

Generation Expansion Planning Toward the Decarbonization of the Baja California Sur Electrical System

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Abstract— This article analyzes the energy transition and decarbonization of the Baja California Sur Interconnected System (BCSIS), an isolated electrical grid with a high dependence on fossil fuels. It proposes a generation expansion plan (GEP) that incorporates renewable technologies such as wind power, photovoltaic (PV), concentrated solar power (CSP), and battery energy storage systems (BESS), with the aim of improving reliability, reducing greenhouse gas (GHG) emissions, and lowering operating costs. To achieve this, three expansion scenarios are evaluated for the period 2025–2039, using simulations carried out with PLEXOS® software.

Link to graphical and video abstracts, and to code: <https://latamt.ieeer9.org/index.php/transactions/article/view/10343>

Index Terms— Investment Cost, Generation Expansion Planning, Renewable Generation, Battery Energy Storage Systems (BESS).

I. INTRODUCTION

IN light of the growing challenges posed by the energy crisis and climate change, the transition to renewable sources and the expansion of clean energy generation capacity have become an urgent necessity. This process involves not only a shift in the energy matrix but also a structural transformation of the electrical system, in which renewable energies must play an increasingly significant role in meeting the rising demand of the Baja California Sur Interconnected System (BCSIS).

According to the International Renewable Energy Agency (IRENA), the global installed capacity of renewable sources reached 582 GW in 2024, representing a 19.8% increase compared to 2023 [1],[2].

Looking ahead to 2050, IRENA projects that the decarbonization of the electricity sector will only be possible through the massive adoption of renewable energies, coupled with the integration of advanced technologies and more flexible electrical systems [3]. Thus, decarbonized Generation Expansion Planning (GEP) frameworks play a challenging role to achieve world energy goals [4], since they support the decision-making process about new generation capacity to meet the forecasted demand. These frameworks are reported in the literature considering isolated and highly interconnected power grids, along with a 10-year planning horizon with an annual demand growth [5, 6]. In [5], authors emphasize that long-term scenarios with intermittent and limited energy resources increase reliability challenges, thus boundary constraints are required to provide the necessary hourly reserve capacity. It is estimated that renewable generation will contribute approximately 85% of global

electricity production by that year, distributed as follows [1], [3]: Wind energy 36%, Solar PV 22%, Hydropower 12%, Concentrated Solar Power (CSP) 4%, Bioenergy 4%, Geothermal 3%, and other technologies 4%.

Within this scenario, wind and solar PV energy stand out as the main technologies to be considered in the energy matrix. However, their intermittent nature poses significant operational challenges, requiring the integration of complementary solutions to address the variability and fluctuations in electricity generation due to high penetration of renewables, such as pumped hydro and hydro reservoirs [7]. Therefore, it is necessary to develop strategies for dealing with key operational issues such as voltage regulation, grid stability, power quality, and frequency fluctuations [8].

In particular, the incorporation of Battery Energy Storage Systems (BESS) enhances operational flexibility, optimizes renewable intermittency, ensures grid stability, and secures supply during periods of low renewable generation, thereby contributing to grid reliability [8].

BESS help to compensate for the intermittency of solar and wind energy, improving power plant operations. It also allows energy to be stored during periods of low marginal costs and injected into the grid. when prices are high, aiding in the recovery of operational costs. Additionally, it enables operation during critical hours, offering greater flexibility through a hybrid renewable generation park combined with storage [9]. With the battery connected to the grid, a Grid Forming (GFM) control scheme can be implemented, operating with the Inverter-Based Resources (IBR), which helps resolve operational issues such as voltage control [10],[11].

On the other hand, CSP emerges as a high-potential complementary technology, especially in areas with high solar irradiation. Its main advantage lies in the ability to integrate thermal storage, allowing large amounts of thermal energy collected during the day to be dispatched at night or during critical hours. With synchronous generating units, this technology contributes inertia and frequency regulation to the system, offering a technical advantage over solar PV generation [12]–[14].

In this context, it is essential to analyze viable alternatives to accelerate the energy transition in regions highly dependent on fossil fuels. This investigation uses the Baja California Sur Interconnected Electrical System in Mexico as a reference, whose strategic location and solar and wind resource conditions make it an ideal case study for evaluating grid decarbonization strategies, given its annual capacity factors exceeding 30% [15].

This paper is organized as follows. Section I presents the introduction and motivation of the present work. Section II provides a detailed description of the Baja California Sur Interconnected Electrical System. Section III outlines the energy transition framework and the current state of generation and transmission in the BCSIS. Section IV introduces the generation expansion plan for the decarbonization of the BCSIS and the

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technology integration scenarios, addressing the assumptions and detailing inputs such as demand forecasts, fuel cost projections, and the economic and technical description of candidate projects. Section V details the evaluation methodology and technical analysis of the projects through which the different scenarios proposed for the decarbonization of the BCSIS are assessed. Finally, relevant conclusions are drawn Section VI.

II. DESCRIPTION OF THE BAJA CALIFORNIA SUR INTERCONNECTED SYSTEM

The BCSIS operates in isolation from the National Interconnected System (NIS). It is divided into three electrical zones: Constitución, La Paz, and Los Cabos (see details in Fig. 1). The main consumption centers are in the cities of La Paz, Cabo San Lucas, and San José del Cabo—regions with significant tourism development where environmental protection is of great importance. These environmental restrictions have limited infrastructure expansion projects from a strategic, technical, and economic standpoint, due to the difficult access to energy resources in the region.

The supply of electricity in Los Cabos Zone is achieved through

a transmission gate between La Paz Zone and Los Cabos Zone. This link consists of two 230 kV Transmission Lines (TL) and one 115 kV Transmission Line. Additionally, Los Cabos Zone has Los Cabos Gas Turbine Power Plant (CE Turbogás Los Cabos), composed of six gas turbine generation units that are used during peak demand periods, as they represent the highest operating cost units in the BCSIS and are utilized in necessity or emergency situations.

Los Cabos Transmission Zone has the highest demand growth within BCSIS. Its main electricity supply comes through the flow corridor between La Paz and Los Cabos electrical zones. This corridor includes two 230 kV transmission lines between the Olas Altas Substation and El Palmar Substation, with an approximate length of 162 km, and a 115 kV line of about 65 km from El Triunfo Substation to Santiago Substation. The rest of the electrical network operates at a 115 kV voltage level. To the north of BCS, La Paz and Constitución zones are interconnected via two 115 kV transmission lines between Las Pilas Substation and Olas Altas and Bledales substations in La Paz zone. This corridor is referred to as “La Paz – Constitución” link.

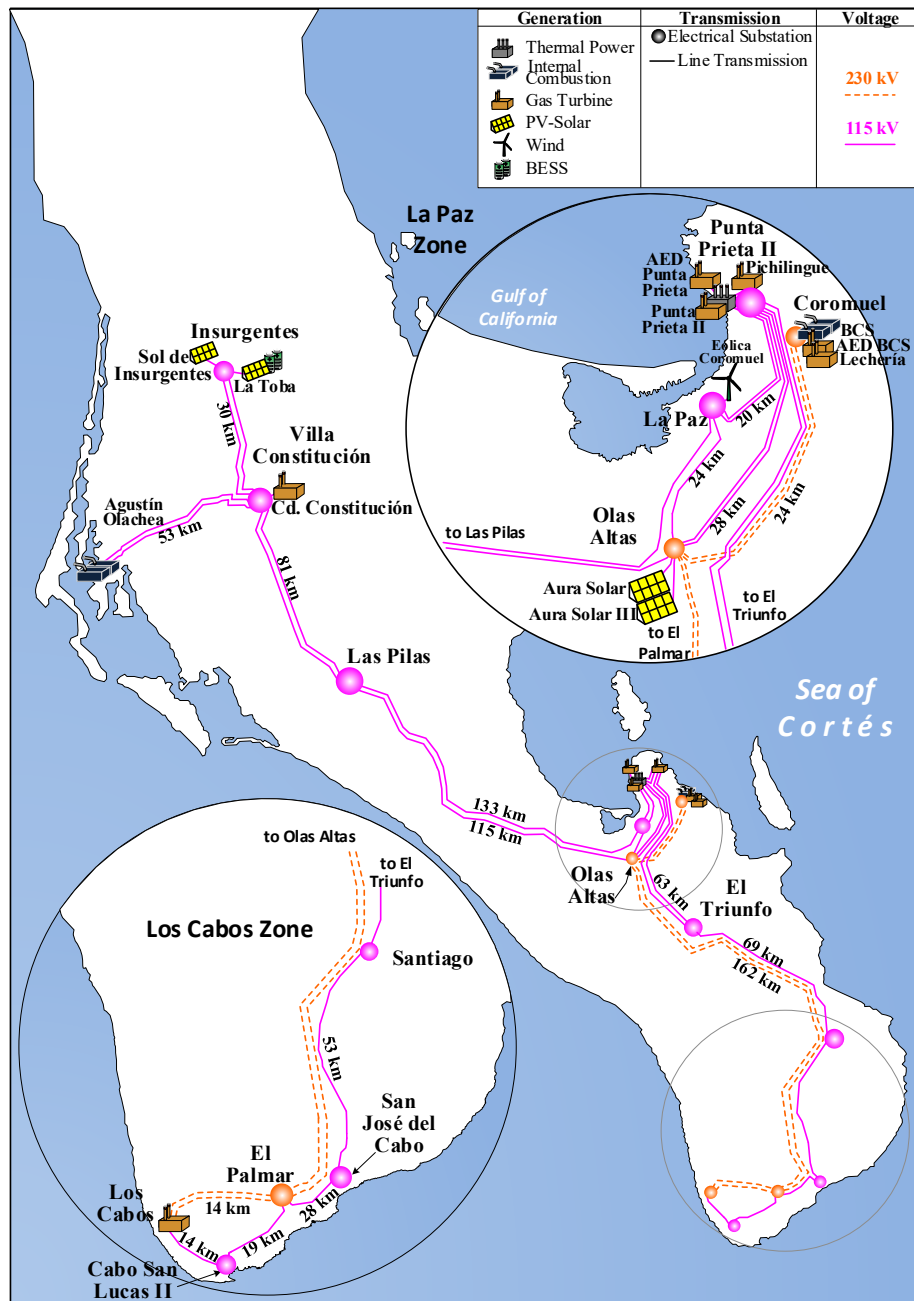


Fig. 1. Simplified single-line diagram of BCSIS 2024.

The expected demand growth in the electric substations (SE) that make up Los Cabos Transmission Zone has experienced a significant surge due to new load connections related to tourism developments, particularly hotel projects and population growth around the city of Los Cabos. Additionally, desalination plants are projected to address the potable water issues faced by the state. It is important to note that it is often complex and economically unfeasible to carry out projects positively impacting on the environment, mainly due to environmental and visual pollution concerns associated with new developments in Los Cabos Zone. To meet the future demand of Los Cabos Transmission Zone, electricity will be supplied through transmission from generation plants installed in La Paz Transmission Zone.

III. CURRENT OPERATING CONDITIONS OF THE BCSIS

The small and limited robustness of the BCSIS electrical grid forces the system to meet demand through small-scale generation units that rely on technologies with negative environmental impacts, primarily using fuel oil and diesel as their main fuels. Currently, the operating costs of the BCSIS units are among the highest nationwide. The installed generation is mostly composed of conventional thermal and internal combustion technologies that operate using fuel oil, diesel, or a combination of both. Additionally, many gas turbine power plants have been incorporated into the system to cover peak demand periods.

In recent years, photovoltaic generation has been integrated into the system, representing an addition of daytime and intermittent energy due to its inherent nature. This makes it necessary to implement energy storage technologies to ensure reliable and secure operation, as well as to maintain a greater energy reserve through conventional thermal units.

In the medium term, internal combustion engine power plants using natural gas will be commissioned into the BCSIS. Initially, these new electricity generation units would be concentrated in Los Cabos Zone with the aim of reducing atmospheric pollutant emissions and meeting the region's growing energy demand. This would result in a significant reduction in operating costs at BCSIS.

The current operational state of the BCSIS includes a generation capacity of 1,173 MW, of which 50 MW corresponds to wind, 98 MW to photovoltaic (PV), and 1,025 MW to thermal power plants. 87.4% of the installed capacity comes from thermal power plants, whereas only 12.6% originates from renewable sources (including wind and PV), indicating a low penetration of renewable energy as of 2024.

In 2024, the BCSIS generated 3,331 GWh, where 432.8 GWh came from renewable sources and 2,898 GWh from fossil generators. This resulted in only 13% of the annual consumption being supplied by clean energy. As shown in Fig. 2, fuel oil was the most used fuel for electricity generation during the period from 2022 to 2024, with a total of 1,528 GWh in 2024.

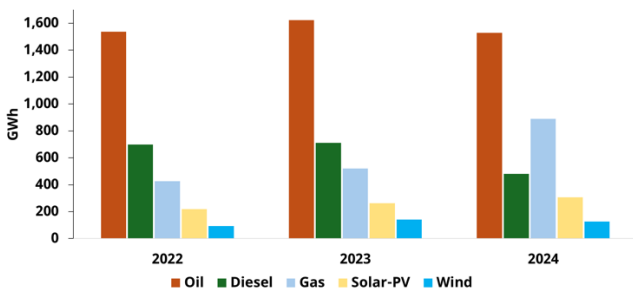


Fig. 2. Electricity generation by fuel type for the BCSIS between 2022 and 2024.

Due to the increasing demand in BCSIS, fossil fuel-based electricity generation has also risen to meet this demand. As a result of this trend, there is an identified need to reduce greenhouse gas (GHG) emissions. Thus, the generation expansion is focused on emerging technologies, such as CSP towers, as well as hybrid wind or solar parks that incorporate BESS. The goal is to ensure optimal operation and preserve the reliability of the system.

IV. GENERATION EXPANSION PLANNING: OPTIMAL FUNDAMENTALS

The mathematical formulation of the GEP aims to minimize operating and investment costs within a planning period. It is formulated using a mixed-integer linear programming model. The objective function that describes this model is presented in (1) for T planning periods and L operation periods, together with its restrictions in (2)-(6). To ensure the solution of the expansion problem, (1) minimizes the operation costs and the number of generating Units Build (UB) in year y for generator g ; considering the Value of Lost Load (VoLL), Discount Factor (DF), overnight Build Cost (BC) or investment cost of generator g , fixed Operations and Maintenance Charge (OMC) of generator g , maximum generating capacity (P_{max}) of each unit of generator g , number of installed generating units (Nu) of generator g , Energy Not Supplied (ENS) in dispatch period t , short-run Marginal Cost (MC) of generator g (composed of Heat Rate \times Fuel Price + VO&M charge), Dispatch Level (DL) of generating unit g in period t , average power Demand (D) in dispatch period t , Maximum number of Units of generator g allowed to be Built by the end of year y (MUB), Capacity shortage (Cs) in year, system Peak power Demand (PD) in year, Reserve Margin (RM) required over maximum power demand in year, Maintenance Rate (MR), Forced Rate (FR), and region Maintenance Factor (MF) [16].

$$\begin{aligned} \text{Min GEP} = & \sum_{y \in T} \sum_{g \in N} DF_y (BC_g UB_{(g,y)}) \\ & + \sum_{y \in T} DF_y [OMC_g P_{max,g} (Nu_g + \sum_{i \leq y} UB_{(g,i)})] \\ & + \sum_{t \in L} DF_{t \in y} L_t [VoLL \times ENS_t + \sum_{g \in N} (MC_g \times DL_{(g,t)})] \end{aligned} \quad (1)$$

subject to:

$$\sum_{g \in N} DL_{(g,y)} + ENS_t = D_t \quad (2)$$

$$\sum_{i \leq y} UB_{(g,i)} \leq MUB_{(g,y)} \quad (3)$$

$$\sum_{g \in N} P_{max,g} (Nu_g + \sum_{i \leq y} UB_{(g,i)}) + Cs_y \geq PD_y + RM_y \quad (4)$$

$$DL_{(g,y)} \leq (1 - MR_g MF_t - FR_g) \times P_{max,g} (Nu_g + \sum_{i \leq y} BU_{(g,i)}) \quad (5)$$

$$AC_{(g,y)} = BC_{(g,y)} P_{max,(g,y)} DR_{(g,y)} / (1 - DF_y) \quad (6)$$

$$DF_y = 1 / (1 + DR)^y \quad (7)$$

Given that real and reactive powers are nonlinear functions of the voltage magnitude and angle, due to the existing decoupling between the voltage angle and reactive power, then the linearized model of the electrical network is derived by approximating a linear relationship for the real power which can be formulated if the following assumptions are considered in the system [17]:

1. The resistance r_{ij} of the k -th branch connecting buses i and j is small compared to its reactance x_{ij} .
2. The voltage magnitude at each bus is equal to the system's base voltage, i.e., 1 pu.
3. The angular voltage difference among buses i and j connected by the k -th branch is sufficiently small, i.e., $\cos(\theta_i - \theta_j) \approx 1$ and $\sin(\theta_i - \theta_j) \approx \theta_i - \theta_j$.

Taking the above assumptions in consideration, power flows are assumed as linearized DC-OPF in this investigation, incorporating variable shift factor.

V. GENERATION EXPANSION PLANNING – BCSIS

The main objective of the generation expansion study is to optimally plan the addition of new power plants required to meet future electricity demand, ensuring a reliable and secure supply, minimizing operating and investment costs, and addressing sustainability goals such as reducing GHG emissions and promoting the use of renewable energy sources. Consequently, the aim is to find a balance between generation supply and long-term electricity demand and thereby identify the appropriate generation projects to be developed within the study horizon, which spans from 2025 to 2039. This also includes compliance with energy policies that prioritize system reliability and the participation of clean energy sources.

The optimization of the expansion plan involves minimizing the cost function in (1), which considers various factors such as investment costs, fuel costs, Operation and Maintenance (O&M) of power plants, as well as penalties associated with ENS, and the minimization of emission costs.

To carry out the generation expansion studies, the commercial software PLEXOS® is used to model the BCSIS. This tool determines the least-cost generation plan expansion based on a portfolio of candidate projects from various technologies, by formulating the expansion problem as a Mixed-Integer Linear Program (MILP) that is solved via embedded simulation packages such as CPLEX 12.1 [18] and Gurobi 12.0 [19]. It performs hourly simulations of the power dispatch, providing a detailed representation of the production costs of each power plant, thereby enabling an optimal long-term planning simulation.

To generate the generation expansion model in PLEXOS®, various inputs are required. The most important include Demand and Consumption Forecasts, Fuel Cost Projections, Generation and Transmission Infrastructure, and Candidate Power Plant Projects.

A. Demand Forecast

Long-term demand forecasting is crucial to identify the annual consumption needs that must be met by new generation additions. The forecast considers factors that significantly influence long-term demand behavior, such as the region’s economic growth, population growth, electricity prices, type of end-use consumption (residential, commercial, services, agricultural, small businesses, large industries, etc.), seasonality (climatic factors), losses, energy efficiency, distributed generation, electromobility, among others.

Figure 3 displays the forecast for the annual net peak demand and the annual net consumption from 2025 to 2039 expected for the BCSIS. In 2039, it is projected that during the summer, a peak demand of 1,060 MW will be reached, along with an annual consumption of 5,310 GWh.

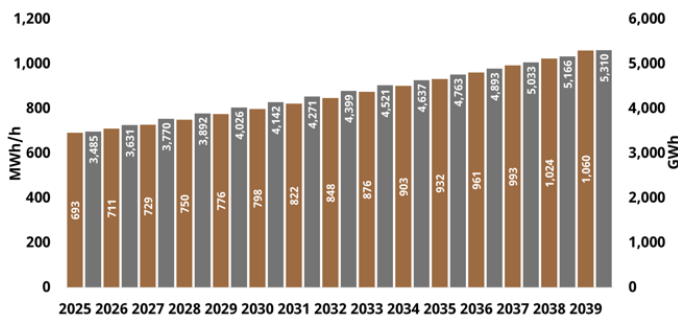


Fig. 3. Forecast for net quantities from 2025 to 2039. Peak Demand in brown color. Consumption in gray color.

The hourly demand forecasts for the BCSIS in 2025 and 2039 are presented in Fig. 4. Notice that the demand increased between May and October compared to the rest of the year. In 2025, the peak demand occurred on 9th September at 693 MWh/h; and in 2039 occurred on 13th September at 1060 MWh/h.

B. Fuel Costs

One of the key inputs that significantly impact the generation expansion is the fuel price scenarios, as they have a direct effect on electricity generation and its planning is closely tied to fuel price fluctuations. The forecasted price is determined by considering the region of origin of the fuel, variable transportation costs, and additional variable charges associated with each fuel to deliver it to the power plants, along with the supplier’s management and administrative costs. Figure 5 shows the evolution of fuel costs for the BCSIS from 2025 to 2039, by fuel type in USD/GJ and by reference node.

C. Power Plants of the BCSIS

The power plants in the BCSIS include CE Punta Prieta II, CE AED Punta Prieta, CE Baja California Sur, CE AED Baja California Sur, CE Lechería, CE Pichilingue, CE FV Aura Solar I y CE FV Aura Solar III, all located in the La Paz Zone, In the Constitución Zone, there are the General Agustín Olachea Power Plant and the Cd. Constitución Power Plant. Finally, in Los Cabos Zone, there is Los Cabos Power Plant (for more information, see Table I, where technologies such as Thermal power (TP), Gas Turbine (GT), Internal Combustion (IC), Solar PV(PV) are considered). Notice that VO&M costs are considered as zero for PV, wind, and PV+ BESS, due to the following assumptions: (i) the fuel costs are associated with the cost of the renewable resources that are assumed as zero; (ii) the usability of the renewable resources does not imply any variable cost to use them; (iii) the internal losses for all three-generation technologies are reflected in the generated power and the plant’s efficiency.

D. Current Transmission Infrastructure

As shown in Fig. 1, the main electrical grid in the BCSIS operates at 230 kV and interconnects La Paz and Los Cabos zones through two transmission lines between Olas Altas Substation and El Palmar Substation, with an approximate length of 164 km.

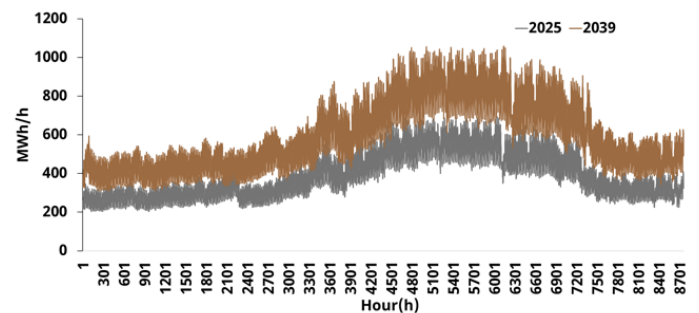


Fig. 4. Hourly Demand Forecast for: 2025 in gray color, and 2039 in brown color.

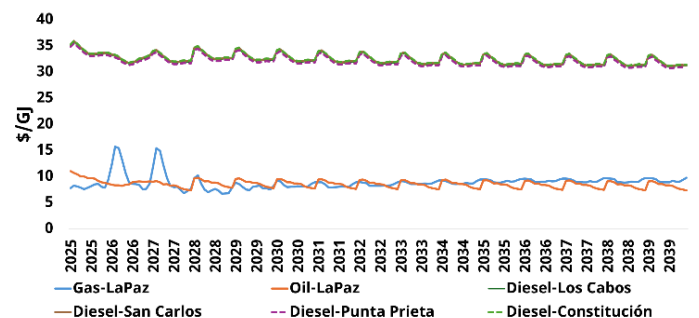


Fig. 5. Evolution of fuel costs by fuel type in (USD/GJ) and by reference node for the BCSIS from 2025 to 2039.

TABLE I
POWER PLANTS' SPECIFICATIONS PER TECHNOLOGY FOR THE
BCSIS

Name	Technology	Cap. (MW)	Fuel	VO&M Cost (\$/MWh)	Heat Rate (GJ/MWh)
CE Punta Prieta II	TP	112.5	Oil	13.5	13.3
AED Punta Prieta	GT	43	Diesel	12.8	16.6
CE Baja California Sur	GT	72	Gas	3.3	10.2
AED Baja California Sur	IC	209.76	Oil	20.3	9.2
CE Lechería	GT	108	Diesel/Gas	3.3	10.2
CE Agustín Olachea Avilés	GT	36	Diesel	3.8	10.5
CE Cd. Constitución	IC	104.12	Oil	12.8	9.5
CE Los Cabos	GT	33.22	Diesel	10.7	15.6
CE Pichilingue	GT	179.7	Diesel	6.4	14.2
Aura Solar Tres	GT	127	Gas	3.3	10.2
Aura Solar Uno	PV	25	Solar	-	-
Sol de Insurgentes	PV	30	Solar	-	-
Eólica Coromuel	PV	23	Solar	-	-
La Toba Energy Center	Wind	50	Wind	-	-
	PV +BESS	20	Solar	-	-

Additionally, a third transmission line operates at 115 kV, from El Triunfo Substation to Santiago Substation, with an approximate length of 65 km. Olas Altas Substation distributes energy within the 230 kV grid coming from the Coromuel Substation toward El Palmar Substation.

The distribution toward the Constitución zone comes from La Paz zone through a 115 kV transmission line that extends to Las Pilas Substation in the Constitución zone. El Palmar Substation is responsible for distributing energy within 115 kV grid to the Electric Substations of San José del Cabo, Palmilla, Cabo Real, Cabo Sol, Cabo Bello, and Cabo San Lucas Dos. Additionally, there are two 230 kV transmission lines of approximately 23 km each between El Palmar Substation and the Los Cabos Substation. Los Cabos Substation distributes energy within the 115 kV grid to Cabo Falso Substation, Cabo San Lucas Dos Substation, and Desaladora Substation.

E. Prospective Power Plants

The objective of the generation expansion plan is to optimally determine the amount and type of generation technology that should be installed based on the requirements of the electrical grid, as well as the timing and location, to ensure a reliable supply to meet demand. The portfolio of candidate generation and storage projects must be defined considering the following: Net capacity, Investment and Fixed O&M Costs, Identification of high renewable potential sites, Operational life by technology type, Hourly profile: wind and solar generation, Clean Energy

goals, Penalty for Energy Not Supplied (ENS in (1)), Cost of curtailment of Renewable Generation.

Candidate generation projects are defined based on renewable sources such as wind, solar, and CSP, as well as energy storage, since the main objective of the expansion plan is to displace fossil-based generation using fuels such as diesel, fuel oil, and natural gas. Tables II and III show fixed O&M costs and the investment costs for each project [20, 21].

Hourly generation profiles for wind and PV-solar renewable energy were developed using the TSL® renewable energy modeling tool described in [24, 25, 26], which generates synthetic future generation scenarios based on detailed historical hourly data.

These profiles are created using reanalysis data of historical wind speed and solar irradiation, and the tool is georeferenced. The flowchart in Fig. 6 exhibits the input data required in TSL® [26], where geographic location and renewable profile of the power plant are required; the historical information of wind, irradiation, temperature, and inflow is obtained via MERRA or ERA database within the TSL® interface®.

After data processing at the TSL® interface, the output data are the renewable and hydro synthetic scenarios. The expected hourly generation for each of the renewable projects is shown in Fig. 7.

In the BCSIS, the highest wind speed potential is found in the Los Filos Zone, where a capacity of 60 MW for wind generation is proposed. For renewable PV-Solar generation, installations are proposed in the zones of Cabo San Lucas Dos, Las Pilas, El Palmar, San José del Cabo, and El Triunfo, with a capacity of 60 MW for each zone.

In the case of CSP technology [22,23], the study will consider a Solar Tower Power Plant with a molten salt storage system of at least 10 hours. This will be proposed in the Olas Altas and Villa Constitución zones in packages of 75 MW and 50 MW respectively, starting in 2030 (these amounts vary depending on the scenario analyzed).

Storage equivalent to 34% of the installed capacity of wind and PV-solar renewable generation will be integrated, with four hours of storage, to address the variability of intermittent generation and ensure system reliability.

VI. RESULTS

The GEP in (1) is solved using the commercial software PLEXOS®, which enables a detailed representation of system operation while accounting for uncertainty. It allows simulation of the BCSIS by regions with a simplified representation of the Transmission Network. It also enables the representation of demand across different periods throughout the year; current and future power plants with their production costs based on fuel prices at the plant; and performance characteristics according to the physical conditions of the region where they are located.

TABLE II
FIXED OPERATION AND MAINTENANCE (O&M) COSTS (\$/KW-PER YEAR) PER TECHNOLOGY

	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Solar-PV	19	19	18	17	17	16	16	15	15	15	15	14
Wind	30	30	29	29	29	29	28	28	28	28	28	27
BEES	35	34	33	32	32	31	30	30	29	29	28	28
CSP	60	57	55	55	55	55	54	54	54	54	54	54

TABLE III
INVESTMENT COSTS (\$/KW)

	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Solar-PV	1,313	1,253	1,193	1,134	1,074	1,015	955	895	881	867	853	839
Wind	1,472	1,440	1,408	1,393	1,379	1,364	1,349	1,335	1,320	1,305	1,291	1,276
BESS	1,555	1,503	1,451	1,431	1,410	1,389	1,368	1,347	1,327	1,306	1,285	1,264
CSP	5,863	5,521	5,180	5,144	5,107	5,071	5,035	4,999	4,962	4,926	4,890	4,854

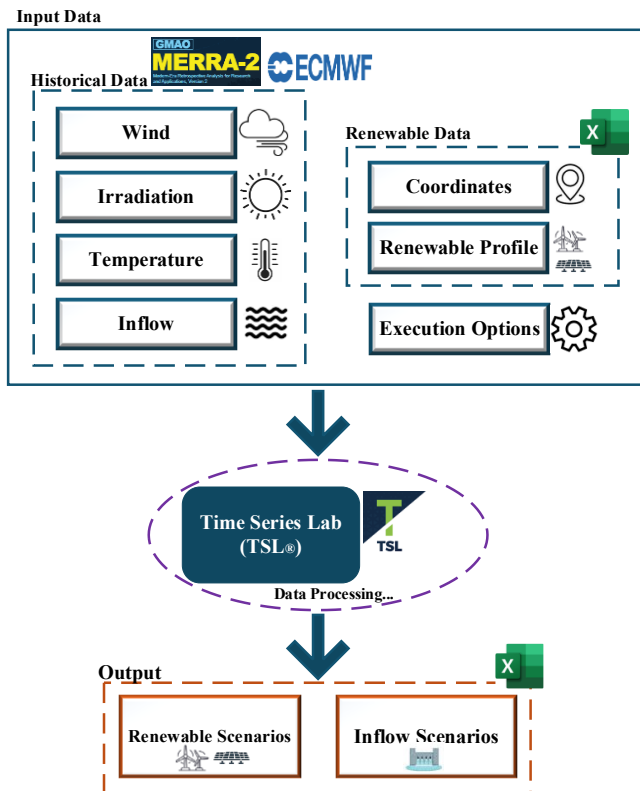


Fig. 6. Flowchart for wind and solar profiles created in TSL®.

The electrical grid is represented through equivalent links with their respective transmission limits, considering both the current and future network. Thermal transmission limits defined by the Transmission Operator are considered, as well as operational transmission limits based on steady-state, angular stability, or voltage studies, as applicable. For the analysis conducted, the model minimizes production costs and the cost of energy not supplied, considering the efficient planning reserve in terms of reserve margin defined in the reliability policy established by the Ministry of Energy (SENER), set at 35% for the BCSIS, with AN-ENS cost of 2.6 USD/kWh [27].

The flowchart in Fig. 8 unveils the methodology to solve the GEP for BCSIS, including all input data required. Technical, economic, and operational data are collected and processed in PLEXOS® via excel or SQL. After executing operational scenarios in PLEXOS, different outputs can be obtained, such as: generation, generation costs, marginal prices, emission costs, unserved energy and other ones.

The Generation Expansion Plan study for the BCSIS includes a base case, where no additional clean generation capacity is considered; only the existing capacity is considered. Then, three scenarios are analyzed, all of them include a repowering of Los

Cabos Gas Turbine Power Plant using internal Combustion technology. This repower consists of 13 units of 20 MW each, of which eight operate on natural gas and the remaining units use diesel. The objective is to reduce the high consumption of fuels such as diesel and fuel oil. Since the base case does not include this repowering, only three scenarios are considered.

B. Expansion Scenario I

In 2028, 60 MW of wind generation will be installed in La Paz Zone, with 20.4 MW of energy storage. Additionally, 260 MW of thermal generation using internal combustion technology will be added, which will repower of Los Cabos GT power plant.

By 2029, 60 MW of solar PV generation capacity will be installed at Cabo San Lucas 2 and 60 MW at Las Pilas, each one with 20.4 MW of energy storage. In 2030, 75 MW of CSP will be installed at Olas Alta and 50 MW at Villa Constitución. The annual investment costs associated with the expansion plan projects are shown in Fig. 15.

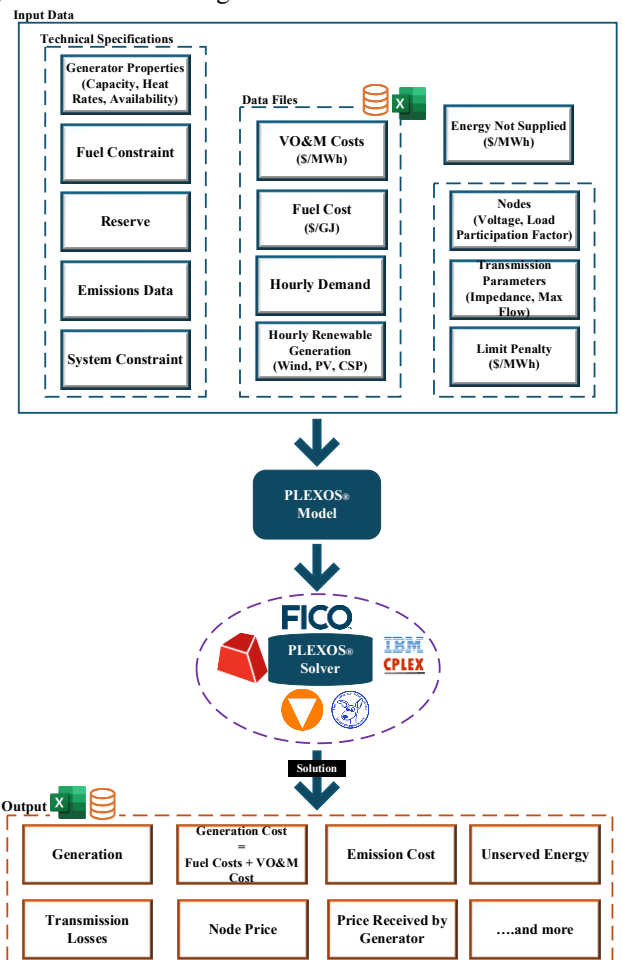


Fig. 8. Flowchart for solving the GEP in (1) using PLEXOS®.

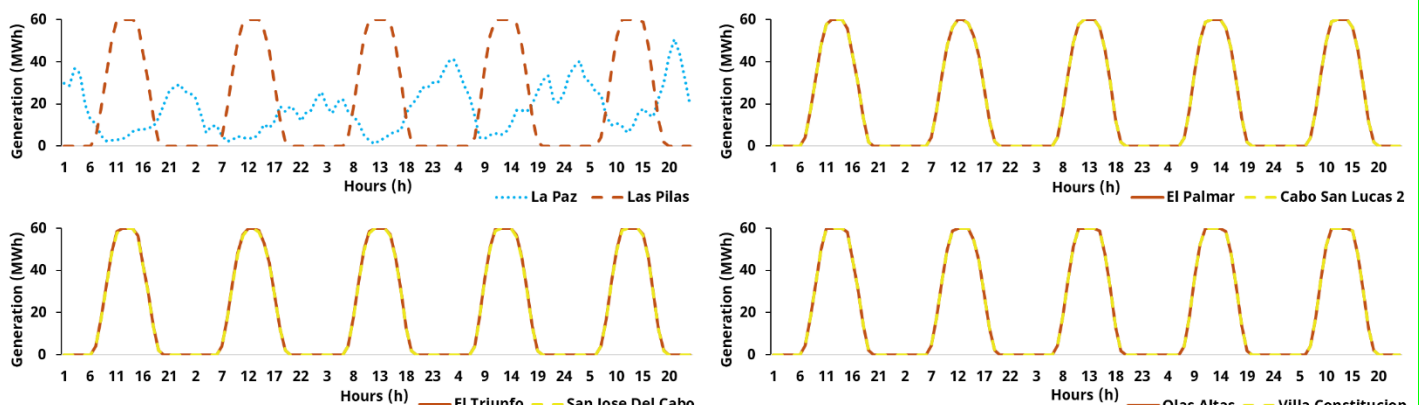


Fig. 7. Hourly generation profile for renewable projects projected in the BCSIS.

A. Reference Case

Fig. 9 shows electric generation exhibiting an intra-annual pattern closely linked to demand seasonality according to Fig. 4. During the first months of the year, a progressive increase in generation levels is observed, reaching a peak in the third quarter. Subsequently, generation displays a declining trend toward the end of the year. By the year 2039, a total net generation of 5,108 GWh is estimated, of which only 406 GWh will come from renewable sources and 4,702 GWh will be generated from fossil fuels. Fossil fuel-based generation shows a consistent upward trend, primarily due to the increased use of diesel and oil required to meet the demand of the Baja California Sur electrical grid.

Figures 10 to 13 show the annual dispatch by power plant and fuel type, and its evolution throughout the study period. By 2039, a total of 406.38 GWh of renewable generation is reported (126 GWh from wind power plants and 280 GWh from solar power plants). From 2032 to 2039, gas generation remains constant at 2,045 GWh annually, fuel oil reaches 1,962 GWh in 2039, and diesel increases from 67 GWh in 2026 to 695 GWh in 2039. Figure 10 shows oil generation exceeding gas generation in Fig. 12 during 2026–2027 due to lower oil prices in Fig. 5. From 2028 onward, gas generation rises to nearly 2 TWh, displacing oil as gas becomes the most cost-competitive option, as exhibited in Fig. 5.

Fig. 14 showcases the generation costs from 2026 to 2039, highlighting an increase due to diesel-based generation between 2030 and 2039. Operating costs from 2026 to 2029 remain with minimal growth, and no penalties for ENS are reported. However, starting in 2030, ENS penalties begin to appear, and operating costs rise, causing the Reference Case to report higher costs, as it does not include any generation expansion plan.

Considering the annual dispatch by power plant in Figs. 10-14, the investment per technology in Fig. 15, and the demand pattern in Fig. 4, the fossil fuel-based generation profile in Fig. 16 decreased significantly. It is estimated that by 2039, the total net generation will reach 5,356 GWh, of which 4,178 GWh will come from fossil fuels and 1,456 GWh from clean energy sources, representing an increase of 1,050 GWh in renewable generation compared to the base case.

Figs. 17 to 20 illustrate the evolution of the annual dispatch by power plant and fuel type throughout the study period. By 2039, renewable generation reaches 1,456 GWh (277 GWh from wind power plants, 590 GWh from solar power plants, and 588 GWh from CSP). Gas-based generation records 2,723 GWh, fuel oil-based generation reaches 1,052 GWh, and diesel-based generation totals 124 GWh. Compared to the base case and scenario I shows a reduction of 910 GWh in fuel oil-based generation and 571 GWh in diesel-based generation by 2039.

Figure 21 shows the operative costs from 2026 to 2039 for Scenario I, compared to the base case. In 2039, there is a reduction of 288 million dollars in fuel costs. Additionally, the system operates without load shedding, as no penalties for ENS are reported in any year. This scenario demonstrates an expansion plan with long-term economic and operational benefits.

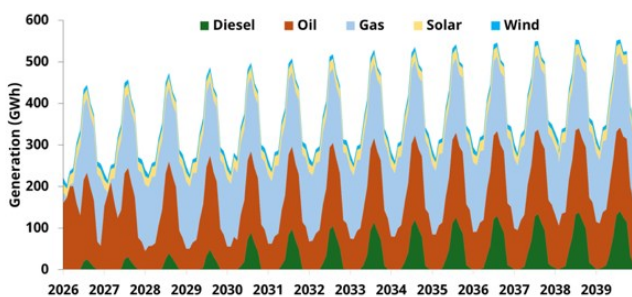


Fig. 9. Generation by fuel type between 2026 and 2039 for reference case.

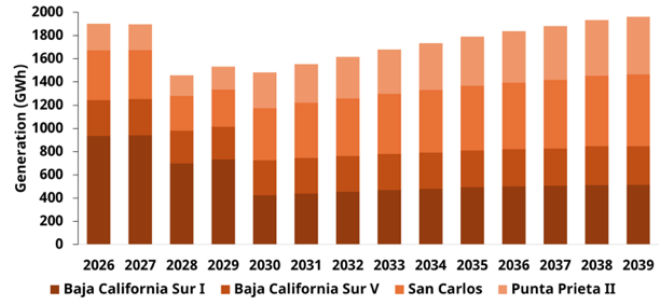


Fig. 10. Generation by oil power plants for reference case.

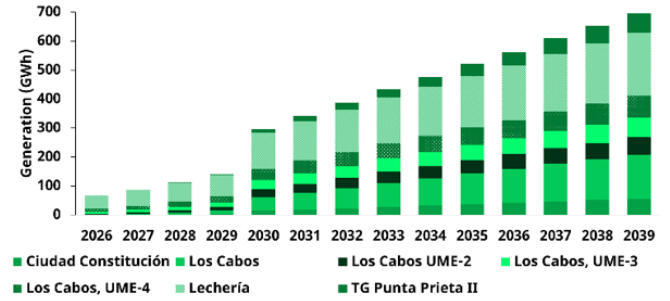


Fig. 11. Generation by diesel power plants for reference case.

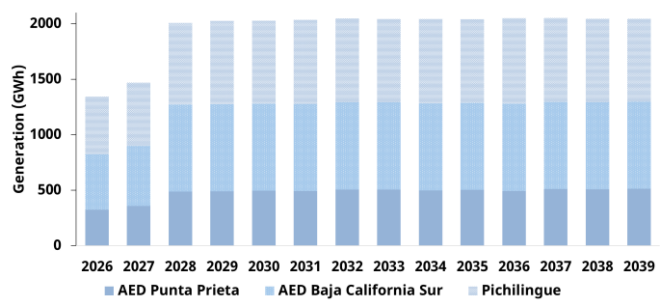


Fig. 12. Generation by gas power plants for reference case.

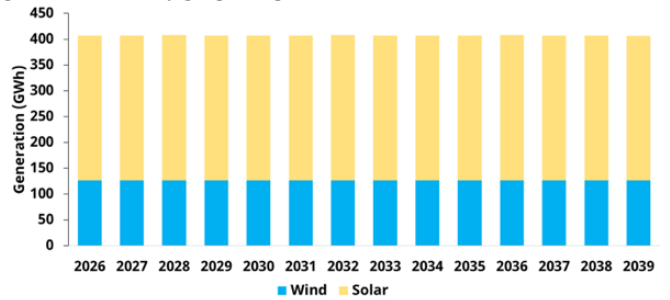


Fig. 13. Generation by renewable power plants for reference case.

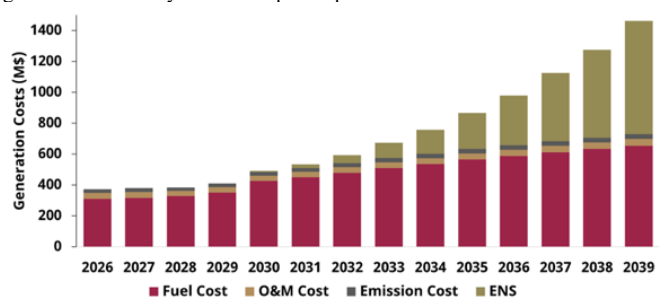


Fig. 14. Generation costs including fuel, O&M, emissions and ENS costs between 2026 and 2039 for reference case.

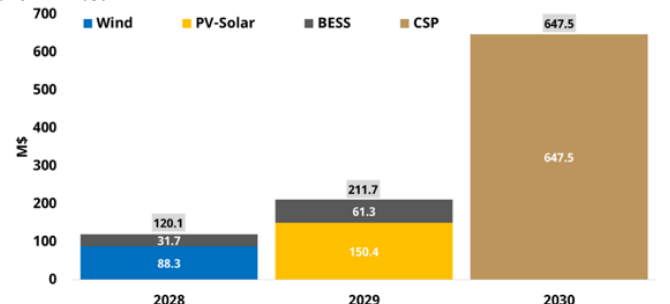


Fig. 15. Investment costs per technology from 2028 to 2030 for Scenario I.

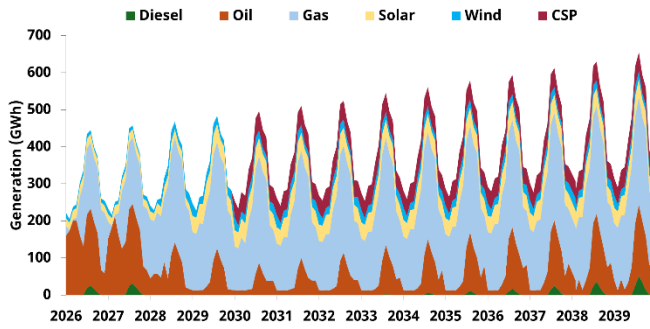


Fig. 16. Generation by fuel type between 2026 and 2039 for Scenario I.

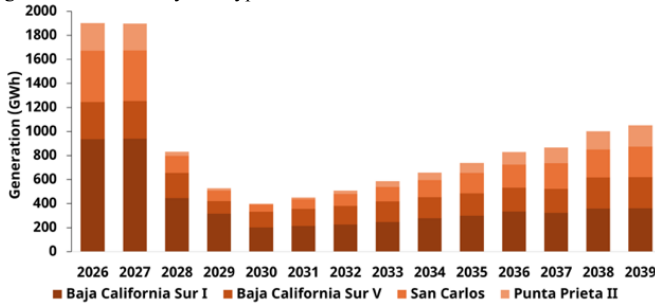


Fig. 17. Generation by oil power plants for Scenario I.

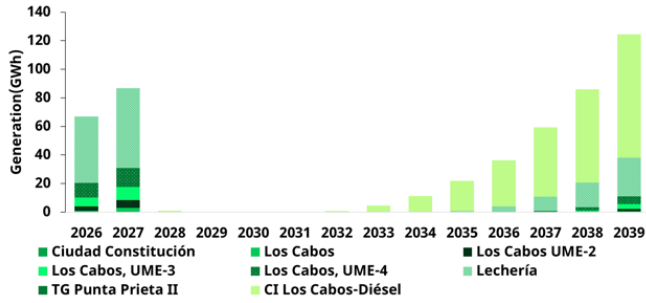


Fig. 18. Generation by diesel power plants for Scenario I.

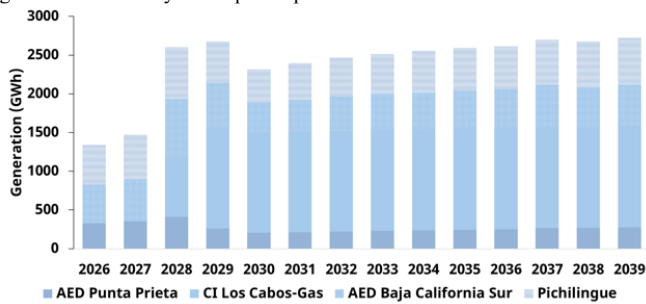


Fig. 19. Generation by gas power plants for Scenario I.

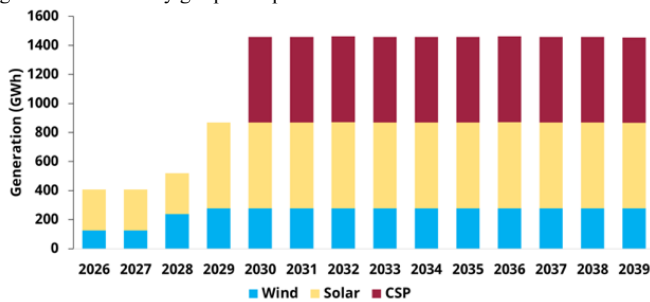


Fig. 20. Generation by renewable power plants for Scenario I.

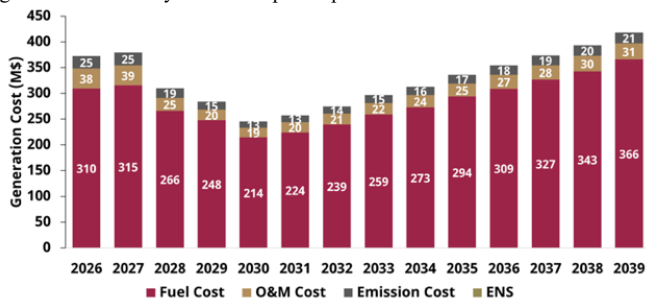


Fig. 21. Generation costs including fuel, O&M, emissions and ENS costs between 2026 and 2039 for Scenario I.

C. Expansion Scenario II

In Scenario II, the expansion plan considers the installation of 60 MW of wind generation in 2028 in La Paz, with 20.4 MW of energy storage. Additionally, 260 MW of thermal generation based on internal combustion will be added, which will repower the generation park of Los Cabos GT power Plant. By 2029, a capacity of 60 MW of solar PV generation will be installed at Cabo San Lucas 2 and 60 MW at Las Pilas, each with 20.4 MW of energy storage. By 2030, 100 MW of CSP generation will be installed at Olas Altas, as well as, 75 MW at Villa Constitución. The annual investment costs associated with the expansion plan projects are similar for 2028 and 2029 in Fig. 15; however the CSP generation costs increase from 647.5 to 905.5 M\$, as described in Fig. 15.

The expansion plan in Scenario II reports an increase in the incorporation of clean energy sources to meet the demanded load in Fig. 4, along with a decrease in the generation profile based on fossil fuels, as shown in Fig. 22. By 2039, a total net generation of 5,356 GWh is estimated, of which 3,665 GWh will come from fossil fuels and 1,691 GWh from clean energy sources, representing an increase of 1,285 GWh in renewable generation compared to the base case.

The evolution of the annual dispatch by power plant and fuel type throughout the study period demonstrated that by 2039, the renewable generation reported at 1,691 GWh (with 277 GWh from wind power plants, 590 GWh from solar power plants, and 824 GWh from CSP). Gas-based generation reaches 2,609 GWh, fuel oil-based generation 973 GWh, and diesel-based generation 84 GWh. Compared to the base case and Scenario II, there is a reduction of 989 GWh in fuel oil-based generation and 611 GWh in diesel-based generation by 2039.

Fig. 23 shows the operative costs from 2026 to 2039 for Scenario II, comparing the base case with Scenario II. In 2039, there is a reduction of 320 million dollars in fuel costs. Additionally, the system operates without load shedding, as there are no penalties for ENS in any year. This scenario demonstrates an expansion plan with long-term economic and operational benefits, superior to those of Scenario I.

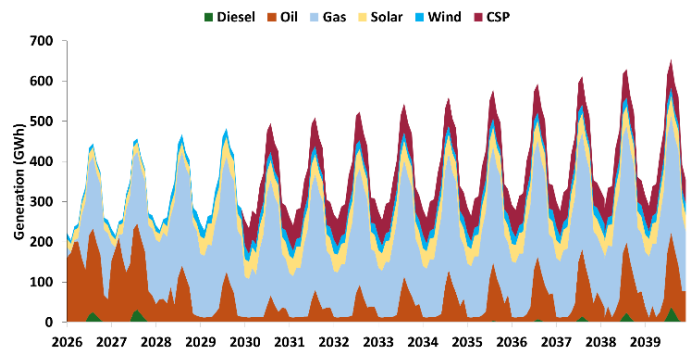


Fig. 22. Generation by fuel type between 2026 and 2039 for Scenario I.

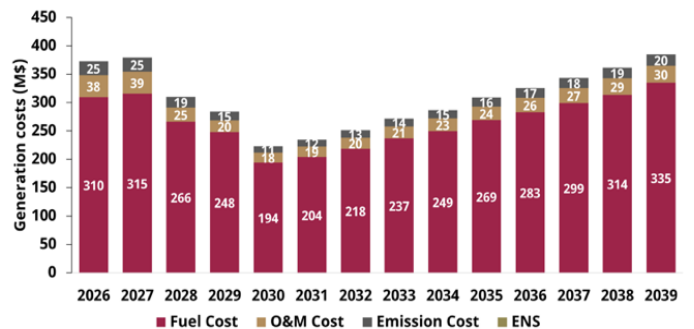


Fig. 23. Generation costs including fuel, O&M, emissions and ENS costs between 2026 and 2039 for Scenario II.

D. Expansion Scenario III

In Scenario III, the expansion plan considers the installation of 60 MW of wind generation in 2028 in La Paz, with 20.4 MW of corresponding energy storage. Additionally, 240 MW of thermal generation based on internal combustion will be added, which will repower the generation park of Los Cabos GT power plant. By 2029, a capacity of 60 MW of solar PV generation will be installed at Cabo San Lucas 2 and 60 MW at Las Pilas, each with 20.4 MW of energy storage. By 2030, 100 MW of CSP generation will be installed at Olas Altas, as well as 75 MW in Villa Constitución. Additionally, by 2033, 100 MW of CSP, 100 MW of solar PV generation, and 100 MW of energy storage will be installed at Olas Altas. The annual investment costs associated with the expansion plan projects are shown in Fig. 24.

After incorporating new investments in Scenario III and the demand profile in Fig. 4, the generation expansion planning in this scenario reports an increase in the inclusion of clean energy sources, as illustrated in Fig. 25. By 2039, a total net generation of 5,363 GWh is estimated, of which 2,933 GWh will come from fossil fuels and 2,430 GWh from clean energy sources, representing an increase of 2,024 GWh in renewable generation compared to the base case.

Figs. 26 to 29 show the evolution of the annual dispatch by power plant and fuel type throughout the study period. By 2039, renewable generation is reported at 2,430 GWh (with 277 GWh from wind power plants, 853 GWh from solar power plants, and 1,300 GWh from CSP). Gas-based generation reaches 2,244 GWh, fuel oil-based generation 685 GWh, and diesel-based generation 4 GWh. Compared to the Base Case and Scenario III, there is a reduction of 1,277 GWh in fuel oil-based generation and 691 GWh in diesel-based generation by 2039, with the CI-Central Los Cabos power plants being the only ones generating energy from diesel. As shown in Fig. 27 for Scenario III, diesel power plants could be decommissioned from 2028. However, for Scenario I, they could be turned off for almost 5 years, technically and financially being worse than decommissioning them forever. Which represents a significant advantage of Scenario 3 over Scenario I.

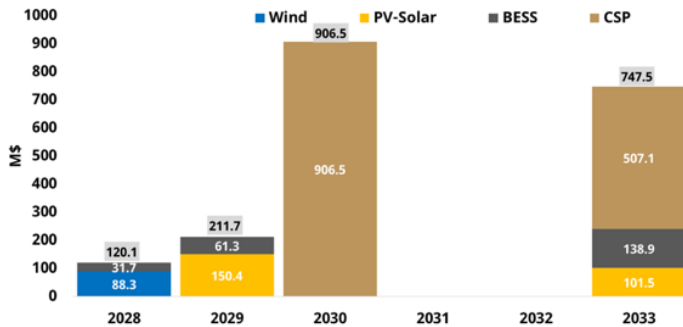


Fig. 24. Investment costs per technology from 2028 to 2033 in Scenario III.

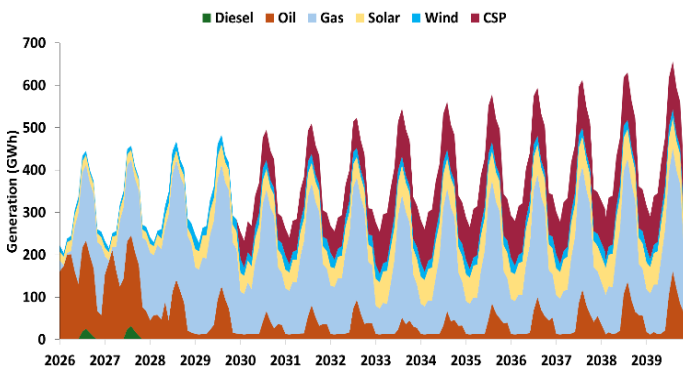


Fig. 25. Generation by fuel type between 2026 and 2039 for Scenario III.

Fig. 30 shows the operating costs from 2026 to 2039 for Scenario III, comparing the Base Case with Scenario III. In 2039, there is a reduction of 403 million dollars in fuel costs. Additionally, the system operates without load shedding, as there are no penalties for ENS in any year. This scenario demonstrates an expansion plan with long-term economic and operational benefits, superior to those of Scenarios I and II.

After assessing all scenarios and the reference case, a matrix arrangement summarizing all four GEP involved is provided in [28].

E. Solver Performance

For the BCSIS, the attained solutions for all three scenarios using the different solvers are presented in Table IV. It can also be observed that CPLEX is able to gain much better results than the GUROBI solver, due to CPLEX exhibiting the best optimal cost, fast speed of convergence, but more iterations in all scenarios. For instance, Scenario III shows a significant reduction of 257,886.48 k\$ using a CPLEX solver to obtain the expansion planning generation.

Figures 31 and 32 show the convergence characteristics of CPLEX and GUROBI optimizers for solving the generation expansion plan of BCSIS

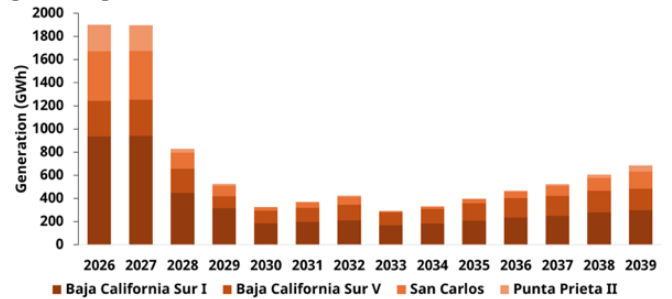


Fig. 26. Generation by oil power plants for Scenario III.



Fig. 27. Generation by diesel power plants for Scenario III.

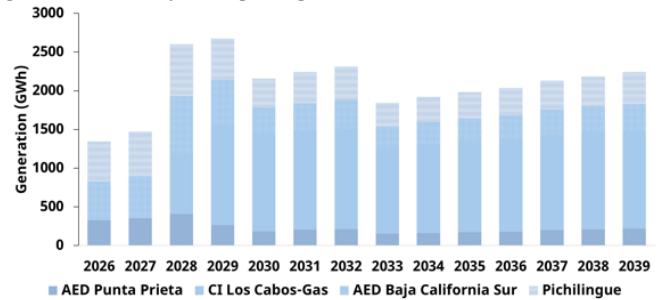


Fig. 28. Generation by gas power plants for Scenario III.

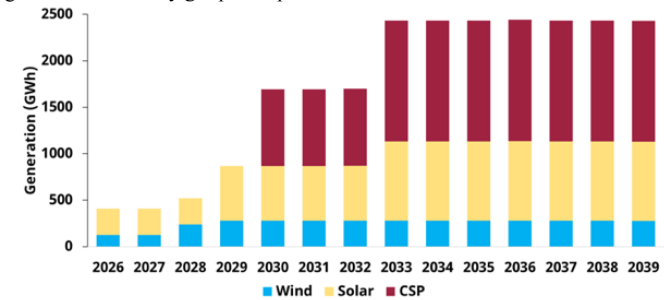


Fig. 29. Generation by renewable power plants for Scenario III.

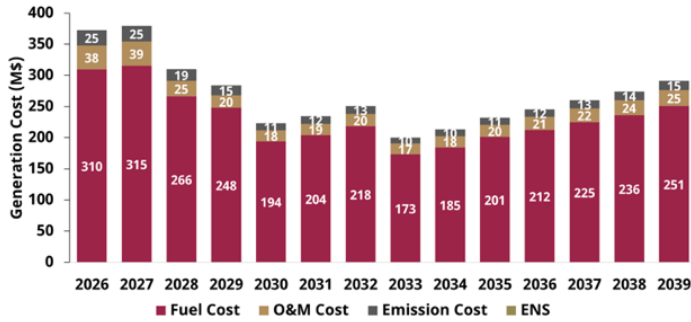


Fig. 30. Generation costs including fuel, O&M, emissions and ENS costs between 2026 and 2039 for Scenario III.

TABLE IV
SUMMARY OF SOLUTIONS

Solver	Scenario 1		Scenario 2		Scenario 3	
	Cost (k\$)	Time (s)	Cost (k\$)	Time (s)	Cost (k\$)	Time (s)
CPLEX	35,647,742	296	38,341,741	398	45,201,104	426
GUROBI	35,647,772	441	38,341,815	517	45,458,990	450
Diff(k\$)	29.23	144.58	74.09	118.57	257.886	23.54

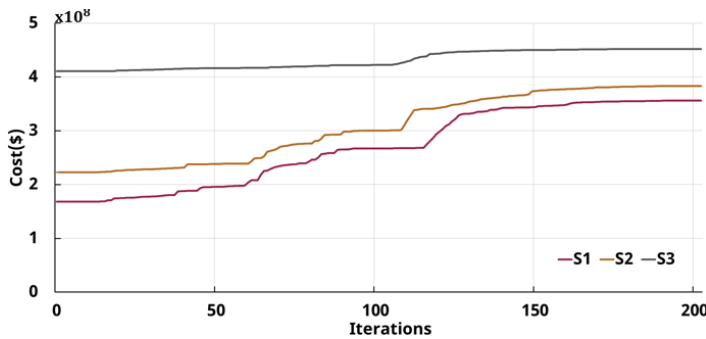


Fig. 31. Convergence characteristics of the CPLEX solver.

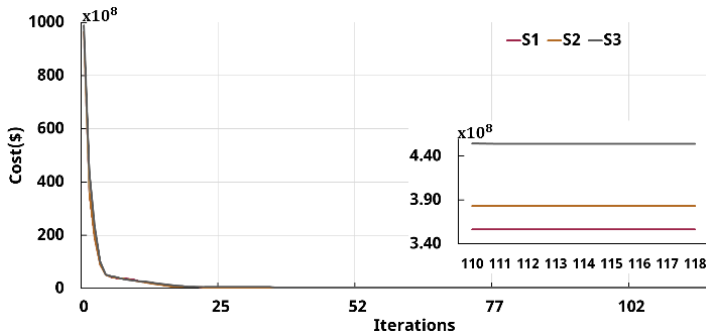


Fig. 32. Convergence characteristics of the GUROBI solver.

The implementation of the PLEXOS® model for the generation expansion planning of the BCSIS was executed on a Microsoft Azure virtual machine with the following high-performance specifications: (i) CPU Type: AMD EPYC 9V33X, a 96-core processor; (ii) physical RAM memory: 768 GB; and (iii) total cores Available: 176 Cores.

These specifications indicate a very powerful computing environment, suitable for handling the complex, large-scale simulations required by PLEXOS®. This level of computational power is essential for: (i) Running hourly dispatch simulations over a 15-year planning horizon (2025–2039); (ii) evaluating multiple expansion scenarios with different combinations of renewable and thermal technologies; (iii) performing optimization tasks involving cost minimization, emissions reduction, and reliability constraints; and (iv) utilizing advanced solvers like CPLEX and GUROBI, which benefit from high core counts and large memory for faster convergence and better solution quality.

VII. CONCLUSIONS

The analysis carried out allows us to conclude that the progressive incorporation of renewable generation, particularly PV-Solar with BESS and CSP, constitutes a technically viable and economically feasible strategy for reducing the use of fossil fuels in the BCSIS, which contributes to the mitigation of emissions and GHG.

In the medium term, across all three scenarios, 60 MW of wind capacity will be installed in La Paz in 2028, with 34% of BESS. For 2029, 60 MW will be installed in Las Pilas and Cabo San Lucas 2, each accompanied by 34% of BESS. These proposed capacity additions significantly displace generation based on fuels such as diesel and fuel oil, reaching an annual production of approximately 462 GWh. This effect contributes to lowering operating costs, improving system efficiency, and reduces dependence on high marginal cost technologies.

In the 2030–2039 horizon, the introduction of CSP capacity in the three evaluated scenarios reflects additional benefits, both in reducing operative and emissions costs. Scenario 3 stands out as the most competitive, by leveraging dispatchable CSP generation, which allows for almost complete displacement of diesel-based generation, leaving Los Cabos IC (Diesel) as the only active power plant with marginal participation between 1 to 4 GWh in the final years of the analysis horizon. This supports the feasibility of planning the gradual retirement of diesel-consuming power plants.

The financial evaluation shows that, although the investments required for Scenario III (906 million dollars in 2030 and 507 million dollars in 2033) represent a significant commitment, the dispatchable nature of concentrated solar power technology, being an ambitious investment, provides relevant systemic advantages. The economic recovery of this technology depends on the expected revenues from participating in energy sales to the system, and therefore, on nodal marginal costs, as well as the operating costs of the power plants involved in economic dispatch. Moreover, by reducing the system's operating costs, price volatility is mitigated, and the competitiveness of the energy matrix is improved.

In summary, the integration of concentrated solar power and renewable generation, complemented by energy storage, constitutes a robust alternative for the energy transition in the BCSIS. This combination not only optimizes system operation by reducing dependence on high-cost and high-emission fossil fuels, but also creates conditions for greater system stability, operational flexibility, and contributes to the reduction of GHG, as well as the consolidation of a pathway toward long-term sustainable decarbonization.

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