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Innovative Pathways to Net Zero Emissions: Subnational Strategies for Distributed Solar Deployment to Improve Grid Quality and Reduce Energy Costs in Argentina

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National Renewable Energy Laboratory

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List of Acronyms

APELP	Administración Provincial de Energía de La Pampa
ATB	Annual Technology Baseline
CAMMESA	Compañía Administradora del Mercado Mayorista Eléctrico Sociedad Anónima
DER	distributed energy resource
DPV	distributed solar photovoltaic
NREL	National Renewable Energy Laboratory
PSS®E	Power System Simulator for Engineering
PSCAD	Power Systems Computer Aided Design
PV	photovoltaic
T&D	transmission and distribution
USD	U.S. dollar

Executive Summary

The Net Zero World Initiative is a collaborative effort led by the U.S. Department of Energy involving 9 U.S. government agencies, 10 U.S. national laboratories, 8 member countries, and other international partners. The primary goal of the initiative is to accelerate the decarbonization of energy systems and ensure a smooth energy transition, helping countries enhance their climate goals by developing and implementing technical and investment strategies for achieving net-zero emissions. The Net Zero World Initiative joins forces with international partners to accelerate the transition to a clean and secure energy system in a worldwide effort to build a net-zero world.

Through Net Zero World, the National Renewable Energy Laboratory (NREL), the National Energy Secretariat of Argentina, La Pampa's Energy and Mining Secretariat, PAMPetrol, and the Administración Provincial de Energía de La Pampa (APELP) conducted an integrated analysis of the power system of the La Pampa province in Argentina. The study assessed the impact that solar and battery energy storage systems could have on the regional grid's reliability and electricity costs, providing insights into long-term decarbonization strategies across Argentina. Both bulk and distributed energy resources (DERs) were considered in the analysis (Jain et al. 2019; U.S. Department Of Energy 2002).[1] While DERs can include various electric power sources like wind or diesel, in this case study, they refer specifically to distributed solar photovoltaic (DPV) and lithium-ion battery energy storage systems. Researchers, in this study, evaluated the voltage regulation capabilities of DERs for the distribution system as well as their potential cost benefits. For simplicity, the terms DER and DPV will be used interchangeably in this report to denote both small- and utility-scale photovoltaic (PV) systems, respectively.

The analysis demonstrated that the strategic deployment of DERs is expected not only to help with decarbonization efforts, but also to bolster grid resiliency, reduce line losses, and improve voltage regulation while lowering electricity costs (Figure ES- 1). These findings signal the promising local social and economic benefits that distributed renewable energy systems can bring to rural regions, providing a foundation for long-term local sustainability. The prospect for DERs to lower electricity costs for residents is particularly relevant as the Argentine government seeks to reduce energy subsidies (Argentina 2024). This case study shows how local utilities like APELP can achieve greater voltage regulation at a lower cost compared to legacy methods, resulting in more affordable and stable electricity procurement and delivery.

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[1] DERs refer to smaller-scale electric power sources that connect to the electric distribution system. For more information on DERs and their history, visit https://www.nrel.gov/docs/fy20osti/72714.pdf or https://www.nrel.gov/docs/fy02osti/31570.pdf

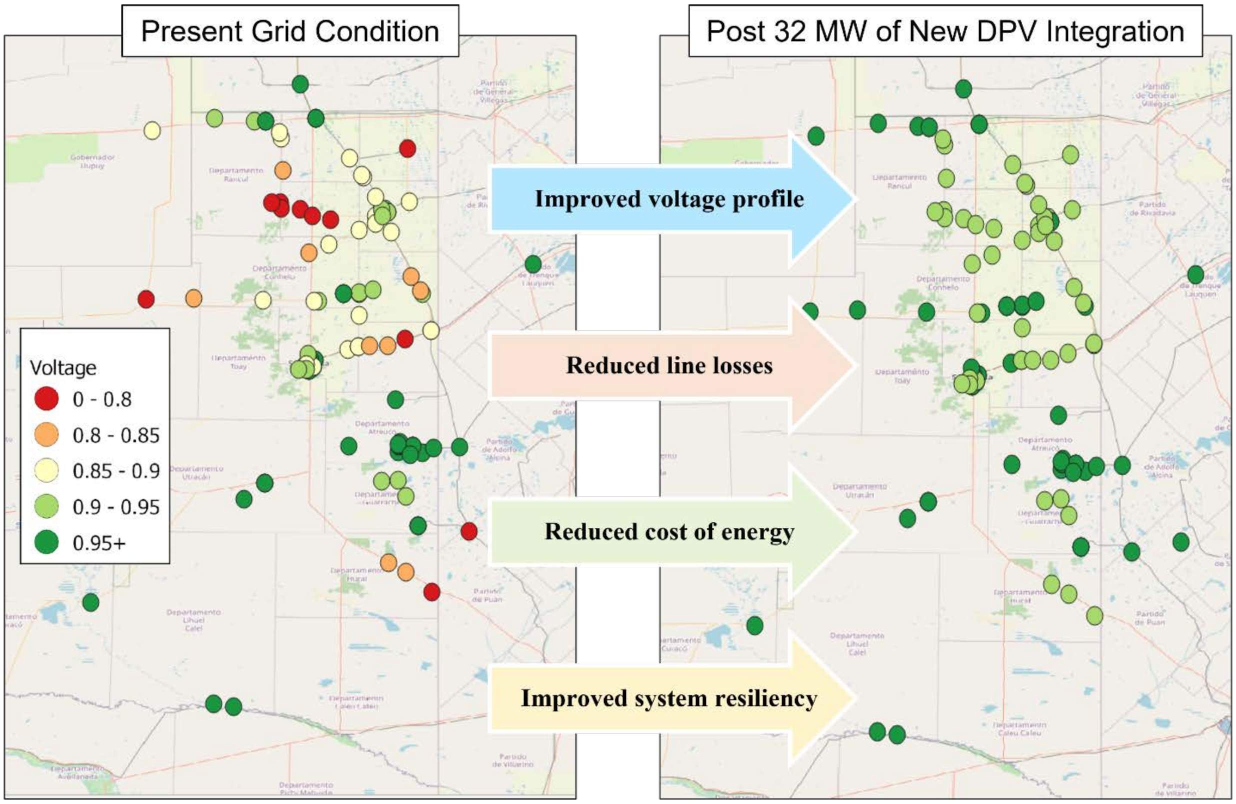

Figure ES- 1. Modeled improvements in the voltage regulation of La Pampa's distribution network with the strategic deployment of DERs

Here, the voltages at various points in the network are shown where >0.9 per unit represents the desired voltage. As shown in the figure, multiple points in the present distribution network experience low voltages; however, the deployment of DERs at strategic locations can alleviate these voltage issues.

Additionally, this case study indicates that there are significant reliability and economic opportunity costs associated with not providing actionable decision support for local distribution grid upgrades through analyses like this one. This is because installing DPV systems at any grid location does not always lead to improved voltage regulation and instead should be determined through strategic assessments to ensure their effective integration into the grid. Our report offers a replicable framework for similar studies across other Argentine provinces, which could inform a national grid reliability plan and enable regional coordination for DER implementation. Such coordination will play a key role in helping to support a nationwide clean energy transition as Argentina increases its share of renewable energy deployment. Follow-up studies will be essential to analyzing national transmission needs and exploring how provinces can integrate distributed renewable generation with bulk power systems, enhancing both local and national grid reliability. By coordinating subnational energy plans with national strategies, Argentina can secure a resilient clean energy future, leveraging the substantial renewable resources available across its provinces.

Table of Contents

List of Figures

List of Tables

1 Background

The complexity of global energy challenges is rooted in the distinct nature of each region, calling for innovative approaches to accelerate the path to a net-zero world. Argentina faces significant energy challenges on many fronts, including an aging infrastructure, a heavy reliance on natural gas generation, and dispersed concentrations of demand (Campos Do Prado, Logan, and Flores-Espino 2019).[2] Nowhere are these dynamics more apparent than within the province of La Pampa. Located in central Argentina, La Pampa spans 143,440 km^2, representing 6% of the nation's total land area. La Pampa, however, is home to less than 1% of Argentina's total population, making it one the most sparsely populated provinces in the country with the second-lowest population density (La Pampa Government 2021). Most of La Pampa's inhabitants reside in the region's two major cities: General Pico and Santa Rosa, the province's capital, but there are urban clusters scattered throughout the province. La Pampa's low population density requires long distribution lines, leading to significant voltage regulation issues that make it difficult to provide reliable electricity service across long distances. These issues need targeted solutions.

Distributed energy resources (DERs), including distributed photovoltaic (DPV) systems, are one solution that La Pampa could pursue to raise voltage levels at locations where the voltage drops by injecting real power into the grid in or near these locations. Real power is the electrical energy consumed by devices to perform real work, such as providing light through a light bulb or mechanical energy through an electric motor. Reactive power is the energy that flows back and forth between the source and the end user. By supplying power closer to the point of use, DERs can increase the local current flowing through the line, counteracting the voltage drops to maintain voltage levels. Even if DPV systems are unable to inject real power due to cloud cover or night conditions, their inverters can still support voltage regulation by injecting and/or absorbing reactive power into/from the grid.[3] By virtue of these capabilities, DERs can reduce the need for costly voltage regulation equipment like capacitor banks and tap-changing transformers. Given that DPV can also supply electricity to customers at potentially lower costs, while helping to decarbonize electricity generation, there are several value streams associated with these assets. For these reasons, provinces like La Pampa have significant potential to integrate renewable resources into their regional power systems and export clean energy generation to the national grid, which could support country-wide decarbonization strategies.

La Pampa has already established an energy transition plan focused on developing its renewable energy resources, including building solar stations, distributed generation, and small photovoltaic systems for general uses (boating, pumping, etc.). The plan also prioritizes energy efficiency by replacing public lighting with LEDs (Figure 1). These technologies will be central to the province's strategy to address local energy challenges and broader national climate goals. Provincial energy transformation efforts like these are critical to supporting Argentina's national

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[3] Reactive power is the power dissipated by reactive components like capacitances and inductances. It is essential for moving active power through the T&D system to the customer end. Reactive power is used to regulate voltage in an electrical system by managing the generation or consumption of reactive power. Reactive power needs to be provided closer to the loads than real power because it does not travel well through the grid.

climate goals, as they help reduce carbon emissions, improve energy resilience, and promote sustainable energy development at the regional level.

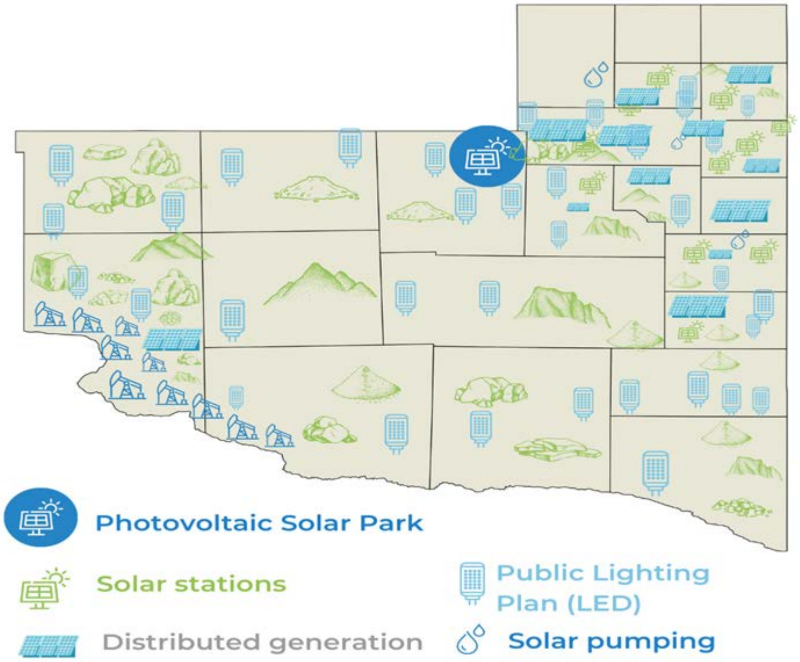

Figure 1. Distribution of net zero projects in La Pampa

Source: La Pampa Energy Transition Plan

1.1 Summary of La Pampa's Electric Grid

Administración Provincial de Energía de La Pampa (APELP) serves as the primary transmission and distribution (T&D) provider in La Pampa, ensuring a reliable electricity supply to over 353,000 residents. APELP accomplishes this by maintaining and operating 14 high-voltage transmission lines at 132 kV, which feed into substations. These substations then deliver power to customers through 33-kV and 13.2-kV distribution feeders in non-concessioned areas and through 13.2 kV feeders to 29 electric cooperatives in concessioned areas. Presently, La Pampa receives the bulk of its power from the national grid from four transmission interconnections at 500 kV and 132 kV. These transmission interconnections are in the southwest to northeast ends of APELP's service territory, with the majority of power (~80% of total load) being fed by a single connection to the national grid near the main load center of General Pico and Santa Rosa.

The national grid is overseen by the Compañía Administradora del Mercado Mayorista Eléctrico Sociedad Anónima (CAMMESA), which manages Argentina's wholesale electricity market and coordinates the efficient dispatch of power throughout the country. Apart from procuring power from the national grid, APELP, the La Pampa Energy Secretariat, and PAMPetrol have embarked on their decarbonization pathway with a recent installation of a 7.2-MW solar photovoltaic (PV) plant in Victorica. The anticipated benefits of the solar PV farm, owned and operated by PAMPetrol, will be detailed later in this report.

1.1.1 Challenges in the Grid Operation

As noted earlier, the distribution lines in La Pampa are long because of the disbursed nature of the population. The longer the distribution line, the greater the power losses along the line, because the electricity is lost to heat from the electrical resistance of the line. Long distribution lines also lead to drops in voltage levels when the power moves farther away from the transmission nodes because the transmission grid acts as the backbone to the power supply and maintains desired voltage levels at various distribution feeders. This raises the issue of maintaining appropriate voltage at various 33-kV and 13.2-kV buses. Buses, also known as busbars, are groups of conductors within a substation that facilitate the transfer of electricity from incoming feeders to outgoing feeders. In this case, they connect APELP's high-voltage 132-kV transmission lines to a transformer, which steps down the electricity's voltage to 33 kV or 13.2 kV for distribution (Atwa 2019).

In a conventional grid operation, it is crucial to supply power to all consumers at a reasonable voltage level (±5% of the buses' nominal voltages). During peak load conditions, when customer demand is at its highest, APELP has reported extreme voltage drops in their distribution grid (33 kV) that can affect end users. These voltage drops, if they extend beyond 20% of the buses' nominal values, can lead to a loss of load, impacting the health of various grid components. APELP has identified voltage regulation and grid resiliency as the key issues to be addressed in the near future.[4]

Furthermore, the national grid, served by CAMMESA's generation mix, relies mostly on natural gas and traditional thermal generators, which in the past has left the country vulnerable to price spikes from fuel shortages.[5] APEPL's current power prices from CAMMESA are fixed under a power purchase agreement, and at the time of the analysis, the price APELP paid for power was 45 USD per MWh. However, with the recent drastic reduction in energy subsidies, APELP has experienced a 55% increase in its power tariff, where electricity costs approximately 70 USD per MWh now to procure from CAMMESA. This case study examined both CAMMESA price points to assess their respective economic impact on the potential energy cost savings from local solar PV generation.

With the dual challenges of voltage regulation and anticipated rising costs, APELP partnered with Net Zero World to conduct an integrated analysis that would assess how DERs like solar PV could provide more cost-effective solutions while addressing voltage regulation issues. Argentina's renewable energy potential is significant, with strong wind capacity in the south toward Tierra del Fuego and substantial solar resource throughout the country, particularly in the northwest as shown in Figure 2 (NREL, n.d.-b). La Pampa's provincial government has already expressed its commitment to boosting the region's renewable energy production and becoming self-sufficient, positioning itself as a leader in sustainable energy development in Argentina.

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[4] Here, voltage regulation describes a grid's ability to maintain sufficient voltage levels across all its distribution feeders, while grid resiliency refers to a power system's ability to recover to normal operations following faults and disturbances (Kundur and Malik 2022).

[5] For a detailed analysis of Argentina's energy mix, refer to the IRENA and Enel Foundation report on Energy Transition Pathways (2023). Argentina remains a net importer of natural gas, which can create economic and energy market challenges during supply shortages. Additional information on Argentina's natural gas dependency is available from the International Energy Agency (IEA).

Under the Energy Deployment Regime, also known as Law 3285, La Pampa plans to construct three solar PV farms, one of which has already been built in Victorica (Sarmiento 2022). The other solar PV farms will be built in phases near General Pico and Macachín, totaling 55 MW of additional renewable power by 2031. In this way, APELP is ideally positioned to construct distributed solar PV systems along its distribution network. Not only would this reduce APELP's reliance on CAMMESA for power supply and move La Pampa closer to renewable self-generation, but it could also improve the regional grid's voltage regulation.

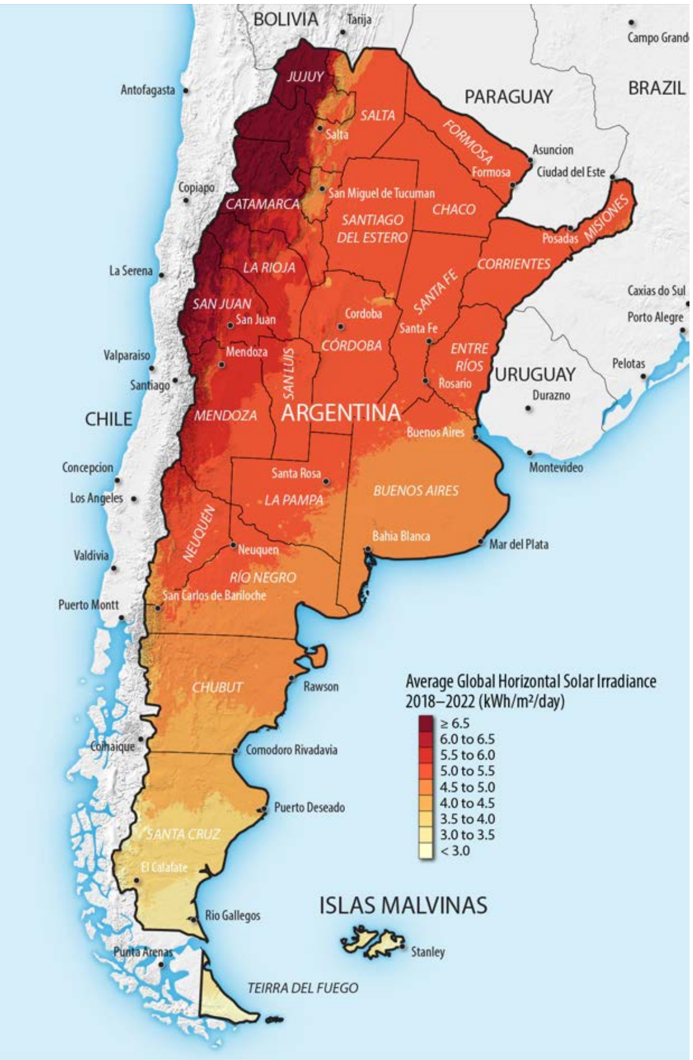

Figure 2. Solar resource potential (average global horizontal solar irradiance) in Argentina

Source: NSRDB (2024)

2 Approach

To examine these objectives in an integrated fashion, the National Renewable Energy Laboratory (NREL) designed a study that would: first, evaluate the viability of DPV as a solution to APELP's voltage regulation challenges and, second, evaluate to what extent generating power locally with PV could be more cost effective than procuring power from CAMMESA. The assessment of the viability for DPV to address voltage regulation was a power flow modeling exercise that identified points in APELP's distribution network that are the most susceptible to voltage drops during peak load. The same model was used to determine how much DPV would be needed to address voltage regulation challenges. The results of this study were incorporated into a techno-economic (capacity expansion) study that looked at the cost-competitiveness of local solar development and battery energy storage systems compared to continuing imports of electricity from CAMMESA from the national grid. This integrated approach effectively combined technical feasibility considerations with economic assessments to provide a comprehensive understanding of the benefits that DPV could provide APELP in achieving grid reliability and sustainability targets.

Net Zero World deployed three modeling tools—Power System Simulator for Engineering (PSS®E), Power Systems Computer Aided Design (PSCAD), and Engage™—to analyze the impacts that DERs could have on La Pampa's power system. The models were shared with APELP to support ongoing study and to prepare for future DER integration. Each of the modeling tools performed different functions to analyze different types of system impact, though their results often informed decisions about similar system parameters. This process provided opportunities to interpret the analyses in an integrated fashion and use the outputs of one model to inform analysis with the other. The integrated modeling approach was refined with input from APELP to ensure alignment with La Pampa's regional conditions, system priorities, and project feasibility.[6]

2.1 Power Flow Analysis

Using the PSS®E software, NREL first developed a steady-state power flow model to analyze the viability of various load and generation conditions and their effects on voltage regulation (Siemens 2024).[7] In PSS®E, NREL analyzed peak demand conditions to represent the worst-case scenario for voltage regulation and line losses. An initial assessment also found that the 33-kV

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[6] APELP provided Net Zero World with data from their Electrical Transient Analyzer Program (ETAP) software, which captured important technical characteristics of La Pampa's T&D network. In addition, APELP provided substation locations and a load profile of the system's total demand at a 15-minute resolution for an entire year. The load profile provided by APELP reflected the entire T&D network as a single demand curve, without differentiating between individual substations, where demand profiles could vary significantly. To account for this, NREL modeled the same demand profile at all substations but adjusted each one by a scale factor to represent the substation's share of total system demand. Based on the annual load data provided by APE from 2022, La Pampa's average electrical load was 150 MW, increasing to 230 MW during the system's annual peak in the summer.

[7] A steady-state model refers to studying how electricity flows across the grid under normal conditions, creating a snapshot of the power flow. This contrasts with a dynamic stability model, which examines how the system reacts over time to disturbances from its steady state. The steady-state approach is valuable for understanding the system's performance under typical operating conditions and identifying potential issues when the system is in a steady, unchanging state. PSS®E is a commercial tool widely used to simulate and analyze electrical grids, assessing both steady-state and dynamic conditions of power systems, from small to very large grid models.

and 13.2-kV feeders downstream from the 132-kV transmission interconnections maintained voltage levels within acceptable ranges; however, feeders located farther away from the transmission grid experienced more significant voltage drops during peak demand. Table 1 summarizes the percentage of 33-kV and 13.2-kV buses that underwent voltage drops below their per-unit (pu) threshold value. The voltage levels of the buses are normalized to account for both 33-kV and 13.2-kV feeders in APELP's distribution network, where a value of 1 pu represents the rated voltage level per unit.[8] As shown in Table 1, 71% of the distribution grid violated its voltage regulation limits by over 5% of its nominal value during peak load and will require reinforcement for reliable operations.

Table 1. Normalized Bus Voltages for Peak Load Scenario

Voltage Threshold	<0.95 pu	<0.9 pu	<0.85 pu	<0.8 pu
Percentage of Buses With Voltage Levels Below Their Threshold Value (represented pu)	71%	46%	21%	12%

For this analysis, the buses that experienced voltage drops below 90% (0.9 pu) of their rated voltage were clustered into smaller groups based on their electrical proximity to each other. The result of the close electrical proximity of members of a group is that any reinforcement aimed at improving the voltage profile of one bus will affect all the buses within its group in a similar way. NREL created five geographical clusters to prioritize areas for DER installation, as depicted in (Figure 3). These were provided to the techno-economic model to inform the buildout of new solar PV generation.

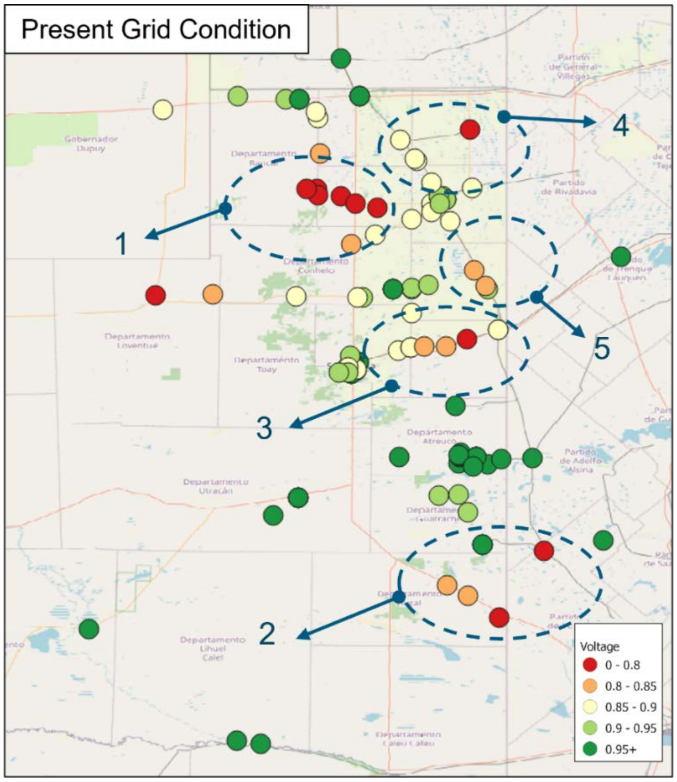

Figure 3. Map of distribution network during peak demand, highlighting normalized voltage levels at different buses

Buses below 0.9 of their normalized voltage level have been clustered based on their electrical proximity and sensitivity.

The second model NREL developed was in the PSCAD software tool, which captures the electromagnetic transient dynamics of a power system. Electromagnetic transient models are necessary for analyzing the dynamic response of a power system to disturbances, including possible oscillations,[9] fault conditions, and instabilities in a grid (Wang 2021). As Argentina expands its renewable energy

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[8] For example, if a bus had the rated voltage of 33 kV but the steady state analysis showed the bus voltage dropped to 28 kV, its normalized voltage value would be (28 ÷ 33 = 0.848) less than 0.85 pu.

[9] Oscillations refer to changes in the alternating current (AC) flow, which can cause different system components like generators to sway between different operating states. Oscillations often occur when there has been a system disturbance like a fault and can lead to system failure if they are not controlled.

capacity, the share of inverter-based resources—such as wind and solar PV—will grow in the generation mix.[10] These inverter-based resources introduce complex and fast dynamics to grid operations, which will require detailed dynamic stability modeling and simulations to evaluate their impact on grid reliability. Even though NREL focused its power flow analysis on the steady-state model and did not use the PSCAD model beyond an example preliminary fault assessment (Next Steps), both the PSS®E and PSCAD models were developed for APELP to conduct future dynamic stability studies.[11]

2.2 Techno-Economic Analysis

For the techno-economic analysis, NREL used Engage, a free-to-use capacity expansion modeling web application developed and web-hosted by the lab. Capacity expansion models simulate investment into new generation, transmission, and storage technologies, given assumptions about future demand, fuel and resource prices, technology costs and performance, and policies and regulations (Boyd 2015). Engage performs least-cost optimizations of the selection, capacities, and dispatches of different generation, transmission, and storage technologies to meet demand, adhering to technical, cost, and sociopolitical constraints set by the modeler (NREL, n.d.-a).

NREL built an Engage model to simulate La Pampa's generation and transmission system[12], starting with a baseline model that included the 7.2-MW solar PV farm in Victorica.[13] The model incorporated interconnection points to the national grid to represent CAMMESA power, assuming an infinite supply of electricity, limited only by the carrying capacities of the downstream 132-kV transmission lines. Power costs from the national grid were initially set at 45 USD per MWh, which was the price at the beginning of the analysis. However, with the recent 55% increase, they were adjusted to 70 USD per MWh to reflect the current cost of the CAMMESA tariff. In the model, both scenarios were run to assess the cost-benefit with and without subsidies.

APELP's existing tariff with CAMMESA limits how much power it can export to the national grid, capping exports to a small percentage of APELP's served demand. The province, however, retains the flexibility to establish power purchase agreements with CAMMESA. For this case study, NREL explored scenarios both with and without export capabilities. In scenarios allowing

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[10] While hydropower is a major source of renewable energy, it relies on turbine based synchronous generators to directly produce AC power synchronized with the grid and hence do not need inverters to converter DC/asynchronous power to synchronized AC power.

[11] NREL validated both models against the known operating parameters of the existing grid and fine-tuned them through regular discussions with APELP engineers to ensure accurate representation of La Pampa's electric grid.

[12] Configured as a capacity expansion model for La Pampa, Engage focused on the transmission system down to the 132 kV level to ensure computational feasibility while accounting for numerous time intervals and variables in the analysis. The 132 kV transmission lines were configured to match the lengths, carrying capacities, and pre-calculated average carrying efficiencies. Projected demand was aggregated at the transmission substation level.

[13] To generate the solar production profiles for existing, planned, and new single-axis tracking solar PV systems for the Engage model, NREL used the PVWatts® Calculator—a solar technical modeling tool that generates location-specific solar PV production profiles based on historical solar irradiation data. For the Victorica solar PV farm, the timeseries was scaled such that the PVWatts profile total annual production matched the reported annual production of the Victorica PV farm. For more information on the PVWatts Calculator, visit https://pvwatts.nrel.gov/.

export, NREL assumed there would be no barriers to exporting excess solar PV production and that the national grid would be able to absorb all the exported generation. When export was permitted, NREL postulated that any renewable generation exported would be remunerated at 20 USD per MWh when CAMMESA power prices were 45 USD per MWh and at 35 USD per MWh when CAMMESA power prices were 70 USD per MWh, respectively.

With feedback from APELP, NREL developed four scenarios that explored the different speeds at which solar PV could be reasonably built in La Pampa, which informed how aggressively the province would need to develop additional solar to become net-zero by 2050. Table 2 summarizes the scenarios explored for their economic feasibility. For all scenarios, the model enabled the construction of lithium-ion batteries, if cost-competitive. In addition to solar exports, NREL performed a sensitivity analysis across all scenarios to examine how asset buildout would change with current or increased CAMMESA power prices.

Table 2. Scenario Formulation for Techno-Economic Analysis

Scenario	Description
Base	Investigated the economics of DPV if APELP only built the currently planned solar PV systems through 2031. This would be an additional 55 MW of solar PV, or 62.2 MW total, including the existing Victorica solar PV farm.
Conservative	Analyzed the economics of APELP building the planned 55 MW of DPV through 2031 and new solar PV being developed at a maximum rate of 9 MW per year after 2031, if cost effective.[14]
Ambitious (Net-Zero)	Examined the economics of APELP building the planned 55 MW of DPV through 2031 with new solar PV being developed on an aggressive schedule with the requirement that La Pampa be net-zero on an annual basis by 2050.[15] During all modeling years, APELP could only export as much solar PV generation as it imported from the grid at night to meet net-zero requirements. NREL exclusively ran this scenario with export capabilities.
Cost-Optimal	Explored the economics of APELP building the planned 55 MW of DPV through 2031 with no constraints on the rate of development.

NREL ran 1-year simulations of the model for each scenario every 5 years, starting in 2025 and ending in 2050, assessing how demand growth and technology costs would influence the constrained cost-optimal plant capacities.[16] To determine the capital and investment costs of building a new single-axis tracking solar PV system in Argentina, NREL referenced the construction costs of the Victorica solar PV farm, which were approximately 1,134.53 USD per

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[14] A 9-MW-per-year development rate was chosen for the Conservative scenario as it represented the average construction rate of La Pampa's planned solar PV farms (55 MW in 6 years).

[15] Until 2030, the Engage model imposed no minimum requirement for La Pampa's demand to be met through in-province generation. However, in 2030, NREL adjusted the model to mandate that 30% of demand be satisfied through solar development on an annual basis, increasing to 50% in 2035, 75% by 2045, and 100% by 2050. NREL did not run the model without enabling exports, because achieving net-zero targets without exports would necessitate substantial, cost-prohibitive investments in large-scale solar PV and battery storage systems to meet demand at every timestep.

[16] In consultation with APELP, NREL assumed that electricity consumption in the province would grow at an annual rate of approximately 3.27% and that the interest rate on any new asset would be 10%.

kW.[17] NREL also modeled 4-hour and 6-hour lithium-ion battery storage systems using data from NREL's Annual Technology Baseline (ATB). The ATB informed the future construction cost curves for both solar PV and battery storage systems, projecting that technology costs would decline overtime.[18]

The geographic clusters of buses that experienced voltage issues identified in the power flow analysis were mapped within Engage using node groups.[19] Minimum build requirements were established for the node groups in Engage, corresponding to the minimum DPV required to improve voltage regulation from the power flow model. In other words, Engage required that new solar PV systems be constructed in prioritized areas first, fulfilling minimum capacity targets before any additional solar PV systems could be deployed to other parts of the grid. In all scenarios except the Base scenario, which only considered planned solar PV, these constraints ensured that the solar PV buildout in the techno-economic model aligned with stakeholder objectives for grid reliability.

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[17] The Victorica solar PV farm cost 8,168,620 USD to construct. Background information on the Victorica solar PV farm can be found at https://pampetrol.com/parque-solar-fotovoltaico-victorica/

[18] The ATB is a dataset of technology-specific cost projections over time, given assumptions about improvements in technology performance, different electricity generation futures, and financial modeling scenarios. The ATB is focused on the North American market, so adjustments may be required to apply it to other markets according to regional factors like the cost of securing financing and skilled labor. NREL pulled the cost forecasts for battery energy storage and solar PV from ATB moderate modeling scenarios. More information on the ATB can be found at https://atb.nrel.gov/.

[19] Nodes represent mathematical intersections of technologies at assigned locations in the model to measure the flow of energy and commodities. Creating a node group in Engage allowed NREL to set overarching scenario constraints, including minimum build requirements of single-axis tracking solar PV systems at specific locations in the model.

3 Findings

The integrated analysis from the power flow and techno-economic studies revealed substantial value in strategically integrating DPV into La Pampa's grid, for improved voltage regulation (to within 0.9 pu or better across all buses at peak load) and reduced electricity costs. The power flow analysis not only confirmed that locally generated solar PV would alleviate voltage drops in the distribution lines and reduce line losses, but also indicated that a relatively small amount (~32 MW) of renewable generation would be sufficient for voltage regulation if deployed in specific areas. The techno-economic analysis revealed that self-generating a substantial portion of the province's load through DPV systems would be significantly more cost-competitive than importing power from CAMMESA. Under the current CAMMESA power price (70 USD), the analysis projected that La Pampa residents could face over 2.5 times higher electricity costs by 2050 if APELP only developed its planned solar PV construction under the Base scenario compared to the Cost Optimal case. The analysis also identified over 1.2 GW of solar PV to be competitive in La Pampa if exports are allowed, highlighting the favorable conditions for solar energy development that Argentina could leverage in its clean energy transition.

3.1 Voltage Regulation Insights

The PSS®E model identified numerous significant voltage violations in APELP's distribution network without strategically placed DPV, with 46% of the system's buses operating at below 90% of their nominal voltage levels during peak demand (Table 1). To determine where DPV systems would have the greatest impact, NREL modeled the incremental integration of DER, assessing improvements to voltage regulation across the geographical clusters with the addition of DPV. NREL first examined the grid's response if only the planned 55 MW of solar PV systems were built, with 50 MW planned for General Pico and 5 MW for Macachín.

As shown in Figure 4, the voltage improvement under the Base case was minimal. At first glance, constructing a large solar PV system in General Pico seems logical, given that it is the second-most-populated city in La Pampa and would supply power closer to high-demand areas, reducing the strain on the grid. The PSS®E model revealed, however, that the planned General Pico PV system would not enhance the grid's overall voltage regulation because the most critical areas, Clusters 1 and 2, are too far away from the General Pico PV injection point to realize voltage regulation improvements. This analysis highlights a key point that constructing DPV systems in non-strategic locations on the grid may not always effectively address voltage regulation issues. It also demonstrates the potential importance of steady-state analysis in maximizing the benefits of DERs through strategic placement.

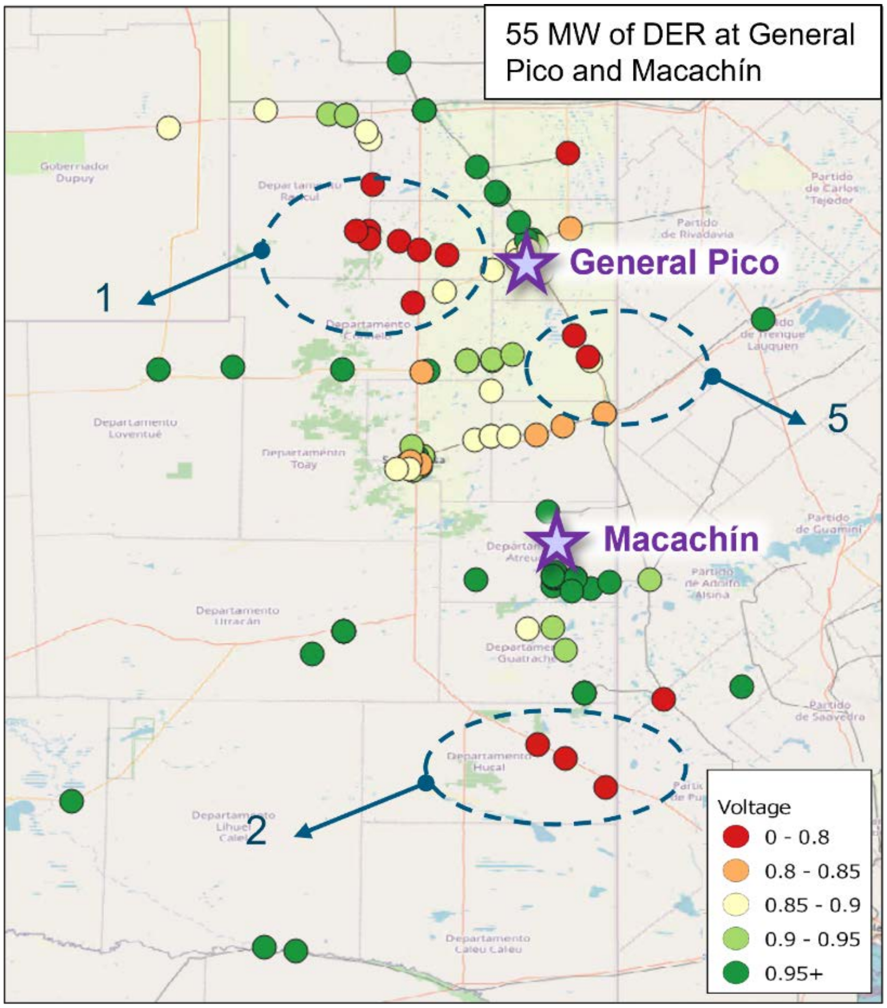

Figure 4. Map of distribution voltage profile when 55 MW of planned PV were integrated to the grid

After grouping the affected buses into geographical clusters, the team modeled the potential impacts of increased DER generation at various points in the grid to identify optimal sites and capacities for DER deployment, specifically to improve voltage regulation. Figure 5 shows the locations and capacities of DER facilities determined by the PSS®E model to be sufficient for remedying voltage regulation issues in their corresponding areas. Beginning with the most critical group of buses under Cluster 1, the team developed 12 successive DER installation cases that evaluated the minimum DER capacity needed at each geographical cluster to adequately boost the voltages of the buses in that region during peak load. The cases and their corresponding capacities for remedying voltage regulation issues in each area are listed in Table 3.

Table 3. DER Integration Sites for Voltage Improvement

Case	Description of Additional DER Installation	Total Cumulative DER Installation
1	Base case	0
2	7.2 MW at Victorica	7.2 MW
3	5 MW at Cluster 1	12.2 MW
4	4 MW at Cluster 2	16.2 MW
5	4 MW at Cluster 2	20.2 MW
6	3 MW at Cluster 5	23.2 MW
7	5.5 MW at Cluster 4	28.7 MW
8	2 MW at Cluster 4	30.7 MW
9	2 MW at Cluster 1	32.7 MW
10	2.5 MW at Cluster 1	35.2 MW
11	2 MW at Cluster 2	37.2 MW
12	2 MW in the northwestern region of APELP's service territory	39.2 MW

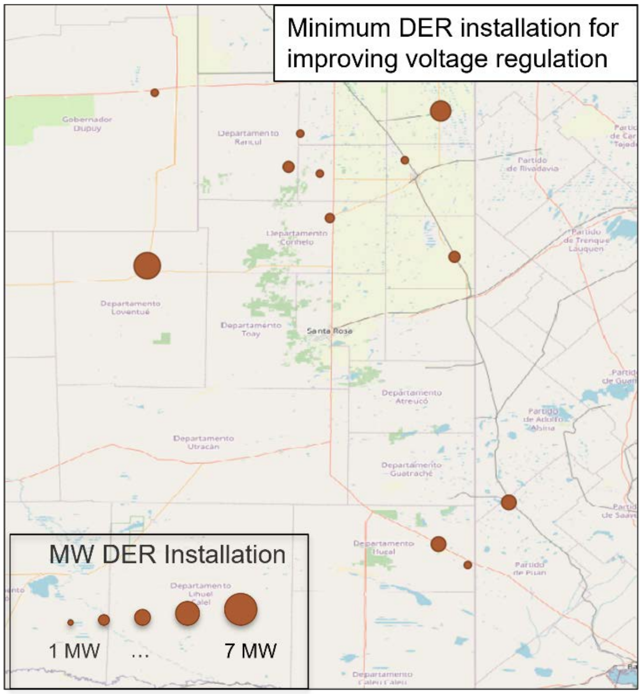

Figure 5. Map of the identified feeders for minimum DER installation to address voltage

The cumulative total minimum DER capacity required to resolve all voltage violations in APELP's distribution network amount to 39.2 MW, of which 32 MW would be new capacity outside of the 7.2 MW Victorica solar PV farm already installed. Figure 6 charts the impact each case had on the voltage regulation on APELP's distribution lines. With just the 7.2-MW Victorica solar PV farm online (Case 2), the analysis showed a 30% reduction in the number of buses with voltages that fell below 0.9 pu at peak. Each successive installation yielded smaller gains in voltage regulation compared to the first 7.2 MW installation; however, the total 39.2 MW of DER capacity, including 32 MW of new DERs, were indicated to fully resolve voltage regulation issues in the bus clusters, restoring voltage levels back to over 90% (0.9), as shown in Figure 7. NREL had set 0.9 pu as a threshold criterion, because if voltage can be regulated above this level during peak load conditions, it is reasonable to assume that the desired 0.95 pu voltage at all buses could be achieved under normal loading conditions.

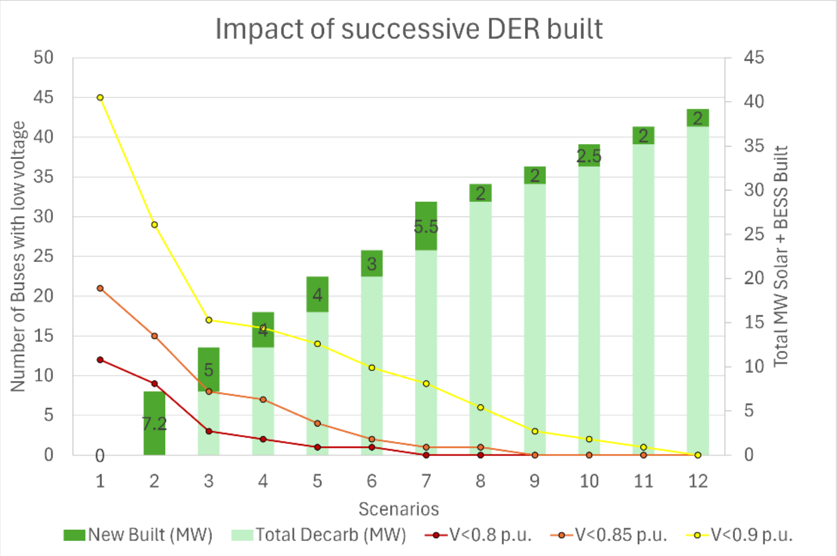

Figure 6. Successive impact of strategic DER integration on voltage regulation in La Pampa

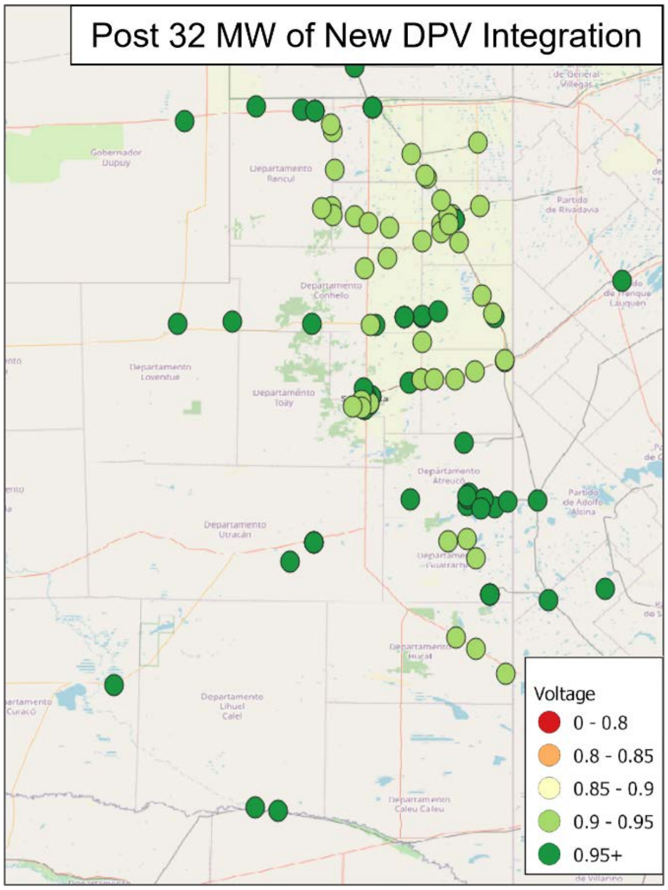

Figure 7. Map of distribution network with the integration of 39.2 MW of strategic DERs

Although the team did not conduct a social cost-benefit analysis for this case study, numerous studies have linked improved grid reliability to social benefits for the end user (Nassif et al. 2022; Wachtel, Melander, and Jeffers 2022). This could include reducing social burdens by minimizing the need for backup generators and storage systems. Additionally, adequate voltage regulation avoids damage to and supports proper operation of electrical equipment, preventing the overheating of generators and motors as well as premature electronic equipment failures. In this way, DERs could more than pay for themselves, saving utilities like APELP expenses on energy while avoiding the cost of traditional voltage regulation equipment. Using the strategic placement of DPV for voltage regulation could lower the bundled electricity costs that disproportionally affect low-income households downstream.

3.2 Techno-Economic Evaluation

The early modeling results from the techno-economic analysis demonstrated significant potential for DPV generation as a cost-effective alternative to importing electricity from the national wholesale market. Under the Cost-Optimal scenario, in which the rate of DPV development was not restricted, the Engage model identified up to 1.2 GW of DPV to be cost-competitive by 2050. This indicates APELP's potential to lower the province's electricity costs through local solar generation while positioning itself to become a prominent clean energy exporter to the national grid. Table 4 describes the amount of DPV capacity constructed across all scenarios over the 25-year modeling period, including under different CAMMESA power prices.[20]

Table 4. Total Single-Axis Tracking Solar PV Capacity (MW) by Scenario (export allowed)

CAMMESA Price refers to the power tariff for which "low" means the initial cost of power at 45 USD per MWh, while "high" means the current cost of power at 70 USD per MWh.

Scenario	Base		Conservative		Ambitious		Cost-Optimal	
CAMMESA Price	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*
2025 Build	22.2	22.2	22.2	22.2	22.2	22.2	22.2	22.2
2030 Build	37.2	37.2	37.2	37.2	32.2	92.2	32.2	92.2
2035 Build	62.2	62.2	98.2	98.2	163.1	175.9	248.8	452.3
2040 Build	62.2	62.2	143.2	143.2	189.1	203.1	320.1	472.7
2045 Build	62.2	62.2	188.2	188.2	372.1	389.7	416.1	971.3
2050 Build	62.2	62.2	233.2	233.2	590.3	597.7	516.7	1,207.7

The Engage model found DPV to be highly competitive against CAMMESA power, building significant DPV capacity when CAMMESA power prices were both low and high. Under the Conservative scenario, Engage built 9 MW of DPV every year, maximizing the development rate to reach 233.2 MW by 2050. This suggests that the major challenge to developing DPV systems in La Pampa will not be DPV's cost-competitiveness against other power sources, but rather the potential speed of construction and APELP's ability to secure reasonable financing.

When the model was not constrained by its build rate, Engage indicated that even aggressive DPV generation targets could be economically viable in La Pampa. While the rate-limited Conservative scenario built 233.2 MW of DPV by 2050, the non-rate-limited Cost-Optimal scenario found that over 248 MW of DPV would be cost-competitive as early as 2035. The Ambitious scenario similarly found that it was more cost-effective to build a substantial amount of DPV as early as possible. The slower buildout timeline observed in the Ambitious scenario in contrast to the Cost-Optimal scenario was not a reflection of solar PV's competitiveness but rather how the model was constrained to meet interim annual net-zero requirements. At points, this created a cap on the Ambitious scenario's DPV build compared to the capacity constructed under the Cost-Optimal scenario. Only under the low CAMMESA power price sensitivity did the Ambitious scenario need to build more than the Cost-Optimal scenario to meet the 100% annual net-zero load requirement in 2050.

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[20] For all scenarios, the model built 22 MW of PV in 2025 because planned solar projects were implemented first. By 2035, all 55 MW of planned solar PV projects were completed, in addition to the existing 7.2-MW Victorica solar PV farm, which was why the Base scenario only built 62.2 MW without further expansion. For the other three scenarios, the model included room for additional solar PV expansion, starting with the prioritized areas for voltage regulation from the power flow analysis. By 2040, all 32 MW of required DPV to ensure voltage regulation was built in the model, with the Conservative, Ambitious (Net-Zero), and Cost-Optimal scenarios differing by how much the model built beyond that.

While CAMMESA prices had no effect on the Base and Conservative scenarios, they did substantially influence the Cost-Optimal scenario. These trends are shown in Figure 8, which presents the levelized costs of electricity for each scenario over the modeling horizon when export was allowed. While scenarios with the high CAMMESA power cost had higher levelized costs of electricity, the divergence between the Cost-Optimal scenario and the other scenarios was striking. When the model was allowed to optimize the build of DPV systems after 2031, the model built significantly more DPV capacity to offset CAMMESA imports with lower-cost DPV generation and increase its exports to the national grid.

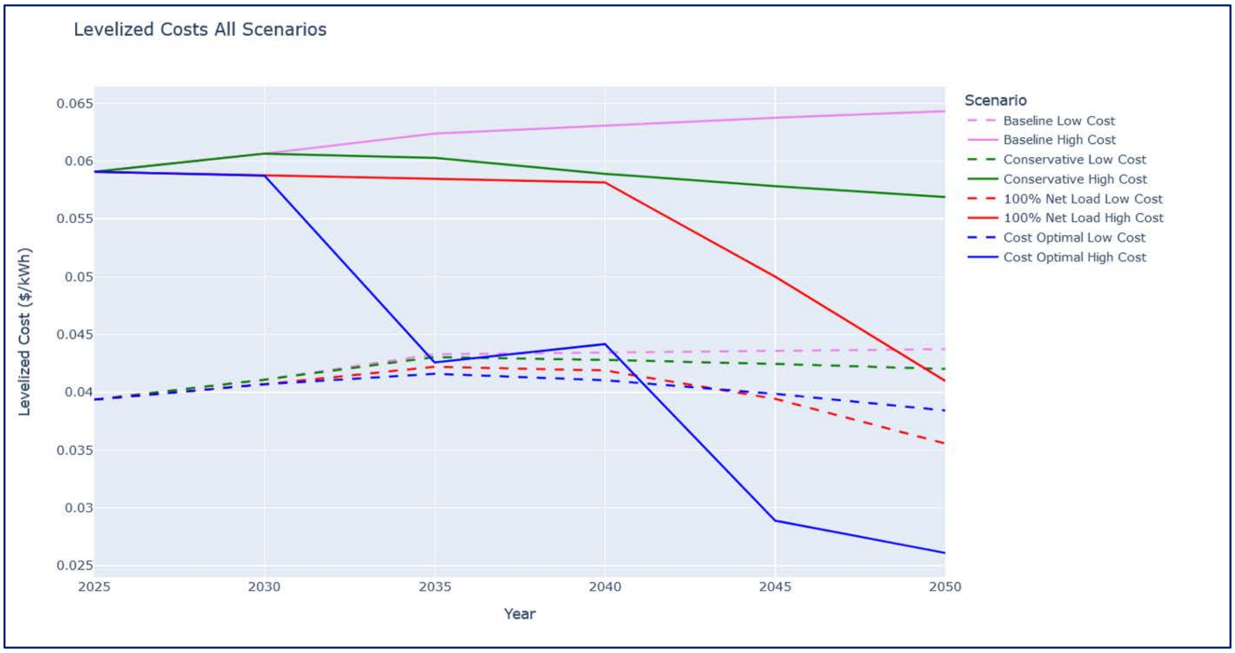

Figure 8. Line graph of the levelized cost of electricity across scenarios and CAMMESA power price sensitivities where export was allowed

The export dynamics in the model did not have any bearing on the Base and Conservative scenarios because of the rate limit on the DPV build. Because of the limited build rate, any solar PV capacity provided greater value by supplying power to meet demand in the province than through export. This is also why the model did not choose to build any battery energy storage systems across all scenarios. When export was permitted, it was more cost-effective to export solar power to the national grid rather than storing power in batteries, as it generated additional revenue, decreasing the system's total electricity costs. Even when export was not allowed, the model did not build any batteries because it was cheaper to reduce demand with solar PV during the day and then import the remaining power from CAMMESA, including with increased CAMMESA power prices. These results indicate that battery energy storage systems in La Pampa are not cost-competitive when the province can rely on the national grid.

Under the Cost-Optimal scenario when CAMMESA powers costs were low, the price APELP received for selling DPV generation to the national grid was similarly low, resulting in little incentive for the model to invest heavily in DPV for export. In the high CAMMESA power price sensitivity, though, the export rate was higher, enough to incentivize the model to build more solar PV than needed to meet demand. This indicates that the ability to export excess DPV generation to the national grid for revenue substantially increases the amount of local DPV that can be constructed economically. The extent to which there will be a national market for PV generation exports, however, will depend upon Argentina's generation mix going forward—in addition to accommodating significant renewable penetration to the grid. For this reason and others, local planning must be carefully coordinated with the national context for accurate assessments of grid asset valuations.

4 Next Steps

This case study provided a high-level evaluation of the likely benefits that DPV systems could bring to rural power systems like La Pampa. The analysis showed that strategic new DPV systems could resolve the province's voltage regulation issues at electricity cost savings for the province (i.e., at a negative cost). Further efforts are necessary, however, to build upon these findings to properly support an actionable path forward for APELP. For one, the study indicates that, while the planned DPV systems will help APELP reduce electricity costs for residents, such systems will not improve the region's voltage regulation, and may, in some cases, even worsen bus voltage levels. Therefore, it may be beneficial either to reassess the locations for the planned DPV systems, prioritizing strategic placements, or build new strategic systems alongside the planned DPV through 2031.

In addition, while the steady-state power flow analysis provided valuable insight into the sites and capacities for DERs to address voltage regulation, a comprehensive dynamics stability analysis is essential to fully understanding the broader system implications of DER integration. To support this effort, NREL developed and shared a PSCAD model of La Pampa's T&D network, positioning APELP to move forward with such a study. Using the PSCAD model, NREL conducted an example preliminary fault analysis to demonstrate the types of dynamics stability studies APELP will need to plan for DER integration, such as evaluating the impact of different DPV systems' inverter capabilities on system resilience. As shown in Figure 9, when a DPV resource was not connected to the grid, the voltage drop during a fault event was more severe than when a DPV system with grid-following inverters equipped with basic control capabilities was connected to the grid. The voltage drop was further reduced by grid-forming inverters with fault-ride-through capabilities. As APELP advances its plans for local renewable generation, this type of dynamic stability analysis will be useful in guiding project decisions, because solar PV systems with fault-ride-through capabilities are slightly more expensive to construct but offer greater reliability benefits.

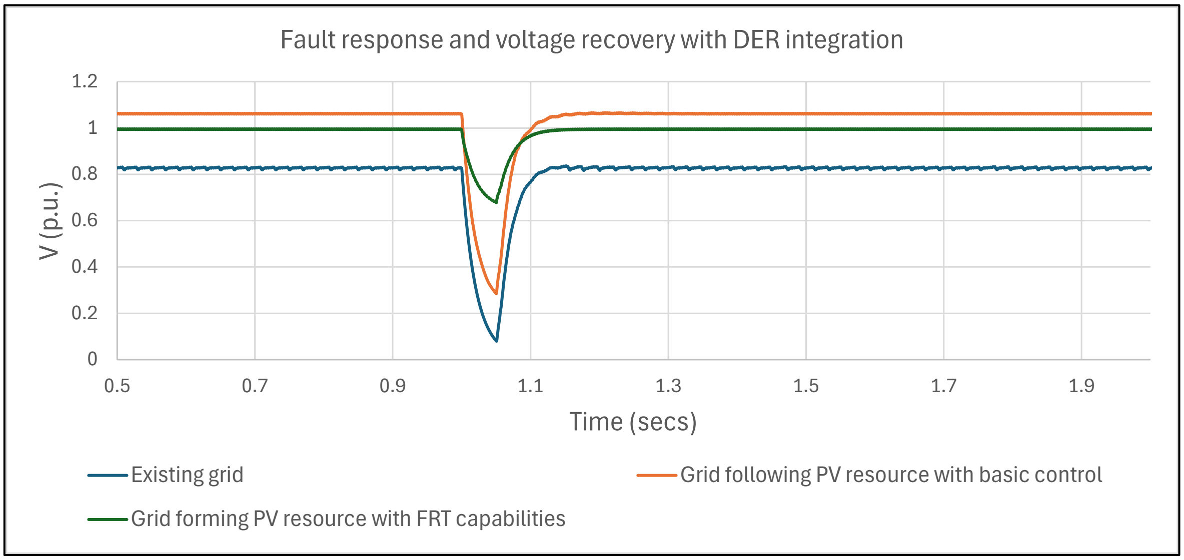

Figure 9. Comparison of fault response at a neighboring bus near Victorica for various inverter capabilities

Furthermore, in this study, the team assessed grid implications of DPV in La Pampa under steady-state conditions with the assumption that the national grid's reliability remained unchanged. If other provinces also adopt DERs, a national-scale reliability study should be conducted to evaluate the full network complexities created by widespread DER integration. This need arises because as the national grid becomes increasingly reliant on variable resources for power, with more provinces moving toward local renewable generation, there could be broad implications for managing the grid, such as high variability, low inertia conditions, and limited grid strength.

These factors should be studied to ensure national coordination among provinces to prevent overcapacity from solar during the day, oscillatory events, and large-scale power outages (blackouts). In addition, datasets might be created and leveraged by CAMMESA and the National Energy Secretariat to identify voltage vulnerabilities in the national grid and coordinate with provinces to address those vulnerabilities through DER integration. The Demand Response Technical Working Group of Argentinean utilities, led by the National Energy Secretariat and supported by Net Zero World, is ideally situated to analyze this data and translate it into strategies for improving grid operations. This could include developing DERs to reduce peak load and maximize regional economic and social benefits.

Although this case study focused on DPV as a DER, wind power also holds promise across a number of regions of Argentina, especially in provinces farther south toward Tierra del Fuego. In a separate Net Zero World case study, NREL and its project partners found that wind farms could cost-competitively serve a significant portion of Tierra del Fuego's load (Harris et al. 2024).[21] Moreover, the province's potential to export excess wind production to the mainland was a key finding, one that may be relevant to La Pampa and other provinces in Argentina. The potential to export surplus renewable electricity is a pivotal insight that may shape Argentina's national grid regulatory framework in the future.

Currently, APELP, like other T&D providers, faces restrictions on what it is permitted to export to the national grid. While APELP could create power purchase agreements to sell power to CAMMESA, this process can be lengthy and highlights the need for creating a regulatory environment that can address these challenges not just in La Pampa but across provinces. Establishing regulations that support large exports to the grid will strengthen national energy planning and enhance coordination among provinces on their renewable energy projects. These regulations should be explored in a national-scale study as well that would consider the effect increased renewable deployment would have on the cost of power. For example, if provinces expand DPV development, generating a significant amount of solar energy during the day, it could lead to an oversupply when demand is low. If unaddressed, this could severely jeopardize the long-term economic viability of DPV deployment for a province by creating solar value deflation as seen in California and European countries. National-scale planning and operational modeling in this way could help provide important data on future power costs to better inform national-scale DER integration and valuation.

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[21] The full report can be read at https://www.nrel.gov/docs/fy24osti/88156.pdf.

5 Conclusion

This Net Zero World case study highlights the great opportunity for realizing the benefits of integrating DPV into the La Pampa electric grid. To address the province's priorities for grid reliability, sustainability, and economic security, NREL created a modeling framework that combined insights from power flow and techno-economic models to evaluate two key impacts from the strategic placement of DPV: improved voltage regulation and energy cost savings.

The study results position APELP to create an informed action plan to pursue local renewable generation with identified strategic sites for DER integration and expected system savings to build a compelling business case. The work performed in this case study could serve as a blueprint for the other provinces in Argentina that experience similar challenges, including dispersed populations and heavy reliance on aging natural gas systems. The case study also indicates the potential for missed opportunities as provinces pursue local renewable generation if they do not conduct reliability studies to ensure that DPV integration is designed to contribute system services maximally. Strategically locating and operating DPV in consideration of reliability concerns, like voltage regulation, can provide multiple economic value streams. This includes a reduced reliance on CAMMESA power as well as avoided costs associated with traditional voltage regulation equipment and premature electronic equipment failures.

Argentina's diverse geography and regional resources offer valuable opportunities for renewable energy deployment, particularly in areas with high solar and wind potential. The insights from this La Pampa study may imply similar opportunities elsewhere in Argentina while pointing to the need for a national study integrating and synthesizing such findings. Accounting for the full value of regional opportunities for DERs in national planning can help advance Argentina's clean energy transition more effectively than approaches that account only for the energy value of transmission-connected grid assets. This strategy will ultimately pave the way for a more sustainable, reliable, and just clean energy future for all of Argentina's provinces.

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