Baja California Sur Renewable Integration Study

Carlo Brancucci, Riccardo Bracho,
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National Renewable Energy Laboratory

Produced under direction of the 21st Century Power Partnership by the National Renewable Energy Laboratory (NREL) under ACT-17-30.

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Technical Report
NREL/TP-5D00-72598
November 2018

Contract No. DE-AC36-08GO28308

CLEAN ENERGY MINISTERIAL
Accelerating the Transition to Clean Energy Technologies

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Acknowledgments

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List of Acronyms

CO_2	Carbon dioxide
BCS	Baja California Sur
CENACE	Centro Nacional de Control de Energía
CIFF	Children's Investment Fund Foundation
CRE	Comisión Reguladora de Energía
GHI	Global horizontal irradiance
INEEL	Instituto Nacional de Electricidad y Energías Limpias
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
SENER	Secretaría de Energía

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Executive Summary

The goal of the Baja California Sur (BCS) Renewable Integration Study is to evaluate the potential impacts of increasing penetration levels of wind and solar power on BCS's bulk power system operations using a production cost model that simulates the operation of the power system for the year 2024, which is the year Mexico has set the goal of reaching 35% of total electricity generation from clean energy sources. The study finds the following impacts from integrating increasing penetrations of wind and solar power: displacement of thermal electricity generation, an increase in the cycling of thermal generators (especially fast-starting and fast-ramping diesel power plants), a reduction in total variable operational costs, a reduction in carbon dioxide emissions, and an increase in wind and solar power curtailment. The study outcomes indicate that the islanded power system of BCS in 2024 (without considering the planned subsea cable interconnection to the interconnected national power system) would be able to serve load and meet operational reserve requirements during every hour of the year under different scenarios of increasing utility-scale wind and solar power penetrations.

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Introduction

The goal of the Baja California Sur (BCS) Renewable Integration Study is to evaluate the potential impacts of increasing penetration levels of wind and solar power on BCS's bulk power system operations for the year 2024, which is the year Mexico has set the goal of reaching 35% of total electricity generation clean energy sources. Studying the impact of wind and solar power on power system operations is interesting and challenging because of the variable and uncertain nature of wind and solar resources. BCS is a very interesting and relevant region to study renewable integration impacts because its power system is an electrical island. Most of its electricity is generated by burning expensive imported fossil fuels (oil and diesel), making it the power system in Mexico with the highest variable generation costs and the most polluting. Its electricity consumption is expected to grow significantly, and it has significant renewable energy resource potential in terms of wind power and especially in terms of solar power.

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Methodology

The study is performed using PLEXOS [1], a commercial production cost modeling tool. It is used to develop a unit commitment and economic dispatch model that simulates hourly bulk power system operations of the islanded power system of BCS for an entire year under different renewable generation (wind and solar power) penetration scenarios. A day-ahead simulation is used to consider the impact of day-ahead load, wind, and solar forecast errors on the commitment decisions of the conventional generators with slower startup times and that are therefore committed one day earlier. These commitment decisions are enforced in the real-time simulation that models optimal hourly generation dispatch decisions to meet demand needs (gross demand that includes network losses) while considering operational transmission flow constraints (DC optimal power flow approximation without considering network losses), generators' piecewise linear heat rate curves, ramping and startup constraints, as well as power system reliability-driven operational constraints. The latter include interface limits between the three transmission zones of BCS (Villa Constitución, La Paz, and Los Cabos), a 50% maximum instantaneous renewable energy (wind and solar power) penetration limit, and a dynamic operational reserve requirement that is equal to the greater value between 11% of instantaneous electricity demand and the installed capacity of the largest generator (including the instantaneous generation level of individual wind and solar power plants). Only thermal generators are allowed to provide operational reserves.

The unit commitment and economic dispatch model of the BCS islanded power system was successfully validated against real 2013 annual electricity generation data provided by Mexico's power system operator (Centro National de Control de Energía, CENACE) BCS control center, as shown in Figure 1. The main difference between the model outputs and the real generation data from 2013 is that the model underestimates diesel-fired electricity generation because it simulates optimal operations under normal conditions without considering maintenance schedules. In reality, maintenance of oil-fired generators, as well as contingency and out-of-the-norm events, increases the electricity generation share of the more expensive and faster generators: diesel-fired power plants.

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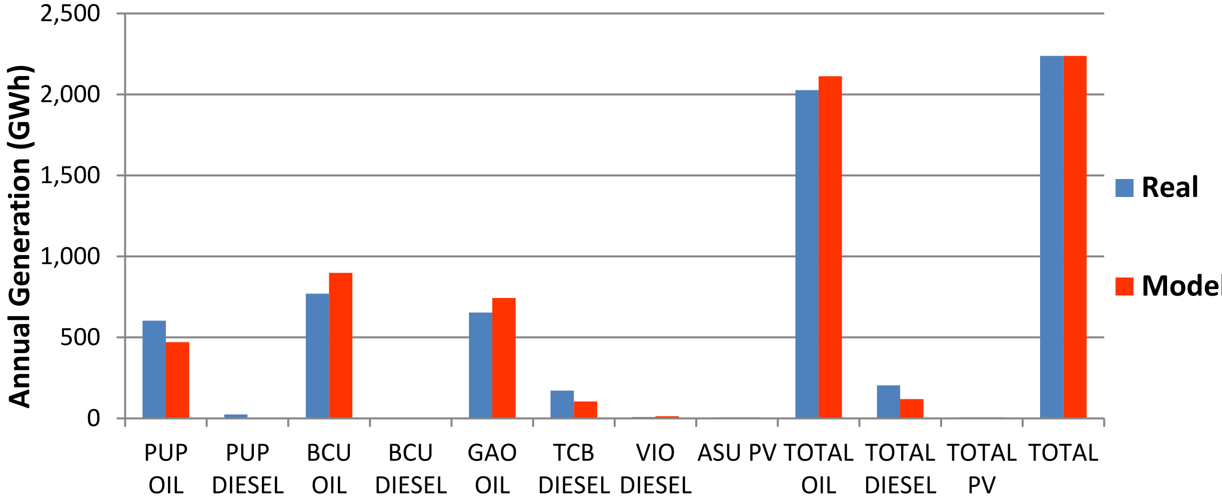

Figure 1. Model validation against 2013 annual electricity generation by generator and fuel type

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Scenarios and Modeling Assumptions

To study the impact of increasing penetration levels of wind and solar power on BCS's bulk power system operations, scenarios of increasing penetration levels of wind and solar power are defined. These scenarios share the same transmission network capacities (115-kV and 230-kV transmission lines and transformers), thermal generation installed capacities (oil and diesel power plants), nodal hourly electricity load, and distributed rooftop solar photovoltaic (PV) installed capacities. The only differences between the scenarios are the installed capacities of utility-scale wind and solar power plants.

The transmission network, the thermal generation, and the electricity load considered in the model represent an approximation of how the BCS power system is expected to look in 2024 based on the two latest official generation and transmission expansion plans published by Mexico's Ministry of Energy (Secretaría de Energía, SENER) (PRODESEN 2016–2030 and 2017–2031) [2], without taking into account any wind and solar developments or the planned subsea transmission line with Mexico's national interconnected power system. Hourly nodal electricity load time series are based on actual 2013 load time series, and different demand growth factors between 2013 and 2024 are applied at each demand node. Installed capacities of distributed rooftop solar PV are based on 2016 estimates and are considered for the larger cities in the three zones.

Figure 2 shows the transmission network as well as the thermal and distributed rooftop solar PV generation assumed in all scenarios. Installed capacities per generation type are shown aggregated by zone, but the model considers individual power plant units interconnected at individual transmission substations. Peak load is also shown aggregated by zone, but the model considers hourly load profiles at the transmission substation level. The peak demand of the entire system is 586 MW. The installed thermal generation capacity is 722 MW (oil: 464 MW; diesel: 258 MW). The oil generators are committed in the day-ahead simulation, whereas the diesel generators are recommitted in the real-time simulation. The following fuel prices ($MXN 2016/BTU) are assumed: 216 for oil and 517 for diesel. The total distributed rooftop solar PV generation capacity is 15 MW (7 MW in Los Cabos, 6 MW in La Paz, 1 MW in Loreto, and 1 MW in Villa Constitución), and it is not dispatchable; it behaves like a negative load. Reliability-driven interface transmission constraints between zones as assumed in the model are also shown.

Transmission network data (including operational capacities and reactance values of transmission lines and transformers), hourly nodal real-time electricity load time-series data, hourly day-ahead regional electricity load forecasts, and thermal generation data (including piecewise linear heat rate curves, upward and downward ramping constraints, and startup costs and times) were provided by CENACE's BCS control center in La Paz.

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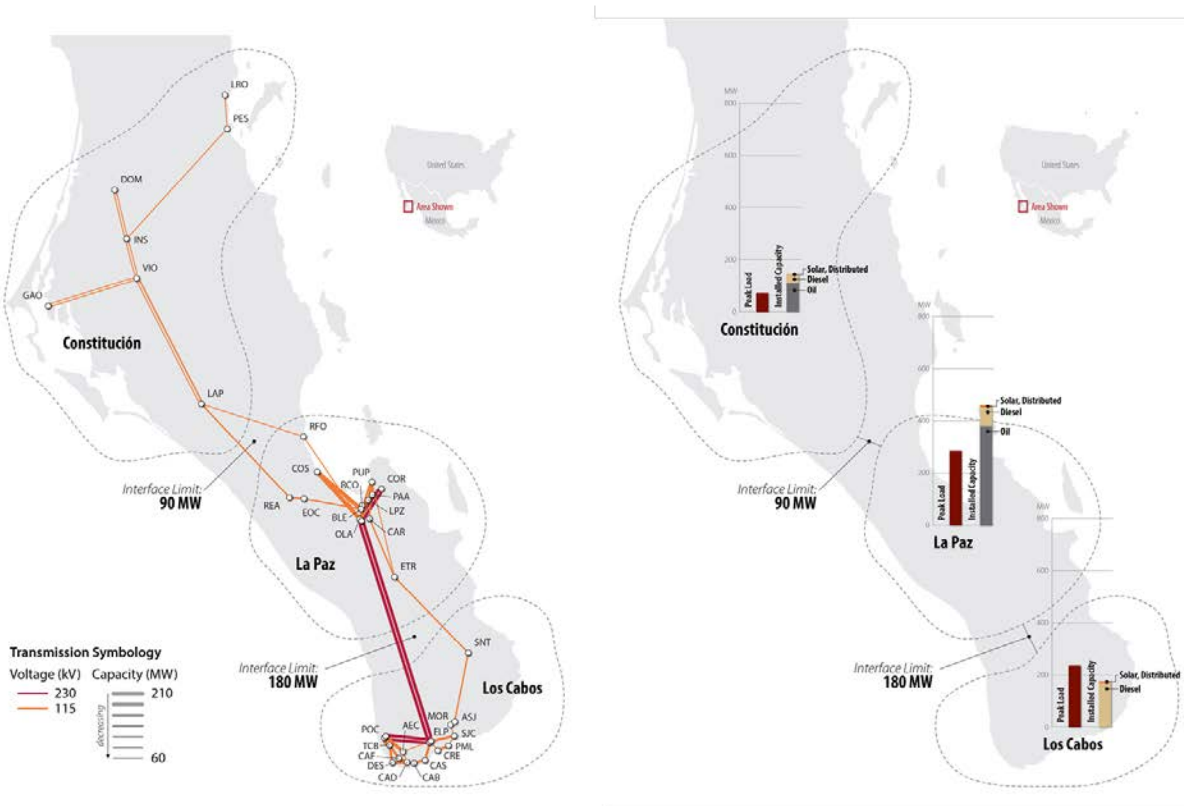

Figure 2. Transmission network and thermal and distributed rooftop solar generation common to all scenarios

To design potential scenarios of increasing penetration levels of wind and solar power, wind and solar resource data sets with high temporal and spatial resolutions that cover the region of BCS were used. The National Solar Radiation Database [3], based on satellite images and a complex physical model, provides solar resource variables for BCS at 4-km by 4-km and 30-minute resolutions. The Wind Integration National Dataset Toolkit [4], based on a numerical weather prediction model, provides wind resource variables for BCS at 2-km by 2-km and 5-minute resolutions. Wind and solar resource time-series data from 2013 were used to match the year to which the load time-series data are based, and they represent the time-synchronous weather impacts on electricity load, wind power, and solar power. Data on the quality of wind and solar resources as well as the distance to major transmission substations were used to create tractable subsets of potential wind and solar power development locations. These subsets exclude locations that are not feasible for wind and solar power developments, such as urban areas, sensitive lands, available build lands, and water bodies. The quality of the wind and solar resources (wind speed at 100 m and global horizontal irradiance [GHI], respectively) excluded lands, and the selected locations of potential developments are shown in Figure 3 and Figure 4.

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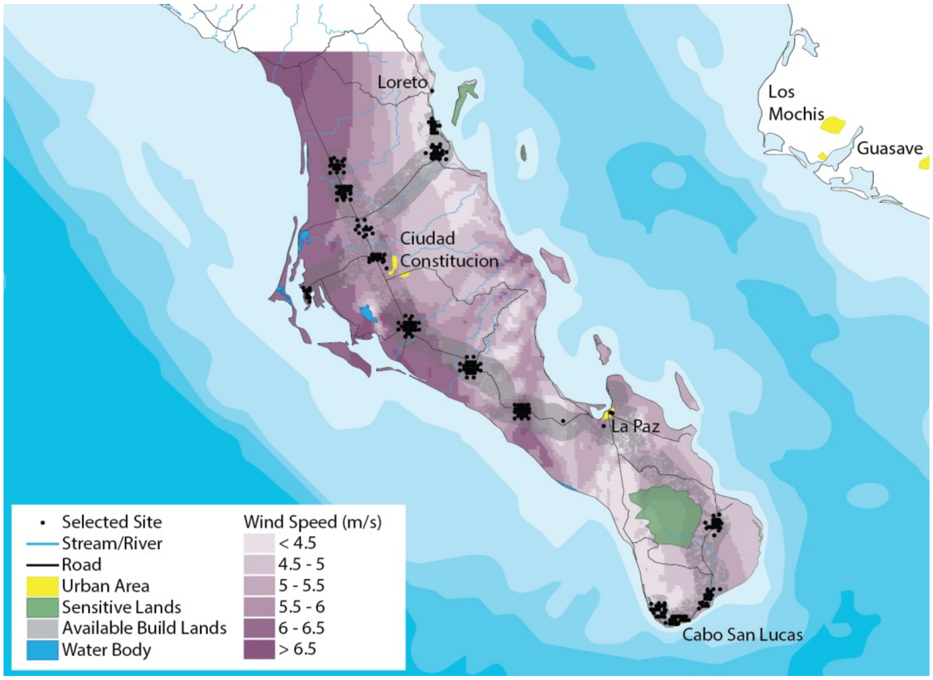

Figure 3. Wind resource and selection of potential wind development locations

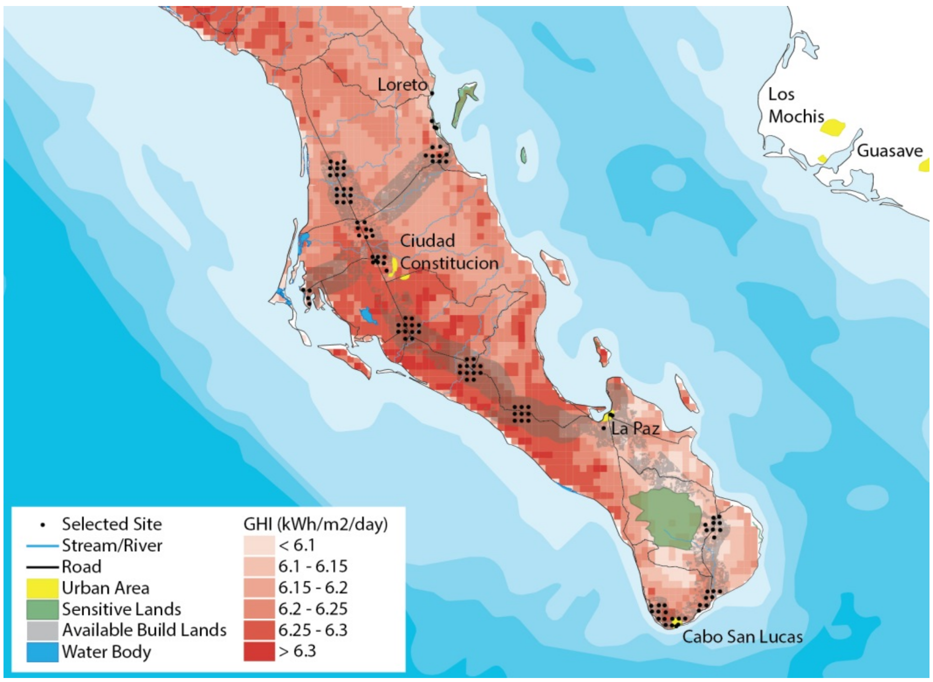

Figure 4. Solar resource and selection of potential solar development locations

The subsets of potential wind and solar power development locations were used by National Renewable Energy Laboratory researchers and CENACE engineers to select a few locations to build six scenarios of increasing penetration levels of wind and solar power. CENACE's knowledge (of the power system, region, existing plans for wind and solar investments, industry interests, and results of the first renewable energy auction) was very valuable when choosing

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specific sites from the wind and solar power subsets. Table 1 shows the aggregated installed capacities for the entire system of BCS for the six scenarios of increasing renewable energy penetration levels. Each scenario builds on the previous one. Table 1 provides renewable generation rates for different penetration definitions. We refer to the definition in the first column throughout the paper: renewable energy penetration as the percentage ratio between annual renewable generation and annual electricity consumption. Table 2 shows the utility-scale wind and solar power installed capacities included in each renewable generation penetration scenario. Figure 5 shows detailed maps of the 9.5% and 32.5% renewable generation penetration scenarios.

Table 1. Renewable Generation Penetration Scenarios (and Installed Wind and Solar Power Capacities)

Renewable Generation Penetration (% Energy)	Installed Utility-Scale Solar Power (MW)	Installed Utility-Scale Wind Power (MW)	Total Installed Renewable Power (MW)	Renewable Generation Penetration (% Installed Capacity)	Renewable Generation Penetration (% Peak Demand)
3.5	60	0	**75**	9.4	12.8
9.5	83	50	**148**	17.0	25.3
15.4	103	100	**218**	23.2	37.2
23.6	168	150	**333**	31.6	56.8
32.5	245	200	**460**	38.9	78.5
40.1	323	250	**588**	44.9	100.3

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Table 2. Utility-Scale Wind and Solar Power Installed Capacities in each Renewable Generation Penetration Scenario

Renewable Generation Penetration Scenario	Wind Power Installed Capacity	Solar Power Installed Capacity
3.5%		60 MW solar in La Paz
9.5%	+50 MW wind in La Paz	+ 23 MW solar in V. Constitución
15.4%	+50 MW wind in Los Cabos	+20 MW solar in Los Cabos
23.6%	+50 MW wind in La Paz	+45 MW solar in V. Constitución +20 MW solar in Los Cabos
32.5%	+50 MW wind in Los Cabos	+50 MW solar in V. Constitución +27 MW solar in Los Cabos
40.1%	+50 MW wind in V. Constitución	+18 MW solar in V. Constitución +60 MW solar in La Paz

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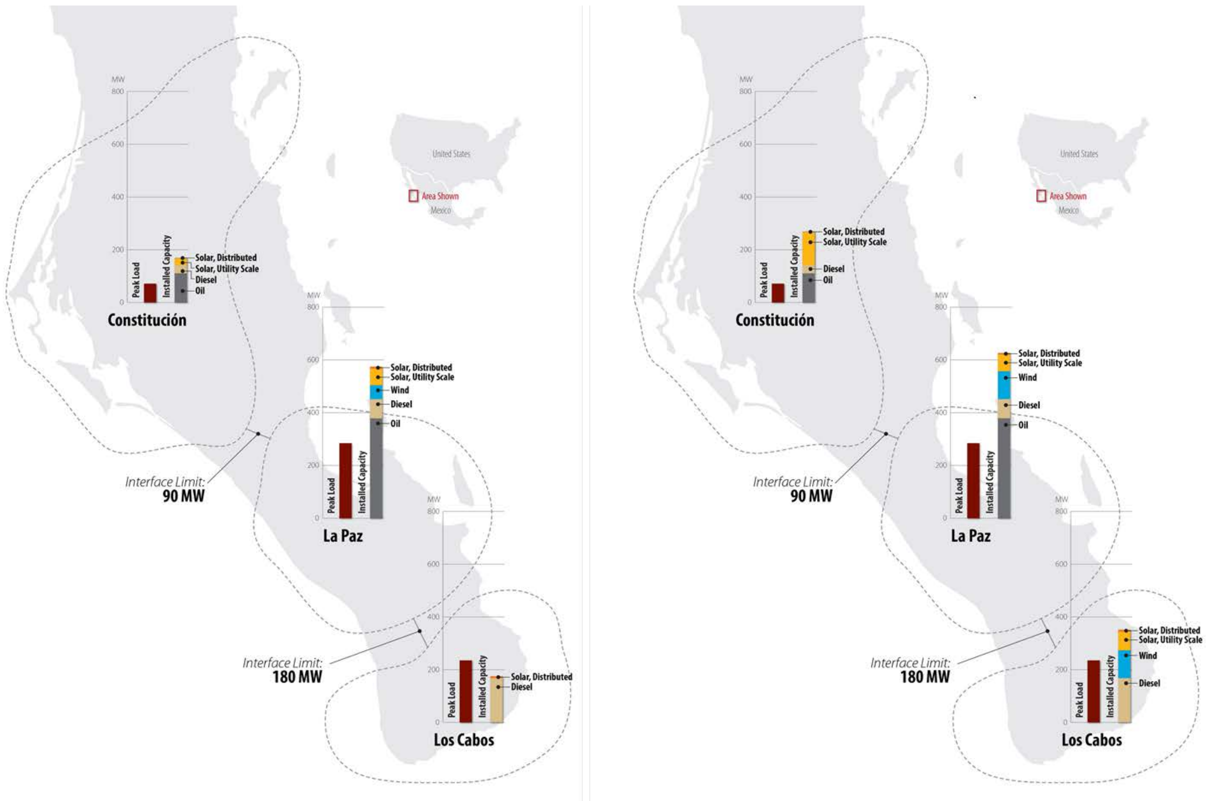

Figure 5. Renewable generation penetration scenarios: 9.5% (left) and 32.5% (right)

Hourly day-ahead wind and solar power forecast time series were statistically created for each power plant to represent realistic distributions of day-ahead wind and solar power forecast errors. The day-ahead forecasts are used in conjunction with the day-ahead load forecasts as inputs to the day-ahead simulation to model the impact of forecast errors on unit commitment decisions.

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Results

To study the potential impacts of increasing penetration levels of wind and solar power, hourly bulk power system operations are simulated for one year for each scenario (seven total: one without utility-scale wind and solar power and six with increasing renewable generation penetration levels) using the production cost model described in the methodology section.

For all scenarios, the BCS power system is able to serve load and meet operational reserve requirements during every hour of the year. Figure 6 shows the impact of increasing renewable energy penetration levels on the annual electricity generation mix of BCS's power system. Wind and solar power displace electricity generation from fossil fuels, oil, and diesel. The overall impact on oil-fired electricity generation is larger because it represents a much larger share of electricity generation. Oil-fired power plants are committed in the day-ahead simulation and have lower variable electricity generation costs (the sum of fuel costs and variable operation-and-maintenance costs). Diesel-fired power plants have higher variable electricity generation costs, but they are used to generate electricity during peak load hours, when the installed capacity of oil-fired power plants is not sufficient to meet load and operational reserve requirements; they are also used to provide generation flexibility with increased ramping capabilities and by being recommitted in the real-time simulation (they can start up in less than one hour). The latter is especially needed in situations with large day-ahead load (as well as wind and solar power) forecast errors.

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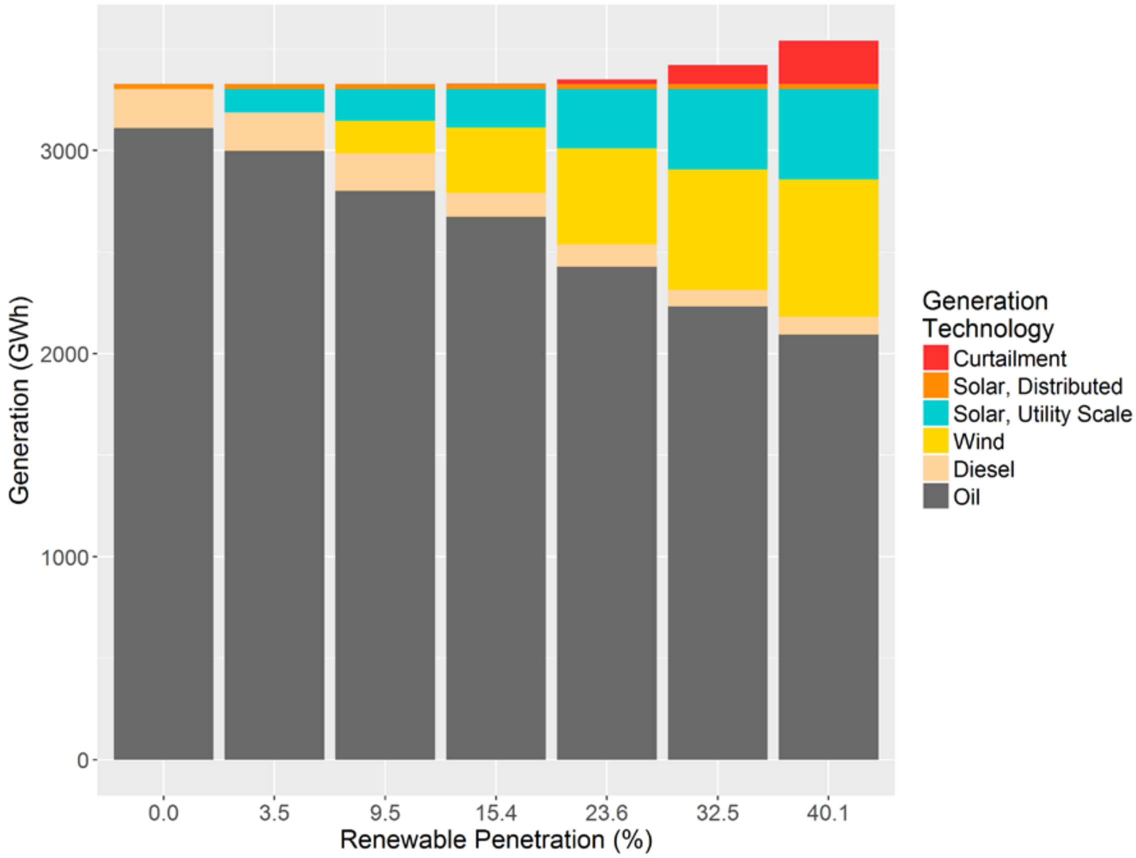

Figure 6. Impact of increasing renewable generation penetration levels on electricity generation mix

Variable and uncertain renewable energy sources displace oil and diesel-fired electricity generation; however, under certain conditions, high penetration levels of wind and solar power can lead to instantaneous increases in diesel-fired electricity generation because of its valuable flexibility. Figure 7 shows the generation dispatch stack of the BCS power system for one week in January for the 9.5% and 15.4% renewable generation penetration scenarios. As shown, during the last evening of the week, the larger downward ramp of solar power in the bottom plot causes an increase in diesel-fired electricity generation. This is mainly caused by the need for fast startup and upward ramping flexibility. The increased startup flexibility needs are also shown in Figure 8. Annual startup costs of thermal electricity generation increase as renewable energy penetration increases and thermal electricity generation decreases. A 32.5% renewable generation penetration (equivalent to 29.7% if we consider curtailment needs) increases the startup costs of the thermal generation by 32.9%.

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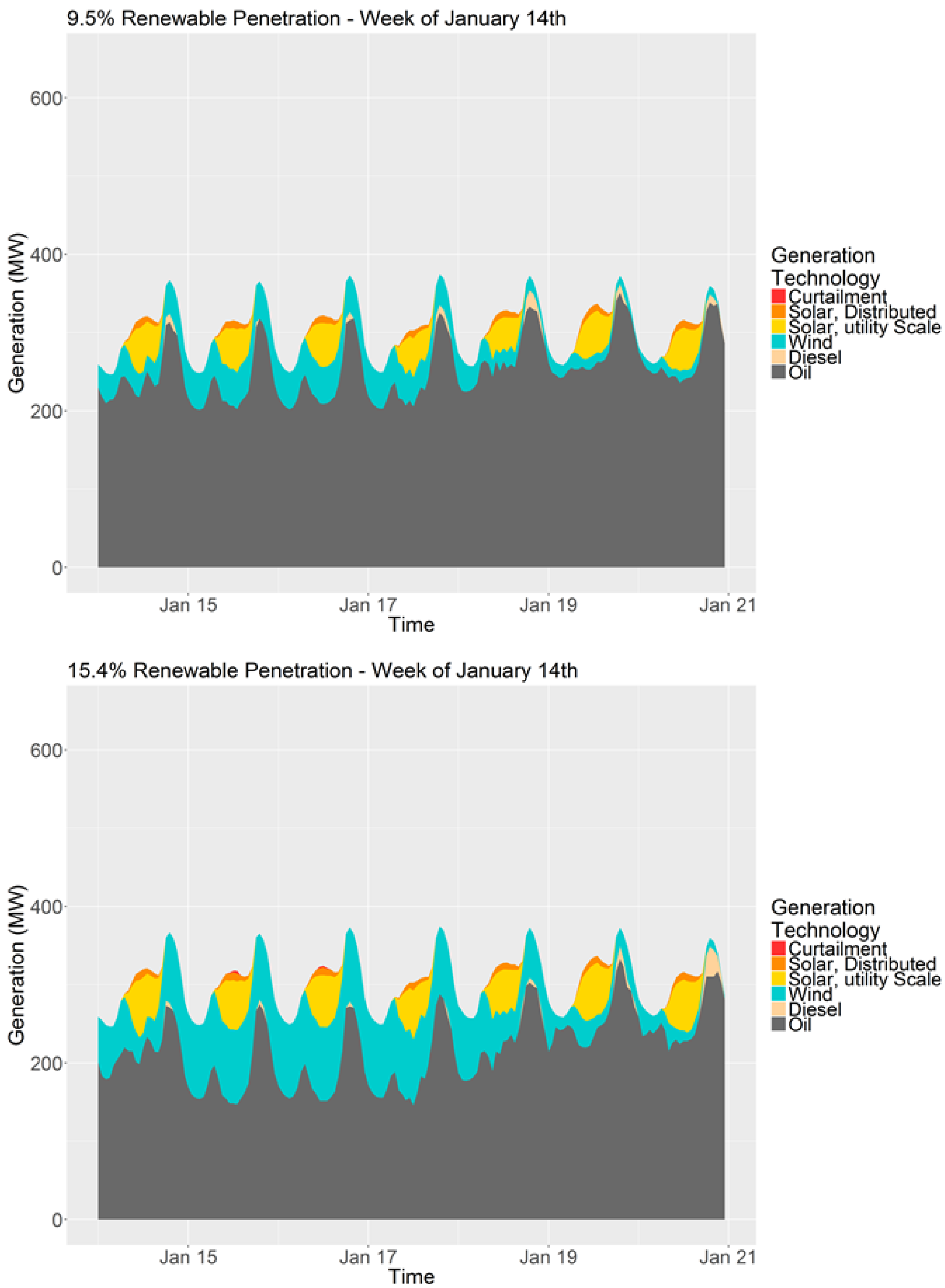

Figure 7. Generation dispatch stack for a week in January: 9.5% and 15.4% renewable generation penetration scenarios

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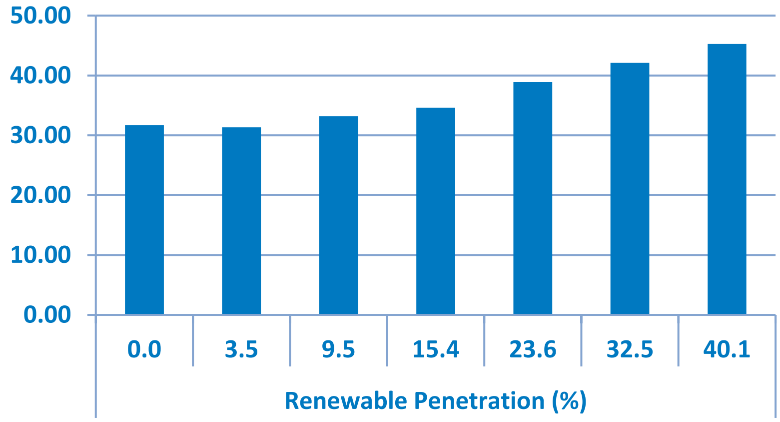

Figure 8. Impact of increasing renewable generation penetration levels on startup costs ($MXN 2016)

Figure 6 and Figure 9 show how increasing renewable energy penetration levels lead to wind and solar power curtailment. Renewable energy curtailment is negligible up to the 23.6% renewable energy penetration scenario, when it reaches 2.7%. For higher penetrations, renewable energy curtailment increases exponentially, up to 8.5% and 16% in the 32.5% and 40.1% renewable generation penetration scenarios, respectively.

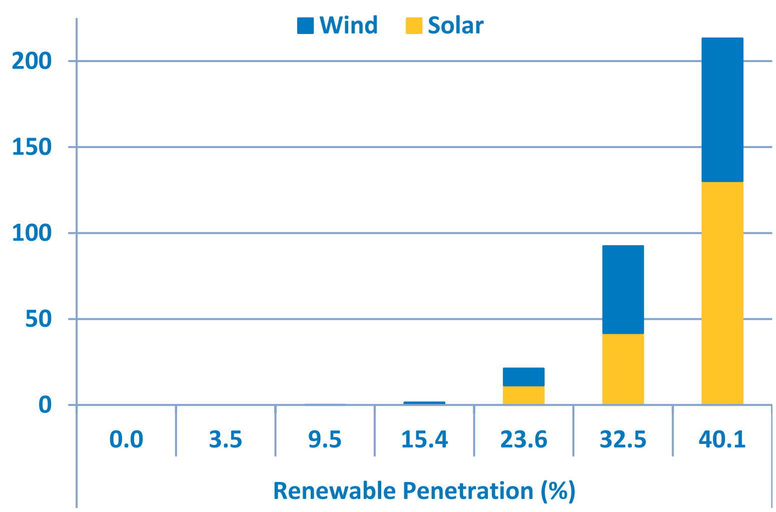

Figure 9. Impact of increasing renewable generation penetration levels on renewable energy curtailment (GWh)

Wind and solar power curtailment is seasonal, and it is mainly caused by the reliability-driven constraint that limits instantaneous renewable energy penetration to 50% of the electricity load. Figure 10 shows the generation dispatch stack of the BCS power system for a week in January and a week in August for the 23.6% renewable generation penetration scenario. As shown, the same installed capacities of wind and solar power lead to no renewable energy curtailment needs when electricity load is high (a week in August) while at the same time leading to very large curtailment needs when the load is low and renewable generation (especially wind in this case) is high (a week in January).

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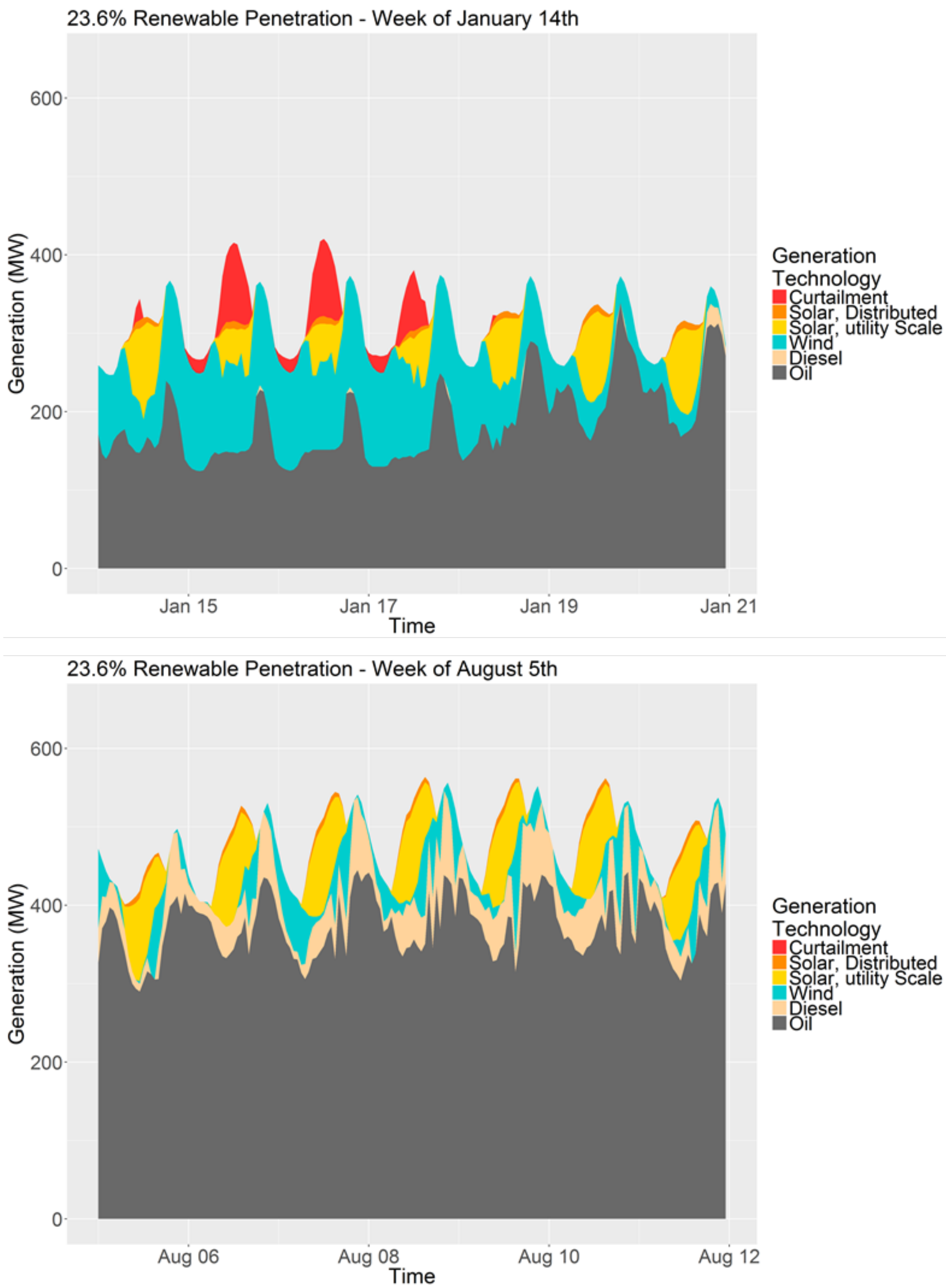

Figure 10. Generation dispatch stack for weeks in January and August: 23.6% renewable generation penetration scenario

Other minor reasons that cause renewable energy curtailment in BCS under the analyzed scenarios include wind and solar day-ahead forecast errors and, in the highest penetration case, transmission congestion. Figure 11 shows the number of hours in the year during which transmission lines and interzone transmission interfaces are congested. A few transmission lines are congested during some hours in the year in the higher renewable generation penetration cases. In the highest penetration scenario, a very large installed capacity of wind and solar power in the zone of Villa Constitución causes congestion during few hours in the year in two lines

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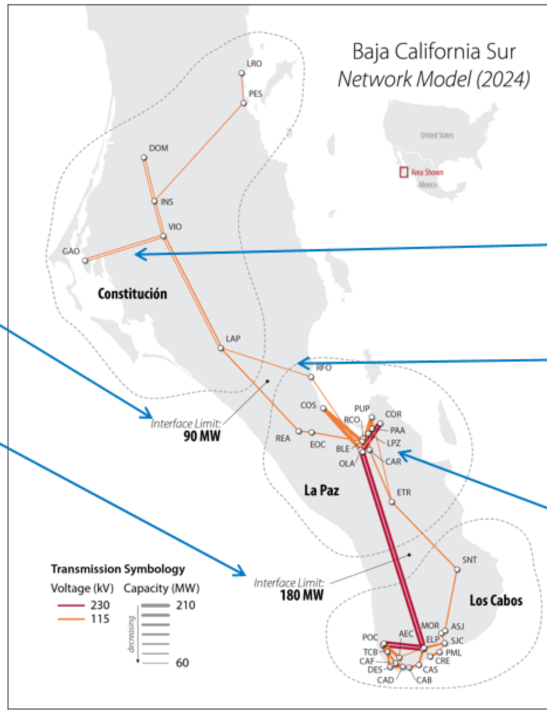
within the zone and during 11.7% of the hours of the year in one of the two lines interconnecting the zones of Villa Constitución and La Paz. In contrast, in a different part of the network, higher renewable generation penetrations reduce network congestion: the congestion of the interzone transmission interface between La Paz and Los Cabos is significantly relieved by the integration of renewable energy sources in Los Cabos.

Interface Constitución – La Paz

RE Pen. (%)	Cong. hours
0.0	0
3.5	0
9.5	0
15.4	0
23.6	67
32.5	659
40.1	295

Interface La Paz – Los Cabos

RE Pen. (%)	Cong. hours
0.0	3,789
3.5	3,807
9.5	3,848
15.4	2,706
23.6	2,490
32.5	1,554
40.1	1,554



2 Lines GAO & VIO 115 kV – 60 MW

RE Pen. (%)	Cong. hours
0.0	0
3.5	0
9.5	0
15.4	0
23.6	0
32.5	0
40.1	57

Line BLE & RCO 115 kV – 60 MW

RE Pen. (%)	Cong. hours
0.0	0
3.5	0
9.5	7
15.4	9
23.6	74
32.5	90
40.1	65

Line RFO & LAP 115 kV – 60 MW

RE Pen. (%)	Cong. hours
0.0	0
3.5	0
9.5	0
15.4	0
23.6	0
32.5	0
40.1	1,028

Figure 11. Impact of increasing renewable generation penetrations on transmission congestion

The integration of renewable energy sources (wind and solar power) in the islanded power system of BCS significantly reduces total variable electricity generation costs (sum of fuel costs, variable operation-and-maintenance costs, and startup costs), as shown in Figure 12. This reduction is mainly caused by the displacement of thermal electricity generation. The increase in startup costs does not have much of an effect because they represent a very small share of the total variable electricity generation costs. With increasing renewable energy penetration levels, the marginal reduction in total variable electricity generation costs is reduced mainly because of the increase in renewable energy curtailment and because more expensive thermal generators are displaced first. For example, a 15.4% renewable energy penetration reduces total variable electricity generation costs by 20.4%, whereas a 40.1% renewable generation penetration (equivalent to 33.7% if we consider curtailment needs) reduces them by 37.9%.

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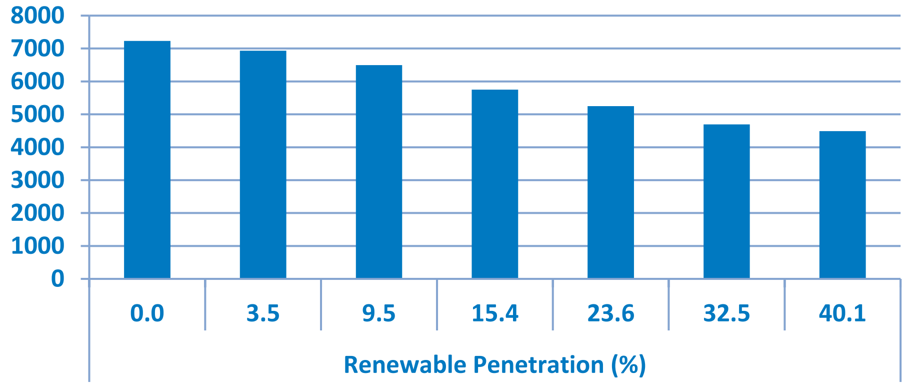

Figure 12. Impact of increasing renewable generation penetration levels on total variable electricity generation costs ($MXN 2016)

Similar to the impact on total variable electricity generation costs, increasing penetration levels of wind and solar power significantly reduce carbon dioxide (CO_2) emissions, as shown in Figure 13. This reduction is caused by the displacement of thermal electricity generation. With increasing renewable energy penetration levels, the marginal reduction in CO_2 emissions is reduced mainly because of the increase in renewable energy curtailment. For example, a 23.6% renewable energy penetration (equivalent to 23.0% if we consider curtailment needs) reduces CO_2 emissions by 17.8%, whereas a 40.1% renewable generation penetration (equivalent to 33.7% if we consider curtailment needs) reduces them by 36.2%.

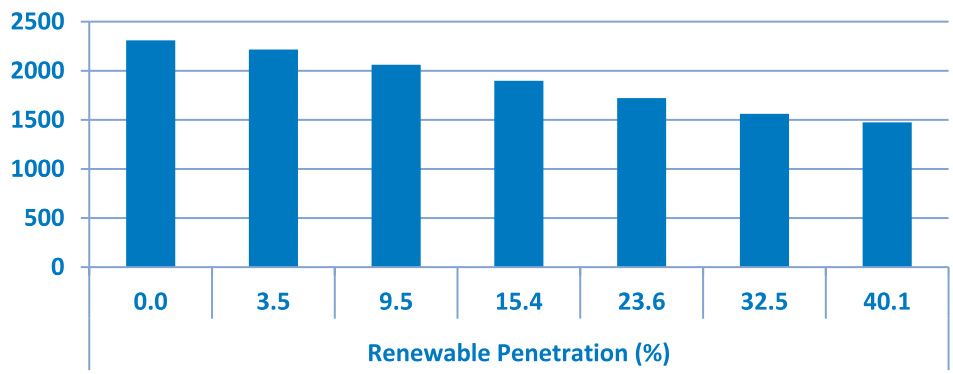

Figure 13. Impact of increasing renewable generation penetration levels on CO_2 emissions (kton)

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Conclusions

The BCS renewable integration study presented in this publication uses a production cost model to evaluate the impacts of increasing penetration levels of wind and solar power on BCS's bulk power system operations. These impacts include, among others: displacement of thermal electricity generation, increase in cycling of thermal generators (especially fast-starting and fast-ramping diesel power plants), reduction in total variable operational costs, reduction in CO_2 emissions, and increase in wind and solar power curtailment.

The study outcomes indicate that the islanded power system of BCS in 2024 (without considering the planned subsea cable interconnection to the interconnected national power system) would be able to serve load and meet operational reserve requirements during every hour of the year under different scenarios of increasing utility-scale wind and solar power penetrations. Simulating bulk power system operations for the 32.5% renewable generation penetration scenario shows that the BCS power system would curtail 8.5% of wind and solar energy, reducing the net renewable generation penetration to 29.7%.

Renewable energy curtailment needs increase exponentially with increasing renewable energy penetrations: with 23.6% wind and solar power penetration, curtailment needs represent only 2.7% of the annual renewable generation; whereas with 40.1% penetration, curtailment needs reach 16%. Once moderate renewable energy penetrations (~30%) are reached, facilitating renewable energy curtailment is vital to the integration of wind and solar power. At these levels, curtailed energy represents a small share of the overall potential renewable electricity generation. Moreover, allowing wind and solar power plants to provide reserves would benefit them as well as the overall system by reducing the variable operational costs of serving load while meeting reserve requirements.

This study does not analyze subhourly operational challenges; however, it considers operational constraints defined by the power system operator (CENACE), such as a maximum 50% instantaneous renewable energy penetration constraint to ensure that the system is operated within reliability limits. A future study running dynamic simulations could be very useful to evaluate how high penetrations of variable and uncertain wind and solar power might affect system reliability after a large disturbance. Moreover, examining system stability and frequency response with high wind and solar penetrations would be very valuable to determine if and when the assumed 50% maximum instantaneous renewable energy penetration constraint is either sufficient or necessary. Further, a detailed analysis of the cost and reliability trade-offs of different operational reserve requirements under different renewable energy penetration scenarios would be very useful to evaluate wind and solar power plants' interconnection requirements, such as the requirement of installing a 15-minute battery storage system with an installed capacity equal to a percentage of the installed capacity of the wind or solar power plant.

A subsea cable interconnection between the BCS power system and the interconnected national power system is expected to be built by 2021 [2], and it will not only reduce electricity generation costs in BCS but also further ease the integration of wind and solar power in the power system of BCS by reducing renewable curtailment needs, among other impacts. Future research could evaluate BCS renewable integration challenges and solutions considering the tie with the national interconnected power system.

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