial activities are a significant sector contributing to the pollution of the region, therefore, this state has been of huge concern to the government due to its current air quality problems.

The Secretariat of Environment of *Nuevo León* issues a monthly Weather and Air Quality Report, detailing weather patterns and gas emissions across the state. These reports aim to present various indicators of parameters, highlighting trends and patterns, to facilitate preventive, controlling, and mitigating actions. Additionally, the report assesses compliance with legislation (NOM-172-SEMARNAT-2019), establishing the "Guidelines for obtaining the Air Quality and Health Risks Index."

As of August 2023, the latest available report indicates that 68.7% of the days did not meet the specified regulations. Only July managed to have a higher number of days complying with the regulatory limits. This concerning trend has heightened worries about the health impacts on citizens residing near the most polluted areas.

Electrical Energy Industry

The National Inventory of Greenhouse Gases and Compounds Emissions (INEGYCEI, *Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero*) showed that during 2019, in Mexico, 740 millions tonnes of CO_2e were emitted, from which 64% of them were due to the energy sector. Furthermore, *Nuevo León* has been the Mexican state with the greatest energy consumption, as seen on Table 1.1, this sole state has averaged an 8.3% of the national electricity consumption among the 32 federal entities from 2002 to 2020 (Energy Secretariat, s.f.), see Figure 1.1.

The Secretariat of Environment and Natural Resources of the state publishes a Pollutant Release and Transfer Registry (RETC, *Registro de Emisiones y Transferencias de Contaminantes*) which reports the general data, emissions, and transfers of different substances of industries. The most recent update incorporates data up to the year 2021. With this registry it was able to determine that from the top ten emitters of CO_2 of the region, six of them belong to the electric energy generation industry.

A growing population equates to an increase in the demand of services such as electricity. According to the National Institute of Statistics and Geography (INEGI, *Instituto Nacional de Estadística y Geografía*), in 1990 the state had a population of 3.1 million, moving forward to 2020, the last study conducted showed that the population increased to 5.8 million.

One of the main reasons as of why it is the biggest consumer of electricity in the country is its industrial activity development; the INEGI has developed a tool to measure this industrial growth, the Monthly Indicator of Industrial Activity (IMAI, *Indicador Mensual de la Actividad Industrial*). This is calculated using a conceptual framework, methodological criteria, economic activity classification, annual and quarterly calculations of the Gross Domestic Product (GDP), and for each state the weight of the contribution in the total indicator (INEGI, 2018). According to the INEGI *Nuevo León* has the greatest contribution to the IMAI in Mexico, as seen on Figure 1.2. Similarly, it was ranked as the seventh most populated state in Mexico in 2020. This high population directly corresponds to a significant demand for electricity for day-to-day activities among its residents. Consequently, the average electric energy consumption was 2.77 MWh per capita annually (see Table 1.2), maintaining the seventh position as one of the highest energy consumers per capita in the country.

Table 1.1. Top five energy consumers states in Mexico (Secretaría de energía, 2023).

Energy consumption [GWh]					
	2019	2020	2021	2022	2023 (june)
Nuevo León	17,655.40	16,000.00	16,880.30	18,758.90	8,486.30
Estado de México	17,489.40	15,980.40	16,434.10	16,914.60	8,667.30
Jalisco	13,851.20	13,043.50	13,193.60	13,642.70	7,139.30
Chihuahua	12,949.70	13,233.00	13,097.20	13,115.60	6,274.80
Baja California	10,489.80	10,820.10	11,925.10	12,982.70	5,866.70

Table 1.2. Top ten Mexican states in electric energy consumption per capita.

State	Per capita consumption [MWh/year/person]
Sonora	3.72
Chihuahua	3.54
Baja California Sur	3.11
Coahuila	3.00
Baja California	2.87
Colima	2.86
Nuevo León	**2.77**
Tamaulipas	2.44
Sinaloa	2.41
Quintana Roo	2.34

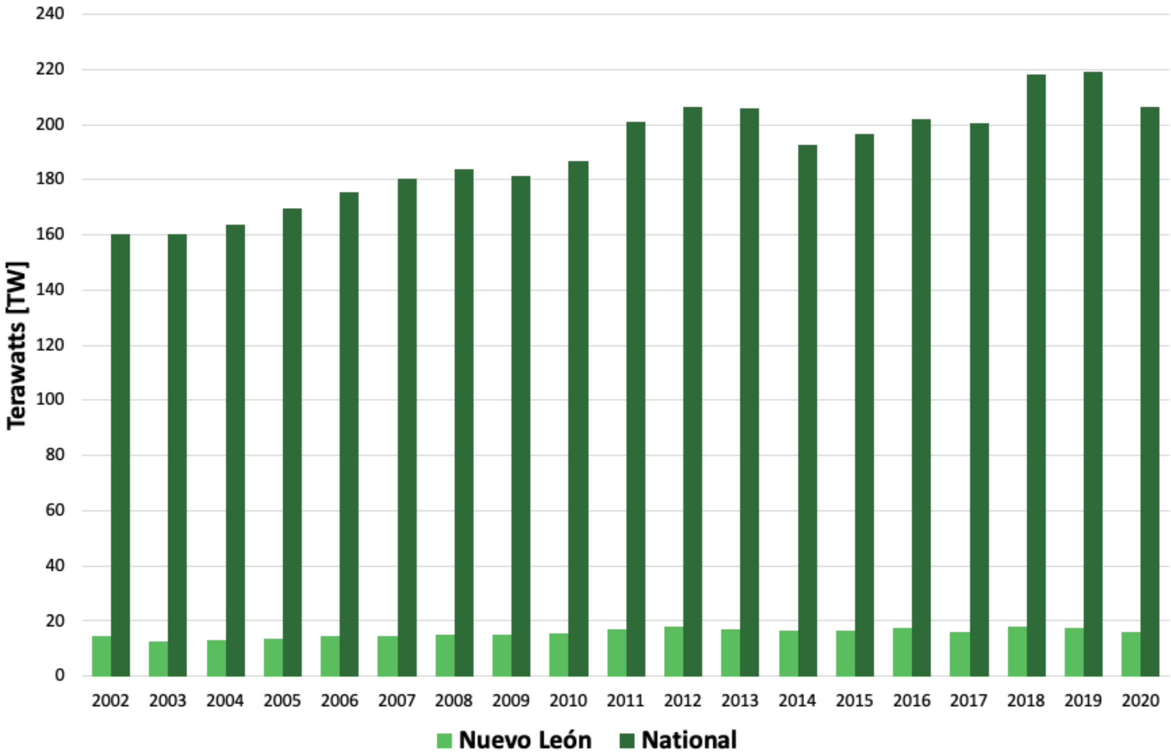

Figure 1.1. Electricity consumption in *Nuevo León* compared to Mexico (made with data from the Energy Secretariat, s.f.).

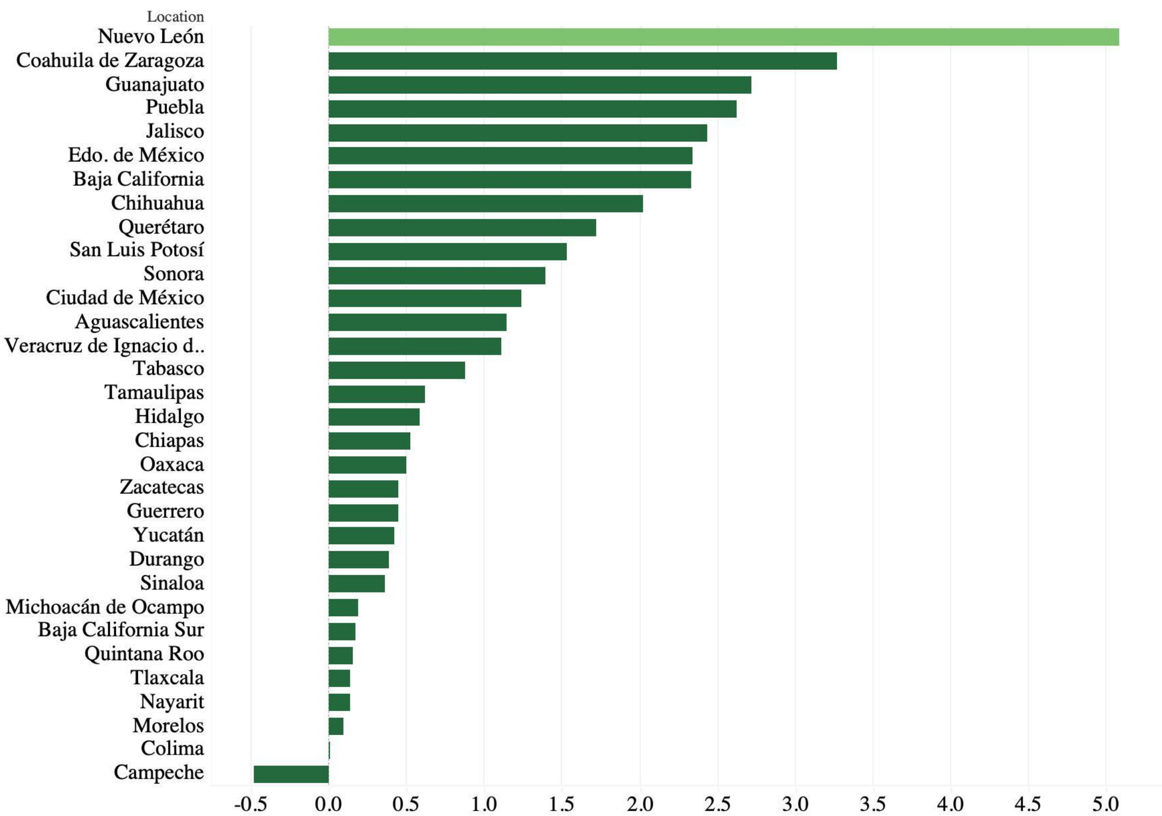

Figure 1.2. IMAI by federal entity during April 2021 (made with data from the INEGI, 2021).

II. Identification of emission sources

<u>Data identification and capture</u>

The RETC (Pollutant Release and Transfer Registry) was used to analyze the emission sources and patterns in the state of *Nuevo León*. With this data, it was possible to determine the major CO_2e emitters from the electricity generation industry as well as its location and its emissions up to 2021. It is important to mention that the NOM-165-SEMARNAT-2013 is a Mexican legislation that states the substances that must be reported in the RETC, where there is a threshold of 100,000 kg/year for carbon dioxide, methane and nitrous oxide (Diario Oficial de la Federación, 2014), therefore, data is limited to the substances registered and the reporting threshold.

From the fifty one municipalities in *Nuevo León*, only nine have emissions higher than the threshold stated in the NOM-165-SEMARNAT-2013 due to electric energy generation industry which are: *Apodaca*, *El Carmen*, *Guadalupe*, *Juárez*, *Los Ramones*, *Monterrey*, *Pesquería*, *San Nicolás de los Garza* and *San Pedro Garza García*.

This can be captured from the RETC webpage (http://sinat.semarnat.gob.mx/retc/retc/index.php). In the main page, as shown in Figure 2.1, a "Consults" section is given; to enter the database, the "*Emisiones y Transferencias*" (Emissions and Transfers) button, located at the bottom left of the page, should be clicked. This leads to the "*Búsqueda de emisiones y transferencias de contaminantes*" (Search for pollutant emissions and pollutant transfers) page, where, as shown in Figure 2.2 there are six different filters to revise the data.

The state from which data may be retrieved is selected in the federal entity (*entidad federativa*) tab, municipality (*municipio*) is an optional filter to select an area within the state, productive sector (*sector productivo)* allows to select an industrial activity, e.g. electric energy generation, productive activity (*actividad productiva*) allows for a more specific field for the selected industrial activity, e.g. testing laboratories or chemical treatment of hazardous waste, substance (*sustancia*) is another optional field which allows selecting a compound emitted, and report year (*año de reporte*) must be selected to analyze said year.

After filtering the desirable data, the results are shown as in Figure 2.3, where the name of the industry, the sector, and the emissions of the substances can be seen.

Figure 2.1. Methodology to obtain data from RETC pt.1. (Image obtained from http://sinat.semarnat.gob.mx/retc/retc/index.php)

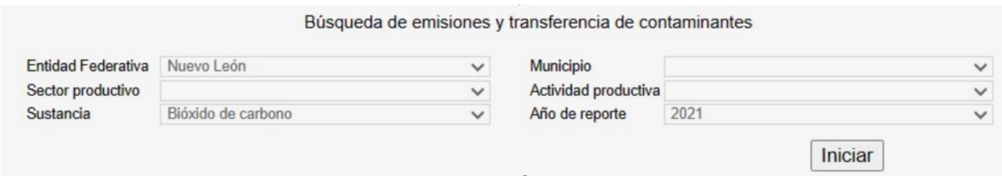

Figure 2.2. Methodology to obtain data from RETC pt.2 (Image obtained from http://sinat.semarnat.gob.mx/retc/retc/index.php)

Figure 2.3. Methodology to obtain data from RETC pt.3 (Image obtained from http://sinat.semarnat.gob.mx/retc/retc/index.php)

Data manipulation

The RETC database provides information about the emissions in kilograms per year of several substances, from which only carbon dioxide, methane and nitrous oxide are greenhouse gasses. Therefore, there was a need to convert the methane and nitrous oxide to carbon dioxide equivalent in order to have comparable values. The Global Warming Potential (GWP) values used in Mexico are stated in the Official Journal of the Federation (DOF, *Diario Oficial de la Federación*) which for methane is 28 kg CO_2/kg CH_4 and for nitrous oxide is 265 kg CO_2/kg N_2O (Secretariat of Governance, 2015).

With this conversion, comparable results of emissions were obtained to determine the major emitters in *Nuevo León* through the years, which are listed in Table 2.1.

Table 2.1. Emissions of CO_2e by municipality in 2021.

Municipality	Kilo Tonnes of CO_2e
Apodaca	0.808
El Carmen	3,963.08
Guadalupe	257.32
Juarez	38.59
Los Ramones	427.04
Monterrey	187.92
Pesquería	1,969.26
San Nicolás	73.43
San Pedro	3.81
Apodaca	0.808

Data analysis Results

The analysis was made for the last five reported years, i.e. from 2017 to 2021, in order to observe the development of the emissions along with the effect of the entry of new industries in the total emissions. In Figure 2.4 a distribution of the CO_2e emissions by the energy sector can be seen from data obtained by the RETC.

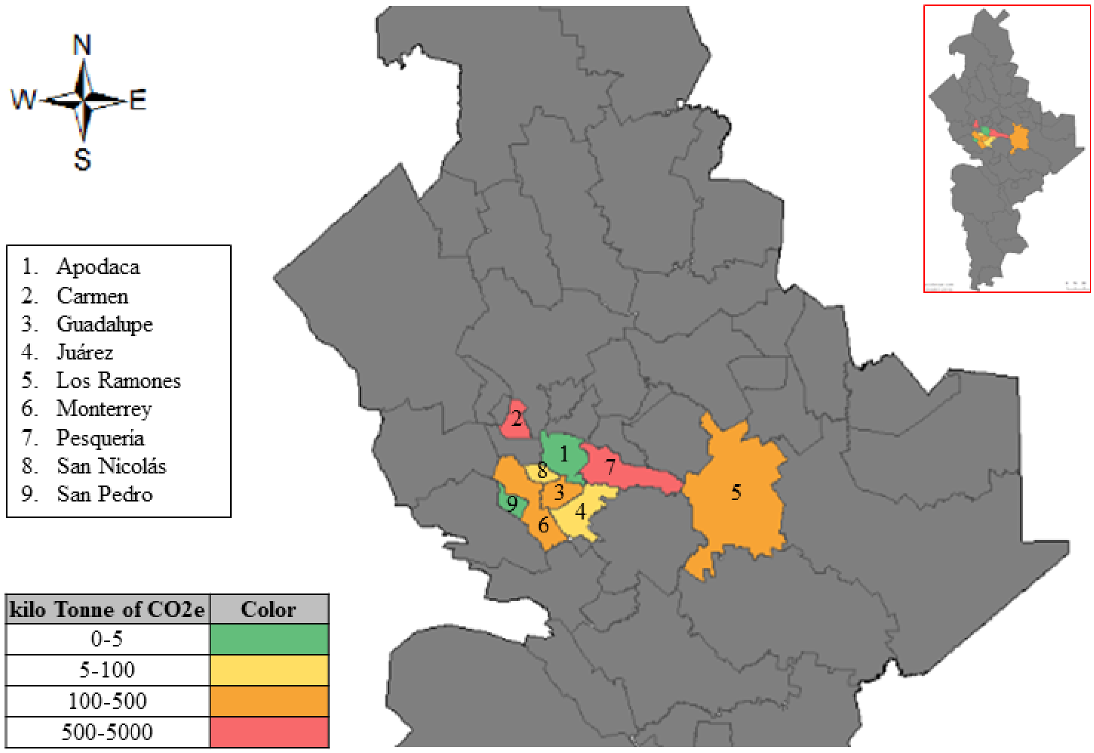

Figure 2.4 Map of CO_2e emissions due to energy generation sector by municipality in *Nuevo León*. *(To make this map, a white map obtained from www.mapasparacolorear.com, source: INEGI/CONABIO, 2010)*

The following highlights were obtained from the data analysis:

- *El Carmen* is a location with a high density in the energy generation industry. This can be attributed to the start of energy generation by the IBERDROLA industry in 2019. By 2021, 97% of the CO_2e emissions in *El Carmen* were attributed to the electric energy generation by IBERDROLA.

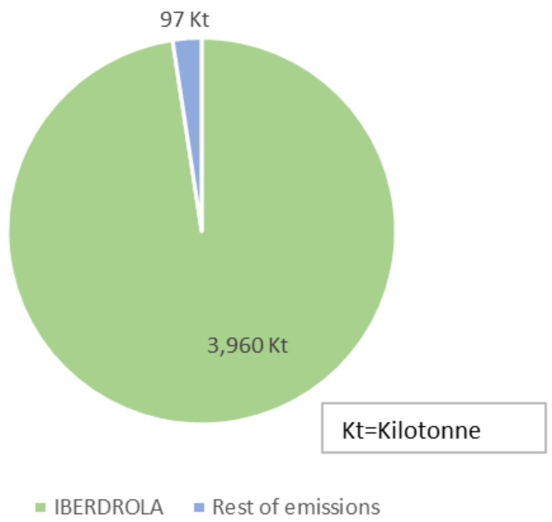

Figure 2.5 CO_2e emissions in *El Carmen*, 2021 (Data obtained from RETC, 2021, http://sinat.semarnat.gob.mx/retc/retc/index.php)

- In *Pesquería*, the Federal Electricity Commission (CFE, *Comisión Federal de Electricidad*) concentrates the equivalent carbon dioxide emissions due to its high electricity production along with the emissions from the *PEMCORP* industry that uses an internal combustion technology. In 2021, the energy generation sector was responsible for 98% of the emissions.

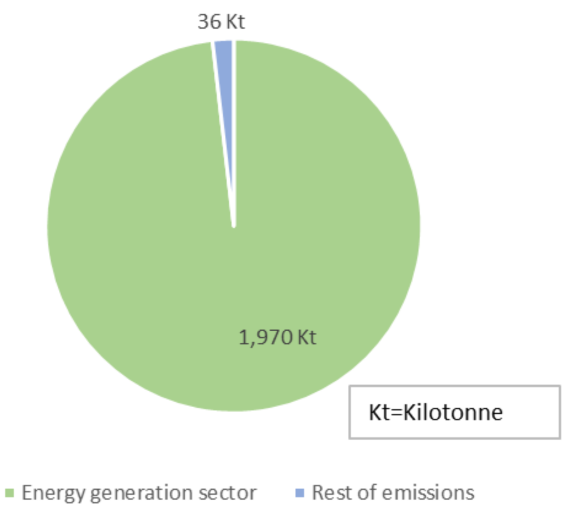

Figure 2.6 CO_2e emissions in *Pesquería*, 2021 (Data obtained from RETC, 2021, http://sinat.semarnat.gob.mx/retc/retc/index.php)

Table 2.2. Key emitters in *Nuevo León*.

Industry	Technology	City	Kilo Tonnes of CO_2e emissions in 2021
IBERDROLA ENERGÍA ESCOBEDO SA DE CV,CC El Carmen	Natural Gas Combined Cycle	El Carmen	2,267.72
IBERDROLA ENERGÍA ESCOBEDO SA DE CV,Central CC Noreste	Natural Gas Combined Cycle	El Carmen	1,695.35
CENTRAL GENERADORA ELÉCTRICA HUINALA, S. DE R.L. DE C.V.,CENTRAL HUINALA	Natural Gas Combined Cycle	Pesquería	835.20
CFE Generación VI,CENTRAL CICLO COMBINADO HUINALA	Natural Gas Combined Cycle	Pesquería	671.66
PEMCORP, SAPI de CV, Central PEMCORP	Natural Gas Internal Combustion	Pesquería	462.41
Compañía de Electricidad Los Ramones, S.A. P.I. de C.V.	Dual Diesel-Natural gas Turbine	Los Ramones	427.04

In 2021, the industries stated in Table 2.2 represented 92% of all equivalent carbon dioxide emissions in *Nuevo León* for the industry of generation of electric energy, which translates to approximately 6.36 million tonnes. This demonstrates the impact of the industries in Table 2.2 and the reason they should be extinguished.

Therefore, to get a more profound detail to the industries with major emissions for every MWh produced, the emissions of equivalent CO_2 were divided by the energy generation in 2023, obtaining the results in Table 2.3.

Table 2.3 Emissions per MWh produced.

Industry name	Tonnes CO_2e/MWh
IBERDROLA ENERGÍA ESCOBEDO SA DE CV,CC El Carmen	0.295
IBERDROLA ENERGÍA ESCOBEDO SA DE CV,Central CC Noreste	0.226
CENTRAL GENERADORA ELÉCTRICA HUINALA, S. DE R.L. DE C.V.,CENTRAL HUINALA	0.216
CFE Generación VI,CENTRAL CICLO COMBINADO HUINALA	0.216
PEMCORP, SAPI de CV, Central PEMCORP	0.401
Compañía de Electricidad Los Ramones, S.A. P.I. de C.V.	0.090

It is important to mention that both CFE industries were calculated as a conjunction, since the energy production is reported as one same. With these results, it was able to determine that the less environmentally friendly process was by PEMCORP industry because it emits the most CO_2e for every MWh of energy produced.

After the analysis, the key emission sources were identified, with a major concentration in the municipalities of *El Carmen* and *Pesquería*. The major industries contributing to the CO_2e emissions in the energy generation sector are IBERDROLA, CFE, PEMCORP, and *Compañía de Electricidad Los Ramones*. It was confirmed that the technology used for energy generation has a significant impact on the emission factor per energy produced. Therefore, more focused reduction of CO_2e emission options can be obtained by having the key emitters identified.

III. Reduction of CO_2e emissions Options

After having identified the key emission sources in *Nuevo León*, some reduction options were proposed. There are technological and non-technological solutions that could be used; the proposals are not independent one from another and can be conjoined in order to obtain the best results.

Policy and Regulations

The first option explores the implementation of policies and regulations that penalize high-emission practices and low efficiencies as a way to incentivize the use of clean energies and their technologies making them more competitive.

The "carbon tax" is a price set by the government, emitters must pay according to each tonne of CO_2e they emit. This method has already been executed in many other countries around the world, showing a positive impact. In fact according to the Organisation for Economic Co-operation and Development (OECD), "an increase in the effective carbon rate by EUR 1 (approximately 1.08 dollars) per tonne of CO_2 leads on average to a 0.73% reduction in emissions over time". Therefore it is estimated that if a 10.38 dollar tax per tonne of CO_2e is applied a 7.3% reduction in emissions could be observable.

Every country has its own rules for carbon tax. Usually, a limit is set on the amount of carbon emissions allowed (known as a cap), and the tax is applied to any emissions beyond that limit. The tax price varies from each country (see Table 3.1).

Table 3.1. Carbon tax prices in different countries (*Tax Foundation*, 2022).

Country	USD/Tonne	Year of implementation
Liechtenstein	$129.86	2008
Norway	$87.61	1991
Luxembourg	$43.35	2021
Sweden	$129.89	1991
Poland	$0.08	1990
Ukraine	$1.03	2011
Estonia	$2.21	2000

In México, five states are implementing carbon taxes these are: Zacatecas, Tamaulipas, Querétaro, Yucatán and the State of México (*Inter American Center of Tax Administrations,* 2023). The average price is approximately 14.62 USD. However Natural Gas is entirely exempted (*International Energy Agency*, 2023).

In *Nuevo León* the carbon tax can be applied to the Electrical Energy Generation sector. It can be based on the efficiency of the plant, for example *PEMCORP* should have the lowest cap of CO_2 because it emits the most for every MWh of energy produced while *Compañía de electricidad los Ramones* should have the highest since it has the lowest emissions per energy produced.

Starting with a tax of 10.38 dollars, the objective is to reduce emissions from the electricity generation industry by 7.3%, as indicated in Table 2.2 from 2021. This reduction corresponds to 464,234 tons of CO_2e.

The revenues coming from carbon tax can be collected by the *Nuevo León* Environmental Secretariat and be used to fund their projects or support the industry on their path to lower their emissions.

Solar Farm

The increase in worldwide demand in clean energies has impacted the expansion of solar manufacturing. Currently, there are investments for the development of solar modules with capacities from 640 GW in 2022 to 1,200 GW in a medium term. Because of the huge development of these technologies, from the estimated increase in global renewable capacity made by the International Energy Agency, two-thirds are due to solar PV capacity from small and large scales (IEA, 2023).

Nuevo León is considered a state with great potential in the development of solar panels due to the irradiance of the sun in the state. In the Global Solar Atlas, posted by the World Bank Group, the region is shown with values of Direct Normal Irradiation of more than 2,500 kWh/m^2, as seen in Figure 3.1.

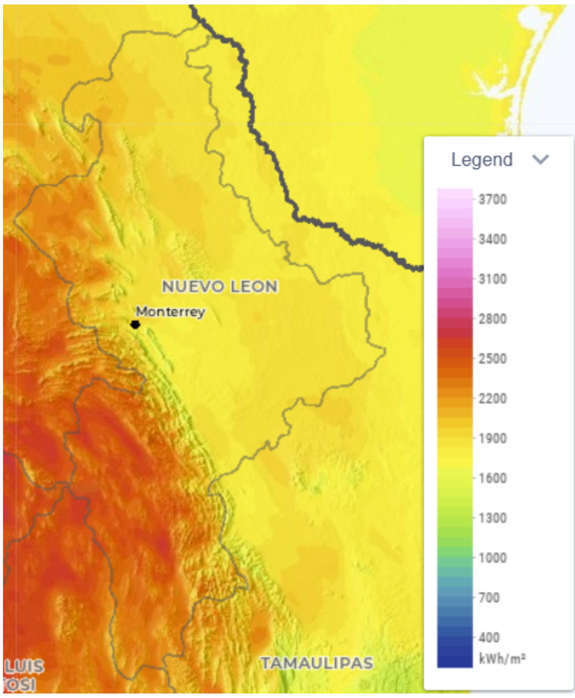

Figure 3.1 Direct Normal Irradiation ranges in *Nuevo León*. (Picture obtained from Global Solar Atlas, 2023)

This demonstrates the big opportunity that *Nuevo León* has to develop solar farms to replace fuel processes that produce carbon dioxide emissions. The proposal consists of investing in a new solar farm located in the southwest of the region where the best irradiance is obtained.

An important parameter to consider when designing a solar farm is the material used which determines the efficiency obtained. In 2021, Crystalline silicon technology had a market share of 95% in total PV cell production with an efficiency between 14 to 20%, however, their efficiency is expected to increase to 25% because, as mentioned before, the investment in the development on solar technologies is increasing (ETP Clean Energy Technology Guide, 2023).

Another relevant parameter to consider are the costs of creating a solar farm; even though the levelized cost of electricity has fallen about 90% for solar PV in between 2010 and 2022, developing economies such as Mexico, need better access to finance and reduced costs of capital in order to maximize the opportunity of accelerating the uptake of solar PV (IEA, 2023).

A 1 GW solar farm would be needed to replace the 1,154,000 MWh/year of electric generation by PEMCORP in 2023, according to data from the Energy Institute Statistical Review of World Energy 2023, which is seen in Figure 3.2.

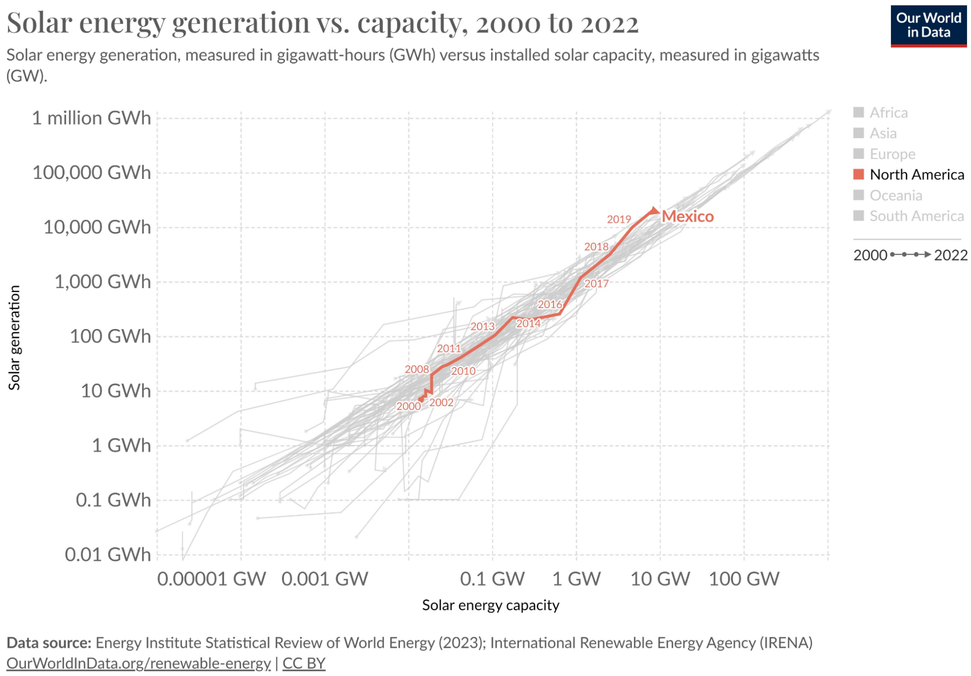

Figure 3.2 Solar Energy generation vs capacity (Obtained from Our World in Data, 2023, https://ourworldindata.org/grapher/solar-pv-energy-consumption-vs-solar-pv-capacity)

However, it is important to mention that having a 1 GW capacity solar farm would also mean a big investment and area usage. A thumb rule states that a solar farm requires from 4-7 acres of land per megawatt (SolarLandLease, n.d.), which translates to 22.3 km^2 to replace PEMCORP emissions. As for the investment needed, the National Renewable Energy Laboratory (NREL) showed that as for 2022, solar farms cost $1.06 USD per watt capacity. Therefore, this project would have an investment of 1.06 billion USD. A solar farm has an average payback period of 10 years (MarketWatch, 2023), which can vary depending on the price of the electricity and location of the solar farm. However, it is crucial to consider that since this proposal would prevent the emissions of equivalent carbon dioxide, the costs of the industry would also decrease because no more carbon dioxide emissions taxes would have to be paid. Usually the operation cost for modern solar farms is around 40 USD/MWh of electricity produced (Euronews, 2023)

The full life cycle of the PV panels should also be considered; according to the National Renewable Energy Laboratory, 40 kgCO_2e/MWh is emitted for the full life cycle. Therefore, for this project, a total of 46,160 tonnes of CO_2e will be emitted. Therefore, with this proposal, 90% of CO_2e emissions by PEMCORP would be prevented.

However, a more profound economic analysis should be made in conjunction with a good selection of energy storage, solar inverter and transmission line. It is crucial to consider that this technology is inclined to be more efficient and used throughout the years, therefore, the solar farm could be constructed from time to time, enabling the newest technologies to be used, making the solar farm more efficient and at lower costs.

Direct Air Capture

Direct air capture (DAC) are technologies which sequester CO_2 directly from ambient air. Many sorbents may be used for this purpose, for instance amines, hydroxides, aluminosilicates (Aines et al., 2021). The latter are compounds which can occur naturally or be synthesized, often in the form of zeolites, and are composed from aluminum, silicon, oxygen, among others. These materials, such as zeolite 13X, have gained attention as solid sorbents for DAC since they have a defined crystalline structure, great surface area, and can selectively adsorb CO_2. In Mexico where zeolite deposits are abundant, the most studied and important are shown in Table 3.2 (Costafreda et al., 2018), these materials are a plausible alternative for carbon recovery in areas such as *Nuevo León*.

Table 3.2. Zeolite deposits in Mexico.

Location	Reserve [metric tonnes]	Type of zeolite
Oaxaca, Municipio Laollaga	15,120,000	Clinoptilolite, mordenite
Sonora, El Cajón	10,000,000	Clinoptilolite
Sonora, Agua Prieta	3,000,000	Erionite
San Luis Potosí, El Chap	2,708,000	Clinoptilolite

Some aspects which make DAC a viable option in the region are the higher concentrations of CO_2, higher concentrations make carbon recovery an easier and more efficient processes, availability of electric energy for material regeneration, the use of solid sorbents avoid wasting water in regions with recurrent droughts, for instance the selected region, and the proximity to zeolite deposits in the area of *San Luis Potosi*.

Zeolite is an attractive sorbent for its use in DAC due to the properties mentioned above, mainly its selectivity for CO_2 in dry air. These kinds of materials can capture around 2 moles of CO_2 per kilogram of sorbent (Nikolaidis et al., 2018; Rajagopalan et al., 2016), however adsorption capacity varies with pressure, temperature and humidity. Therefore, conditions in DAC plants are not extreme but must be controlled at all times or the efficiency of the materials and process may decrease substantially. An air drying stage is vital to maximize the adsorption capacity of zeolites, this can be easily achieved by using other materials such as silica, which is also a solid sorbent that has a higher affinity for water molecules in air and requires less energy compared to other drying mechanisms.

By leveraging the available resources in nearby regions, such as *San Luis Potosí*, it is feasible to establish DAC plants in Monterrey with the capacity to capture up to 110 tonnes of CO_2 per cycle, using only 0.037% of the available resources in such deposits, the equivalent of 1,000 tonnes of zeolite. With this amount of resources it is possible to capture up to 160,000 tonnes of CO_2 annually. Recovery streams typically have a purity greater than 95% (Nikolaidis et al., 2018; Rajagopalan et al., 2016), making it an added value product which can be used in varied processes or as a raw material.

In terms of CO_2 net removal, an analysis for emissions of the DAC process must be made in order to verify it is indeed carbon negative. This process captures gasses from the atmosphere, however, an energy input is required for its correct functioning, for compressors and regeneration of the materials principally, therefore, it will also account for some emissions. Whether the process is viable or not depends on the difference in the capture and emission of CO_2. Approximate calculations of said emissions were made taking into account adsorption capacities, regeneration heat, heat capacities, energy source for regeneration, and the usage of two solid sorbents, silica and zeolite. Results showed that only 0.2 tonnes of CO_2 are emitted per every tonne captured, meaning it is effectively carbon negative, however, more detailed calculations should be made to account for changes in the variables described to make this analysis. Furthermore, energy integration techniques to preheat materials in the regeneration process can help reduce energy consumption and consequently the emissions per tonne captured. According to the IEA, capture costs for DAC range from $125 USD to $335 USD per metric tonne of CO_2 (IEA, 2022), and the investment for a plant in the region can be up to $771 million USD.

Gasification of Municipal Solid Waste

In *Nuevo León* 5,310 tonnes of garbage are collected daily. Only 5% of waste is recycled while the rest end up in landfills. The most common waste to energy methods is incineration in which toxic gasses are produced and the main benefits are land use optimization, but there are no significant ecological benefits and it comes at a higher construction and operation cost than most energy production technologies. Gasification has been implemented in waste management which consists in breaking down materia to its molecular level in order to produce syngas, which is made from municipal solid waste and is mainly composed of H_2 (49.21%), CO (21.7%), CH_4 (12.78%), CO_2 (5%), and C_2H_2 (2.91%) (Nemmour, 2023.) Syngas can then be used as a precursor in numerous industrial processes, feedstock for the production of various fuels, including synthetic natural gas (SNG), hydrogen, and liquid fuels through processes such as Fischer-Tropsch synthesis, or be incinerated and with the use of a gas turbine converted into electricity, while obtaining mainly water vapor as a product.

In the following flow diagram Figure 3.3 it can be observed the overall process of Syngas production where it is important to mention that gasification can produce a Syngas of different composition, in this case the input is Municipal Solid Waste (MSW) which is composed of 60% of organic materia with a humidity of 20% (for energy production calculation, only dry weight was considered according to Sierra Energy data). Once syngas is produced, it can not be used to produce energy but also as a reactant in the production of many chemicals, the most common ones are ethanol, methanol, diesel and jet fuel (Reisch, 2019).

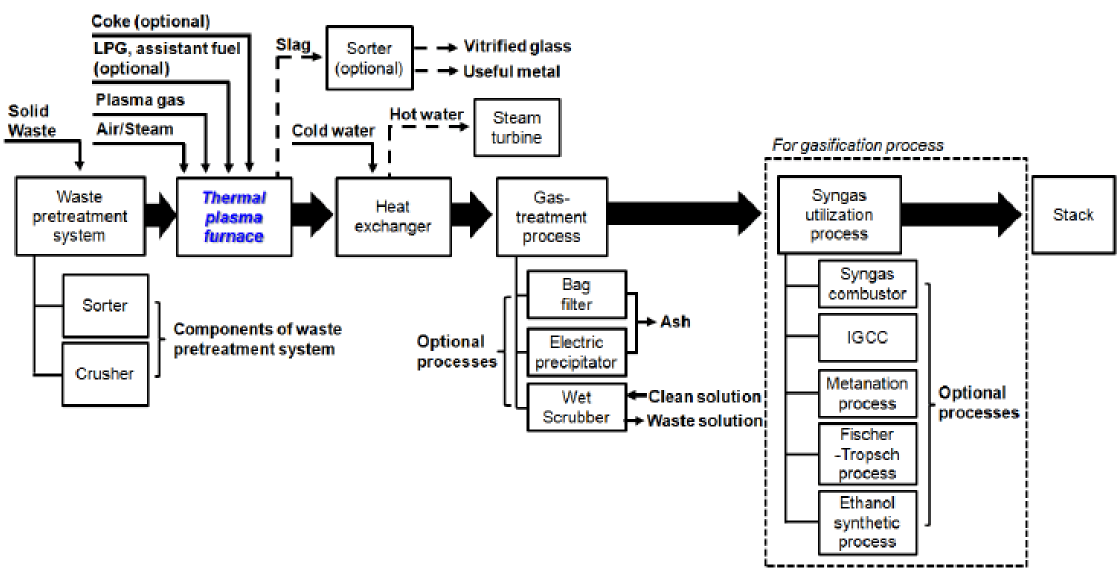

Figure 3.3. Process of Syngas production (Byun, 2012).

The largest gasification plant operates in New Jersey and has the capability to process 430 tonnes of waste per day. An investment of 65 million USD was required, while the operation cost ranges between 40-100 USD per tonne (*Mukherjee*, 2020). Due to scale economics and location of the facility it can be concluded that the operation cost per tonne will be on the lowest end of the range. This considers that labor cost is lower in Mexico and the plant design considered for this project is currently the largest one in existence. In Mexico the average production cost per MW is 43.4 usd while the production cost for MSW to energy is 59 when 1 tonne of dry MSW generates 0.673 MW. In figure 3.4 it can be seen a comparison of the production cost of different technologies produced by both private and public sector.

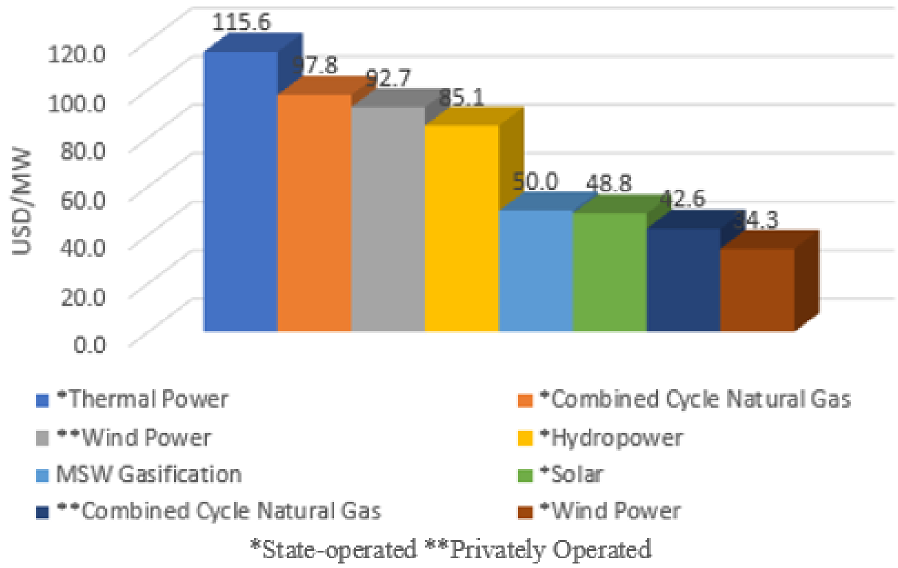

Figure 3.4. Energy Production costs for different Technologies (*Animal Político*, 2021).

If 89% (the capacity of 11 New Jersey facilities) of MSW in *Nuevo León* was converted to energy that would give the state a capacity to produce 929,758 MWh/year. This would represent 5% of the electricity production for 2022. As this process is carbon neutral, if every MWh produced from MSW was reduced from the PEMCORP plant this would translate into a decrease of 372,554.6 tonnes of CO_2e which would represent a 5% reduction.

Public Policies and Cost reduction

Between 2013 and 2018, 15.9 million USD from the Secretary of State for Environment were used to finance waste management projects across the country from which *Nuevo León* was the only state that did not use a single dollar to finance any project. In 2023, 128.16 million USD were designated to be invested by the National Fund for Energetic Transition from which to this date none has been invested in the region. The state pays 10.72 UDS for every tonne confined by the landfills, with the gasifiers there would not be a necessity for the construction of new landfills and the 10.72 UDS should be used instead to make the facilities more profitable. On the other hand 5% to 10% of the waste input is converted into char (De Gisi, 2016) which can be used in the construction industry to create decorative concrete. CEMEX is one of the largest cement manufacturers in the world whose headquarters and numerous facilities are located in *Nuevo León*. Providing this company with an option to reduce its environmental impact with carbon neutral material is surely a mutual benefit relationship. Although no information could be found regarding the price that MSW char could be sold, any benefit would make gasification a more economically viable solution.

In gasification projects across Europe, the primary factor affecting the payback period is the expense associated with waste management fees for landfills. France, with a fee of 162.7 USD per confined tonne, significantly enhances the profitability of this technology by reducing the reliance on landfills. This higher cost results in a payback period of approximately 3 years. Conversely, Portugal, despite having a similar fee for municipal solid waste (MSW) management, incurs landfill costs of 11.9 USD per confined tonne. This leads to a much longer payback period, estimated at around 18 years. Based on these metrics, it is anticipated that the payback period in Mexico will be comparable to that of Portugal.

Green Hydrogen (Tentative proposal)

Direct electrification is hard to achieve in certain applications where decarbonation is still needed, however, the development of green hydrogen gives a glimpse of the possible achievement to be obtained.

Hydrogen is a suitable energy carrier for applications who are not connected to electricity grids or that require high energy density (International Renewable Energy Agency, 2020).

As explained by the IEA in 2020, green hydrogen is generated through electrolysis, by an electric current which splits water to its components of hydrogen and oxygen. Oxygen is formed at the positive anode and hydrogen is released at the negative cathode. In polymer electrolyte membrane, a proton membrane replaces the additives, making the process friendlier with the environment. The hydrogen product obtained can be compressed and stored, allowing an easier transportation. There are many ways to store hydrogen, such as geological storage, liquified hydrogen, compressed hydrogen, and material-based storage. The electricity used for the electrolysis is decarbonised electricity since it comes from renewable energies. Also, the use of hydrogen for the production of energy, reduces the greenhouse gasses emissions since hydrogen only produces heat and water vapor.

In spite of the efforts to develop economical ways to use this technology, the levelized cost of green hydrogen production is in the range of 3 to 6 dollars/kg, making it uninteresting from the economical aspect (Saini, 2023).

Therefore, this proposal consists of using this technology once the development on efficiencies of the electrolyser and decrease in the levelized cost is achieved, in the meantime, opting for gray hydrogen processes while using hydrogen as an energy carrier is the best path.

IV. Options comparison

For this analysis, a comparison is conducted among the proposals to determine which one can be achieved sooner as well as having a greater impact on the near-term future of *Nuevo León*. While all the options presented can be implemented, one stands out as being potentially more economically, socially, and environmentally efficient.

A ponderation method was used to classify the proposed options according to key factors from each, these are listed below in Table 4.1. This analysis allows for an extensive assessment of each mitigation strategy, offering insights into their economic viability, and environmental impact. The state of *Nuevo León* can use this information to make informed decisions aligned with sustainability goals, considering both economical factors and environmental benefits of each option. According to the values assigned in Table 4.2, it was determined that the best mitigation options for this region are both the implementation of policies and regulations, and solar farms for electric energy production.

Table 4.1. Mitigation options general review.

Criteria	Policy and Regulations	Solar Farms	Direct Air Capture	Gasification
Initial Investment	$0	$1.06 B USD	$771 M USD	$715 M USD
Annual CO_2e Emission Reduction	464,234 tonnes	415,840 tonnes	160,000 tonnes	372,555 tonnes
Annual Energy Production	NA	1.154 TWh	NA	0.929 TWh
Marginal Cost USD/MWh	NA	40$/MWh	NA	59$/MWh

Table 4.2. Mitigation options comparison.

Criteria	Ponderation	Policy and Regulations	Solar Farms	Direct Air Capture	Gasification
Initial Investment	0.15	10	5	7	8
Viability	0.20	10	10	5	5
Annual CO_2e Emission Reduction	0.25	10	8	4	6
Annual Energy Production	0.15	NA	10	NA	8
Marginal Cost USD/MWh	0.17	NA	10	NA	8
Law Approval	0.08	5	10	10	10
Classification (Value)	-	High	High	Low	Medium
Total	**1**	**9.41**	**8.75**	**5.66**	**7.06**

For the comparative analysis of the options, a decision matrix was employed, as it proves to be a valuable tool for decision-making regarding technologies and decarbonization strategies, as demonstrated in this work. This tool facilitates the selection of the criterion to be analyzed and the determination of the weight assigned to it.

Table 4.2 illustrates the comparison among various decarbonization proposals presented in this research. Some proposals synergize well when implemented together, while others significantly benefit from the approval of laws and policies to amplify their impact. Options are compared based on their immediate impact in Mexico, particularly in *Nuevo León*.

To determine the weighting of each criteria, the objective of the project was taken into account. Considering that the main purpose of this project is to decrease the CO_2e emissions in specific emissions sources, carbon benefits and feasibility are major factors to consider; whereas, being an economically viable solution is also considered as an important factor of the sector.

The first criterion under scrutiny is the initial investment, with a weighting of 15%. This aspect carries significance as it plays a crucial role in the replicability of the technology, ensuring its acceptance by the industry as an economically viable solution.

The assessment considers the likelihood of the policy implementation and evaluates the level of advancement and development of the chosen technology. The assigned grades for this criterion are 0, 5, and 10. A score of 0 indicates that the proposal is not fully developed, possibly at the laboratory scale, or has not been applied. A score of 5 suggests that the proposal is being used on a large scale, but it is relatively new, and limited data has been collected. A score of 10 denotes a fully developed proposal implemented in large-scale power plants. This criterion holds a weight of 20% as the proposed projects must exhibit reliability for prompt applicability. This is particularly crucial due to the cumulative nature of CO_2 emissions. Halting emissions at the earliest opportunity is vital to preventing future increases. Additionally, ongoing projects lack certainty regarding their efficiency on a larger scale.

“Annual CO_2e emissions reduction" represents the saved CO_2 emissions per year compared to a reference scenario. This has the highest weight of 25% as it is the main objective of the research and the projects proposed.

The criterion “annual energy production”, as the name implies, measures energy production in terawatt-hours (TWh). This criterion cannot be applied to non-technological or direct reduction projects. Nevertheless, it holds significance in the energy sector, warranting a 15% weight.

Similar considerations apply to the “marginal cost” criterion. While some projects may not be applicable, it is crucial to assess marginal costs when considering an investment project for energy generation. Therefore, a weight of 17% is assigned to this criterion.

Regarding “law approval”,it indicates whether the proposal can be achieved within existing laws or if new policies need to be developed for implementation. This criterion is assigned a weight of 0, 5, or 10, where 0 corresponds to non-compliance with current laws, 5 signifies non-compliance with current laws but with potential approval of new laws, and 10 represents the possibility to create the proposal within existing laws.

Following this analysis, projects are categorized as “high value”, “margin benefit vs costs”, or “low benefits at high cost”. High-value projects yield significant carbon benefits at reasonable costs, margin benefit vs cost projects offer moderate carbon benefits compared to their costs, and low benefits at high cost projects provide limited carbon benefits at a higher cost.

V. Policy and Tax Analysis

It is important to highlight the policies of *Nuevo León*, the analyzed state and Mexico the federation. In Mexico there is the General Law of Climate Change (LGCC, *Ley General de Cambio Climático*), it was actualized in 2018 and its function is "regular las acciones para la mitigación y adaptación al cambio climático en México" [regulate the actions for the mitigation and adaptation to climate change in Mexico] (*Naciones Unidas*, 2012).

As part of one of the policies of the LGCC, the establishment of various registration instruments is stipulated, where one of them is the National Emissions Registry (RENE) and its regulations. This registry contains essential information pertaining to Greenhouse Gases (GHG) emissions. It contains the potential for global warming of various gasses, emission factors of human activities, formulas for the application of methodologies for calculating emissions of greenhouse gasses or compounds, operational agreements, lists of fuels and their calorific powers, among other things. (Secretaria De Medio Ambiente Y Recursos Naturales, 2023).

After considering the existing laws in Mexico, it is crucial to examine the policies and decisions implemented concerning climate change. According to the Climate Action Tracker (CAT), the assessed policies are deemed highly insufficient based on their analysis. This indicates that, rather than achieving a reduction in the average global temperature to 1.5°C, Mexican proposals could result in an increase of the average temperature by 4°C. CAT is a collaboration between Climate Analytics and NewClimate, two non-profit organizations. It serves as an "independent scientific project that monitors government climate action and evaluates it against the globally agreed Paris Agreement" (Climate Action Tracker, 2022).

In the article made by CAT it discusses the policies implemented after the arrival of the current president Andrés Manuel López Obrador. For instance, a portion of the federal budget was allocated to the Federal Electricity Company (CFE) for the modernization of various coal, diesel, oil, or gas plants that were planned to be closed by the previous administration. (Secretaría de Gobernación, 2018, cited in Climate Action Tracker, 2022). It also discusses the dissolution of the National Institute for Climate Change (INECC) in December 2021, the purpose of INECC was to empower the Mexican government with scientific data about climate change. (Secretaría de Medio Ambiente y Recursos Naturales, 2021 cited in Climate Action Tracker, 2022). In general, the article references that Mexican laws are being directed to increase the share of energy generated by fossil fuels.

Another example of these policies is the change in methodology to measure clean energy, according to the “Acuerdo Núm. A/018/2023” the definition of clean energy changed. This change has a notorious impact, specially section sixteenth, subsection K, that makes certain plants of cogeneration to be considered clean energy, adding roughly 7.502 GWh of energy that already were produced, but now are considered clean energy (García, K., 2023).

For these reasons, Mexico is considered one of those that lacks the most policies to help it end climate change.

VI. Conclusions

Through the exploration and analysis of data from the RETC database, this study analyzed the key CO_2e emitters in the electricity generation industry by volume and by MWh produced in order to know where the best CO_2e mitigation techniques should be used. This analysis revealed the major emission contributors namely IBERDROLA, CFE, PEMCORP, and *Compañía de Electricidad los Ramones*.

Furthermore, four proposals were made, three technological and a non-technological one, in order to counteract the effects of the emissions from the analyzed generation plants. After evaluating these proposals, it was concluded that “*Solar Farms*”, and “*Policy and Regulations*” were the best.

Although the solar farm has the greatest initial inventions, its energy production, marginal cost and low emissions of CO_2e made it one of the best options. It has the lowest marginal cost being 33% less than the second best option in this category. Also has the highest energy production, being 1.24 bigger than the second best option in this category.

On the other hand, the “Policy and Regulations” proposal has a great viability and it is the one that has the greatest annual emission reduction being 1.1 bigger than the second highest proposal and 2.9 bigger than the lowest annual emission reduction.

These two policies can complement each other; the carbon tax would put the focus on clean energy, and projects like the solar farm would provide an energy source almost free of CO_2e.

Although there is still work to be done, it is anticipated that this work will pave the way for a more in depth analysis of *Nuevo León* and its municipalities. This will facilitate the updating of information on carbon emissions offering a more precise scope to benefit future projects, upcoming constructions, and policy updates.

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