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PROVIDENCIA ISLAND HIGH-LEVEL POWER SYSTEM CAPACITY EXPANSION ANALYSES

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DISCLAIMER

The following slides constitute an initial, high-level analysis and should not be the sole basis of future design or investment decisions. Other power system studies and proposal reviews are required before finalization of system architecture and procurement. Studies are often iterative. Vendor quotes and assessment of existing conditions by integrators, review of offered warrantees, vendors' track records, and other details should all be considered when determining resultant economic impacts and when selecting and implementing the technology vendor, integration and control strategies, and the technology mix.

SCOPE OF ANALYSES

- NREL performed an economic analysis of the costs and benefits of integrating renewable energy and energy storage on Providencia Island's remote power system.
- Capacity expansion modeling for Providencia Island power system included the following:
  - A high-level cost-benefit analysis has been conducted, which focused on integrating solar photovoltaics (PV) and a battery energy storage system (BESS) using fuel costs of existing generators, provided discount rates, and NREL-derived capital cost estimates.
  - A third-party review of Ecopetrol's capacity expansion plans was conducted.
  - An analysis of Ecopetrol's plans and additional PV planned by other entities was conducted.
- The analysis considers investment capital costs and the impact on power system operating costs:
  - An impact of investments on electricity costs for island residents has not been determined; a separate cost of service study, cost recovery, and rate analyses would be needed and are not within the scope of this effort.
- The HOMER model was used (www.homerenergy.com) to conduct this analysis.

STUDY RESULTS

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1. HIGH-LEVEL CAPACITY EXPANSION MODELING RESULTS

- These techno-economic capacity expansion results are high level. Results are based on fuel costs, discount rates specified or provided as input to the analysis, and capital cost estimates developed by NREL.
- PV is found to be cost-effective for displacing high-cost diesel fuel. At high levels of PV penetration, battery energy storage is required for maintaining system stability and reliability. On Providencia Island, battery storage is also cost-effective for storing some PV generation in excess of load for later use when PV contribution is lower or unavailable to further offset diesel costs.
- For the costs assumed by NREL and for the economic parameters provided, 1,400 kilowatts (kW)-alternating current (AC) of PV coupled with a 500-kW | 500-kilowatt-hour (kWh) BESS is found to be most cost-effective for reducing diesel fuel consumption.
  - Estimated net present value (NPV) is $180,000 USD over 25 years based on the 11.5% real discount rate specified.
  - This system is estimated to displace 2,600 megawatt-hours (MWh)/year of diesel generation, reduce fuel usage by 21% on average, and reduce carbon dioxide emissions by 2,010 metric tonnes per year.
- Results are indicative, and other sizes and mixtures of PV and BESS may be just as appropriate and cost-effective as additional details emerge and are considered.

1. HIGH-LEVEL CAPACITY EXPANSION MODELING RESULTS, CONTINUED (CONT.)

- A key goal of adding renewable energy to Providencia Island's electrical system is to reduce diesel fuel consumption. The table below provides model results for a range of PV sizes. The size of the battery coupled with each PV scenario is the size generated by the model as the lowest life cycle cost solution. The scenario with the greatest estimated NPV is outlined in green.

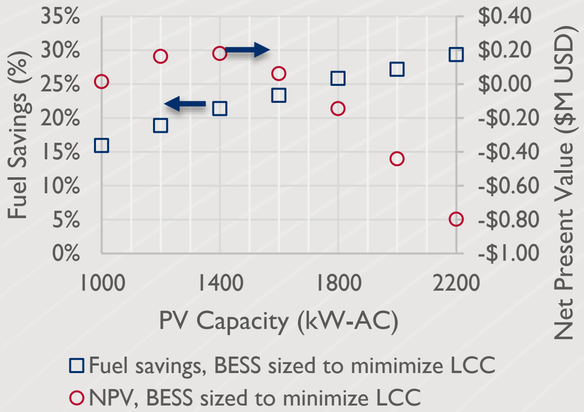
- The adjacent plot shows the fuel savings and NPV for each scenario in the table.

- Increasing PV from 1,400 kW-AC (greatest NPV) to 2,200 kW-AC increases fuel savings from 21% to 29%. The estimated NPV becomes negative with PV above 1,600 kW-AC.

- The economic results are sensitive to the fuel costs, fuel cost escalation rate, discount rate, and capital cost assumptions. The Colombian government's high, real discount rate of 11.5% is challenging for capital-intensive investments like renewable energy that reduce future operating costs over long life cycles. For example, reducing the discount rate by 2% to 9.5% increases the projected NPV of the system from $180k to $1.10 million (MM) U.S. dollars (USD).

PV Deployment Scenario	**Existing System**	**1,000 kW**	**1,200 kW**	**1,400 kW**	**1,600 kW**	**1,800 kW**	**2,000 kW**	**2,200 kW**
PV (MWac)	-	1.0	1.2	1.4	1.6	1.8	2.0	2.2
BESS (MW|MWh)*		0.5|0.5	0.5|0.5	0.5|0.5	0.5|0.5	0.5|0.75	0.5|0.75	0.75|1.0
Fuel savings (%)		**15.9%**	**18.9%**	**21.4%**	**23.3%**	**25.8%**	**27.2%**	**29.3%**
NPV ($MM USD)		$0.01	$0.16	$0.18	$0.06	-$0.15	-$0.44	-$0.80
CAPEX ($MM USD)		$4.05	$4.67	$5.29	$5.92	$ 6.78	$ 7.40	$8.31
Fuel usage (gallons/year)	944,308	794,058	766,147	742,601	723,951	700,406	687,763	667,206
PV potential fraction of load (%)		16.0%	19.2%	22.4%	25.6%	28.8%	32.0%	35.2%
Excess generation (% of PV generation)		**0.1%**	**1.2%**	**4.0%**	**8.2%**	**10.2%**	**15.0%**	**16.8%**

*Note: The model was constrained to a lower limit battery size of 500 kW and 500 kWh.



1. HIGH-LEVEL CAPACITY EXPANSION MODELING RESULTS, CONT.

- In addition to minimizing operation costs, battery capacity requirements for Providencia Island may also be driven by electrical stability and reliability considerations, not just the economic dispatch for fuel savings that an economic capacity expansion model identifies.
- The selected system integrator may specify higher battery energy and power for system stability and/or other operation considerations.
- In addition, final specification of BESS capacity and minimum state of charge (SOC) may be refined later from a cost-benefit perspective using vendor pricing, consideration of warrantees, performance guarantees, and consideration of degradation and useful life of the BESS.
- Higher fuel savings are possible with additional PV, the addition of wind turbine generators, and/or the implementation of energy-efficiency and conservation programs.
- Adding more PV may require additional battery storage to time-shift PV generation, while wind may be more complementary to planned PV and existing load profiles. Utility rate tariff modifications or bilateral agreements with large consumers may also help shift some of the evening peak to daytime for better utilization of PV generation.
- The final design implemented should be robust to accommodate future load growth, customer-sited distributed energy resources, and future utility investments in new diesel generation, additional PV, or wind power.

2. REVIEW OF ECOPETROL CONSULTANT'S RECOMMENDATION

- Ecopetrol consultant's recommendation:
  - PV 1,800 kW-AC; 2,500 kW | 2,500 kWh BESS; One existing diesel generator always on; 50% Li-ion battery min. SOC
  - Fuel savings: 30%; NPV +$0.58MM USD.
- The recommended PV system is larger than the lowest cost system found in NREL's high-level capacity expansion modeling but is reasonable and will result in more fuel savings than the highest NPV system found with NREL modeling (1,400 kW-AC PV).
- The consultant's 30% fuel savings is consistent with 28% fuel savings results of NREL's modeling for consultant's system.
- The consultant finds their recommended system has a positive NPV of $580,000 USD, while NREL's analysis suggests this system will have a negative NPV of -$1.8M USD; however, different discount rates, fuel costs, and capital costs exist between the two analyses. NREL did not attempt to "reverse engineer" the consultant's analysis to try to completely replicate it.

- NOTE: Economic and technical performance in the middle column of the table is based on the costs and performance model used in NREL's high-level capacity expansion modeling, not the consultant's. **Results in this column use the consultant's architecture only.**
- **An alternate architecture to achieve 30% fuel reduction is shown in the last column:**
  - **2,200 kW PV + 750 kW | 1,250 kWh BESS results in higher NPV with lower capital cost investment.**

Scenario	Ecopetrol Consultant's Results	NREL Model Results of Ecopetrol Consultant's System	NREL Model Alternate System Architecture to Achieve 30% Fuel Reduction
PV (MWac)	1.8	1.8	2.2
BESS (MW|MWh)	2.5 | 2.5	2.5 | 2.5	0.75 | 1.25
NPV ($MM USD)	+$0.58	-$1.80	-$0.88
Capital costs ($MM USD)		$8.84	$8.56
Fuel savings (%)	30%	28%	30%

2. REVIEW OF ECOPETROL CONSULTANT'S RECOMMENDATION, CONT.

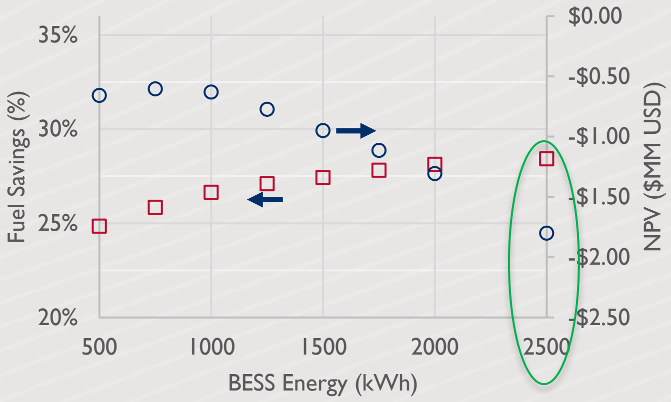
- The NREL-developed model was applied to the consultant's recommended architecture to examine the impact of both BESS capacity (kWh) and BESS power rating (kW). Figures of these sensitivities are shown on the next slide. Summary statements on this slide are supported by the plots on the next slide.
- When NREL's model is applied, the NPV increases when the consultant's BESS power and energy capacity ratings are decreased.
- There does not appear to be a fuel savings benefit and there is an economic penalty for specifying a BESS power requirement above 1,500 kW. This is true for both the consultant's recommended 1,800-kW PV system and for the additional potential of 550 kW of PV added to it; however, a larger power rating may be a more robust design for future load growth, and there may be other technical reasons for the additional power capacity.
- Although there seems to be an economic penalty for the consultant's 2,500-kWh recommended energy capacity, it does allow greater utilization of PV potential generation (less curtailment). It also accommodates future installations of PV.
  - Reducing the consultant's recommended energy storage capacity (kWh) increases the NPV but fuel savings will decrease. This is true for the 1,800-kW PV scenario and 2,350 kW of PV.
  - If the consultant's recommended 2,500 kWh of energy storage capacity is installed and if 550 kW of PV are added to the 1,800-kW system the consultant recommended, fuel savings are projected to increase from 28% to 34%. If a smaller, lower cost 1,500-kW | 1,500-kWh BESS were installed instead, the fuel savings for 2,350 kW of PV is estimated to be 32%.

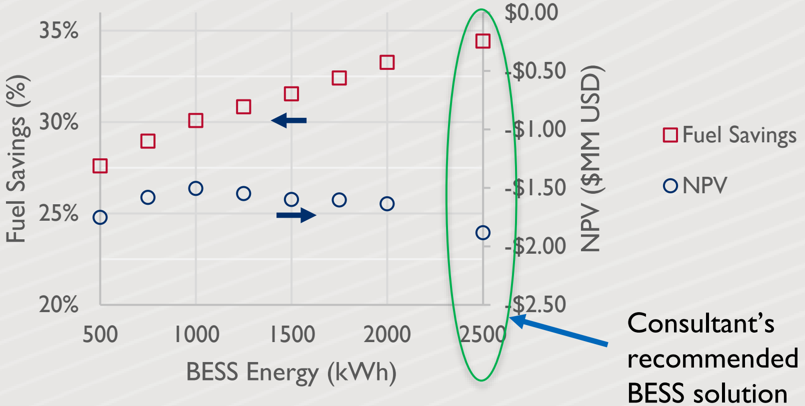
2. REVIEW OF ECOPETROL CONSULTANT'S RECOMMENDATION, CONT.

Consultant's 1,800 kW of PV

Consultant's 1,800 kW of PV + additional 550 kW, 2,350 kW total

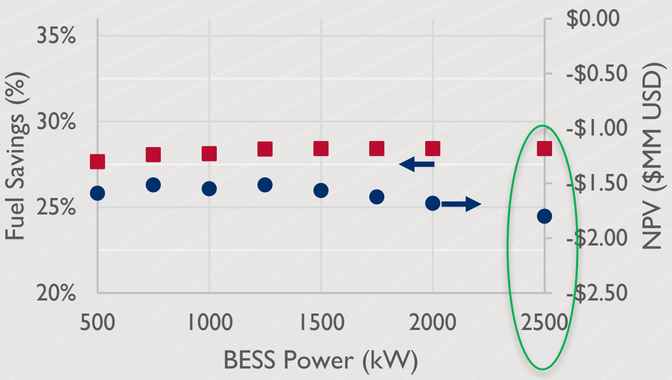
BESS **power constant** at 2,500 kW, **variable energy capacity**

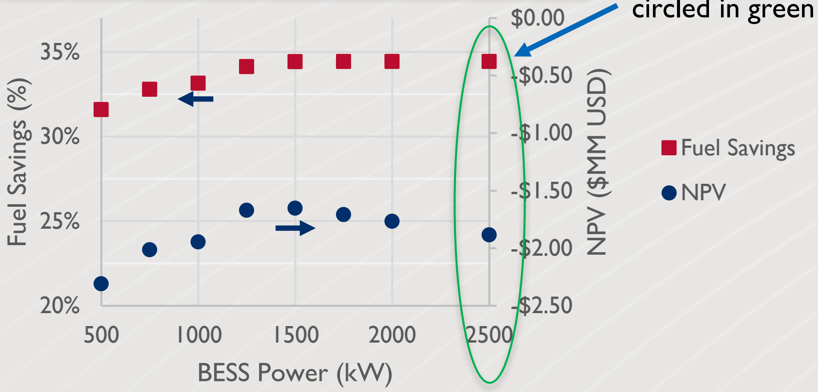




Consultant's recommended BESS solution circled in green

BESS **energy constant** at 2,500 kWh, **variable power capacity**





2. REVIEW OF ECOPETROL CONSULTANT'S RECOMMENDATION, CONT.

- For a peak load of 1,800 kW, the existing largest generator of 1,400 kW, and planned PV installation of 1,800 kW, the purpose of Ecopetrol's consultant's 2,500-kW BESS power requirement is unclear and appears oversized. Higher power capacity may be more robust against future load growth and may be useful for increasing the short-circuit contribution of BESS; however, since the consultant's recommendation is that one diesel generator always operates, BESS may not be intended for short-circuit contribution. Synchronous condensers may also be a lower cost solution for increasing available short-circuit current than increasing the power capacity of BESS. It may be possible to convert one of the diesel generators to a synchronous condenser.
- BESS energy capacity of 2,500 kWh is oversized for economic benefit alone, but it does provide increased utilization of the consultant's recommended PV as well as PV that may be installed by other entities in the future. Also, the consultant may have other reasons for longer duration storage, e.g., extending battery useful life. It is recommended that this be discussed with Ecopetrol before final specification and procurement.
- Although the consultant has specified that one of the diesel generators will always operate, if the 2,500-kW | 2,500-kWh BESS is pursued, diesel-off operation could be accomplished. Fuel savings estimated by NREL assume the diesel generator can turn off when operating reserves are met with BESS.
- A 50% minimum SOC requirement is conservative. A 20% minimum SOC for Li-ion BESS is achievable although decreasing the usable capacity range as the consultant assumed can extend BESS useful life. BESS degradation can result from deep depths of discharge, among other parameters, so increasing BESS capacity can be used to effectively decrease deep depths of discharge on a relative capacity basis.
- Fuel costs and the discount rate used by the consultant are different than the values provided to NREL for this analysis.
- The consultant indicated the diesel-on requirement is necessary for reliability. With future potential PV and/or wind power additions, diesel-off operation could result in increased fuel savings. NREL suggests that BESS be specified as grid-forming capable such that diesel-off operation can be a future option. Designing a system for periodic diesel-off operation can be reliably achieved.

3. UPGRADES DESCRIBED BY OTHERS

- In addition to the plans by Ecopetrol to add 1,800 kW of PV and 2,500 kW | 2,500 kWh of BESS on Providencia Island, additional PV generation is being considered and has been described in meetings, including:
  - 300 kW of distributed residential rooftop PV
  - 250 kW of ground-mounted PV on Catalina Island
  - Possible replacement of power plant generation.
- NREL recommends that any planned or contemplated system changes be considered together and developed as part of an integrated plan:
  - For example, size and number of diesel generators should be considered together with planned PV and BESS additions. Diesel generator operational flexibility requirements and control capability should also be specified as part of the system operation needs and scheme.
  - The results of NREL's and Ecopetrol consultant's analyses assume the existing diesel plant configuration will remain.

MODEL INPUTS

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ECONOMIC PARAMETERS

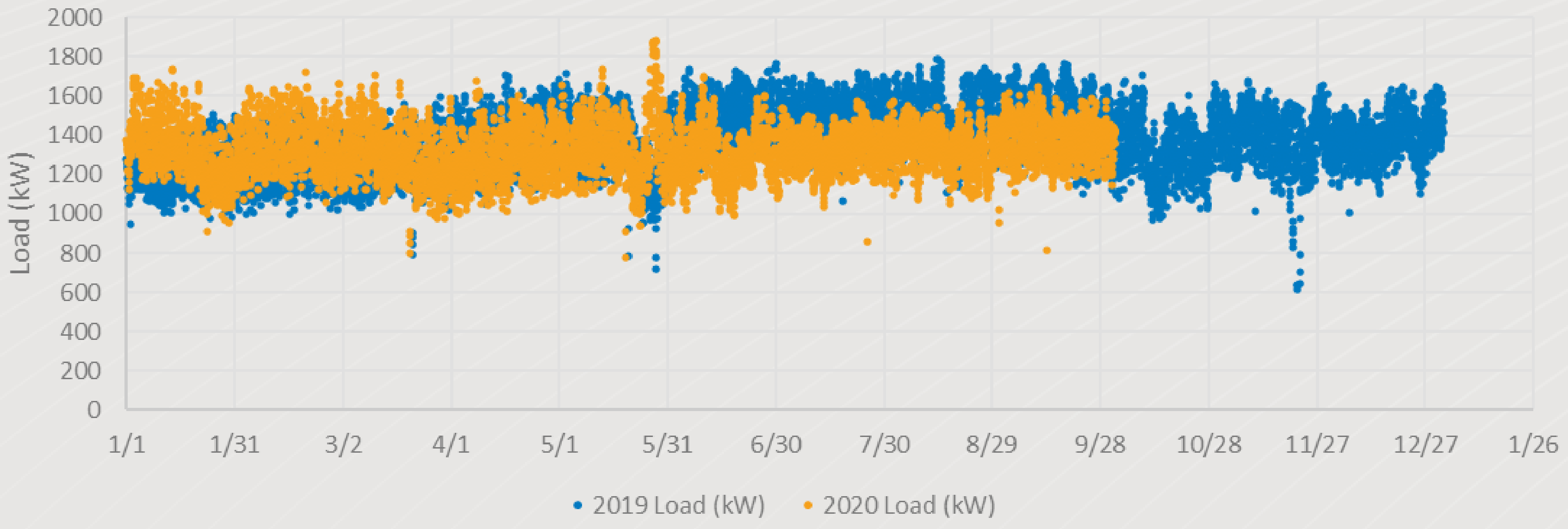
- Discount rate of 11.5% real, specified by the Ministry of Mines and Energy
- 25-year analysis period assumed based on projected useful life of PV. Battery replacements over the analysis period are costed.
- Fuel cost escalation rate for diesel fuel from the U.S. Energy Information Administration (EIA). A reference for Colombian projected future fuel costs could not be located by NREL (additional details on a later slide).
- Automated dispatch of diesel generators, battery, and PV is assumed in this analysis for achieving estimated fuel savings.
- Existing diesel generators are sunk costs.
- Fuel economy of existing generators was estimated using generic fuel consumption rates for diesel generators found online for the generator sizes on Providencia Island.
- Nonfuel operation-and-maintenance (O&M) costs for diesel generators are based on standard assumptions.

Parameter	Value
Discount rate, real	11.5%
Analysis period (years)	25
Current fuel cost	$2.97
Fuel cost escalation rate (%/year)*	2.55%
Variable generator costs ($/kW rated/run time hour)	$0.02

* Average, but annual values are used in the model.

SYSTEM POWER DEMAND

- Hourly interval data were provided by Providencia Island from Jan. 1, 2019, through Sept. 30, 2020. Data are plotted in the figure below.
- 2019 data are used in the analysis as the assumed load to be served over the analysis period.
- **Peak:** 1,786 kW; Average: 1,371 kW.



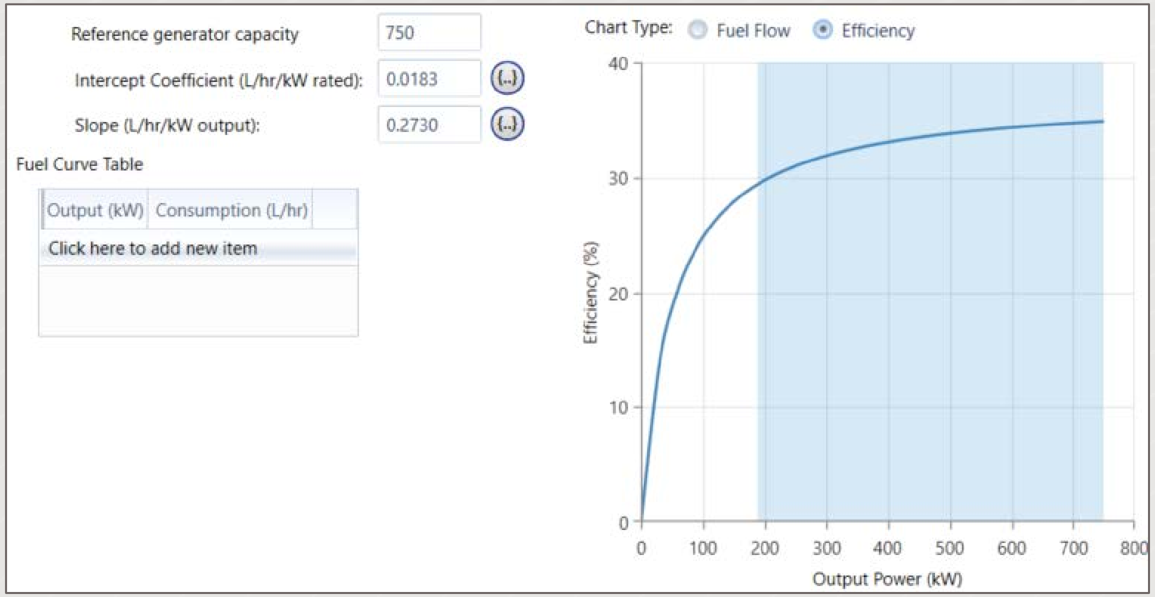
EXISTING DIESEL POWER PLANT

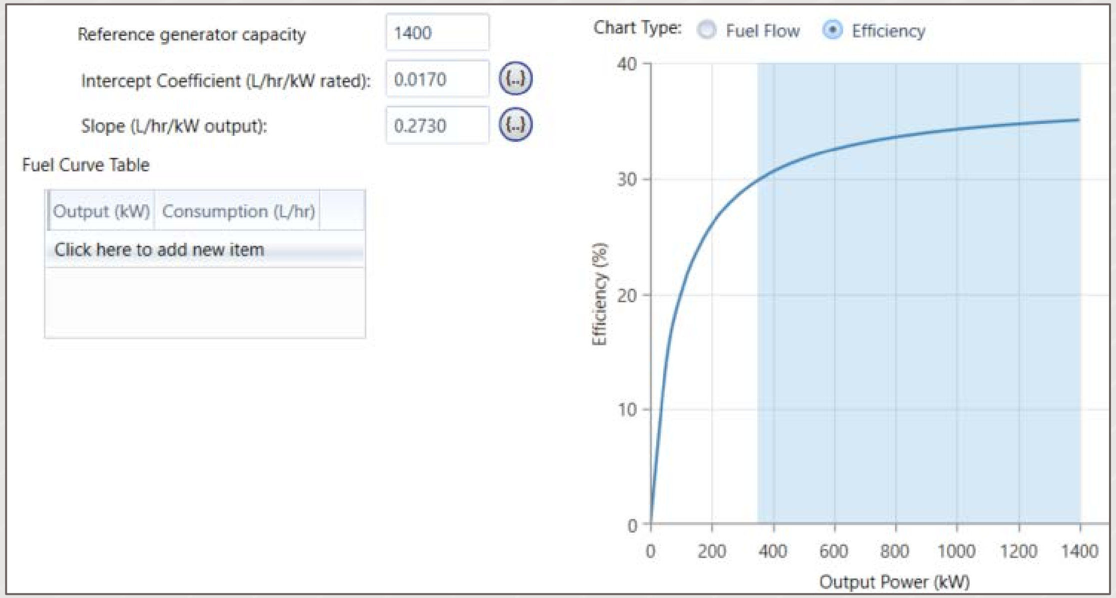
- Data on power plant per spreadsheet provided by Tetra Tech: "2021 02 15 LINEA BASE DE ENERGÍA-english.docx."
- There are (3) operating engine generators, with sizes ranging from 750 kW to 1,400 kW.
- 861,240 gallons of fuel oil were consumed in 2020.
- Average rate of fuel consumption was 0.0812 gallons/kWh, or 12.3 kWh/gallons.

Unit	Generator Make	Capacity (kW)	Installation Yr	Status
EMD1	General Motors EMD	750	1993	Operating
EMD2	General Motors EMD	1,400	1996	Operating
EMD3	General Motors EMD	1,400	2005	Operating
Unidad 4	Cummins	1,250		Out of service
TOTAL		3,550		

POWER PLANT MODEL

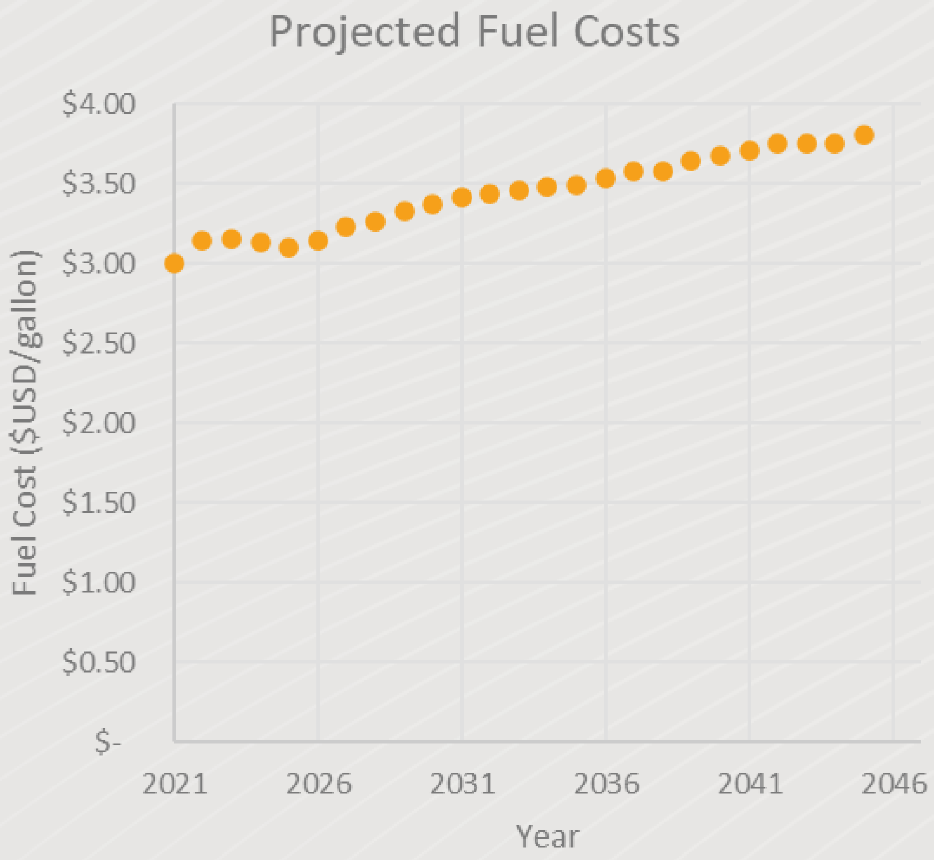
- The modeling conducted by NREL includes variable efficiency of generators with loading.
- Generic fuel burn rates for diesel generators are used (see images below).
- Generic curves are calibrated to provide 0.082 gallons/kWh, which is Providencia Island's average specific fuel consumption, for the base case.





DIESEL FUEL COSTS

- **Price:**
  - Data provided by Tetra Tech: "2021 02 02 SSPD SUI ENERGÍA ELÉCTRICA (version 1).xlsx"
  - Current cost: $USD 2.97/gallon ($USD 0.785/liter), unsubsidized.
- **Fuel cost escalation:**
  - Using U.S. EIA[1] projections for industrial distillate diesel[2] as proxy for Providencia
  - Annual Energy Outlook projections are through 2050.
  - Costs per the U.S. EIA's Annual Energy Outlook used in the model are shown in the figure for the 25-year analysis period.



1. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=12-AEO2021&cases=ref2021~aeo2020ref&sourcekey=0
2. Includes California Low Carbon Fuel Standard (existing law) but no assumed future cost of carbon

COMPONENT COSTS

- Costs for development of energy systems on Providencia Island are highly uncertain.
- This analysis uses some cost estimates for "mainland" installations and then applies a simplistic "island cost factor," or multiplier, for approximating additional mobility, logistics, and labor costs for construction projects on Providencia Island.
  - A conservative "island cost factor" of two is assumed.
- An additional $250,000 USD is included for adding a system controller, and an additional $100,000 USD is included for plant upgrades for automated operation.
  - These costs are placeholders. Actual costs will depend on local conditions and the operations strategy of the selected integrator.
- Costs are "total installed" and therefore assume that standard interconnection equipment is included.
- Costs do not include land or rooftop acquisition costs.
- Costs do not explicitly include sales taxes, value-added tax, and applicable import tariffs.
- See subsequent slides for references and discussion of estimation of costs on mainland Colombia.

Item	Mainland Colombia Cost	Providencia Island Cost
BESS ($/kWh)	$475	$950
BESS O&M ($/kWh-yr)	$5.60	$11.20
BESS replacement costs in Yr. 7 ($/kWh)	$309	$618
Grid-forming BESS power electronics ($/kW)	$100	$200
PV ($/kW-AC)	$1,560	$3,120
PV O&M ($/kW-AC/yr)	$13.20	$26.40
Supervisory controller		$250k
Switchgear and controls for automatic control of diesel generation		$100k

BESS COSTS

- **Reference**: Bloomberg New Energy Finance "Energy Storage System Costs Survey 2020," Dec. 16, 2020.
- Batteries are assumed to be connected to the utility distribution on the utility "side of the meter" and to be operated by the utility for optimizing operations. Customer-sited batteries are not considered in this analysis.
- Costs in the reference are for the useable capacity and "dynamic range" of energy storage capacity, and therefore per-unit kWh pricing does not include the capacity reserved as typically identified as "minimum state of charge." A minimum SOC of 20% is assumed for modeling purposes.
- In this analysis, using the $380/kWh-usable, average for data as presented for 1-, 2-, 3-, and 4-hour commercial-scale systems in the Americas region (mainly U.S.). This has an equivalent cost of $475/kWh nameplate capacity assuming the 20% minimum SOC applied in the model.
- Fully installed costs in the reference include "containers" to house the BESS; therefore, it is assumed the BESS are installed in containers. If a battery storage building is instead required, additional development costs would be incurred.
- O&M ranges from $0.75 to $13/kWh, with an average of $5.60/kWh. This analysis is using the average for the mainland estimate.
- Bloomberg costs include power electronics. For grid-forming capability, a cost premium of $100/kW is assumed.
- Replacement costs for commercial systems are not provided in the reference, but cost projections are included for both utility-scale and residential systems. The average cost reduction for 7 years from now, the assumed replacement year for the generic Li-ion battery in HOMER, is 35%. This 35% cost reduction projection is used in this analysis for battery replacement costs.

PV COSTS

- **Reference**: Cox, Molly; "Latin America and Canada Solar PV System Pricing 2020"; Wood Mackenzie Power and Renewables; October 2020.
- The cost function includes different costs for ground-mounted and rooftop systems.
- The costs for mainland Colombia:
  - $1.34/Watt-direct current (DC) for 6-kW residential
  - $0.77/Watt-DC for 50-MW utility system
  - Assuming 1.2 AC-to-DC ratio
  - Estimating then that ground-mounted PV, by interpolating between the cost points, is $1.56/Watt-AC before applying the "island cost factor."
- O&M is not provided in this reference. Assumes $13.20/W-AC per NREL 2020 Annual Technology Baseline.

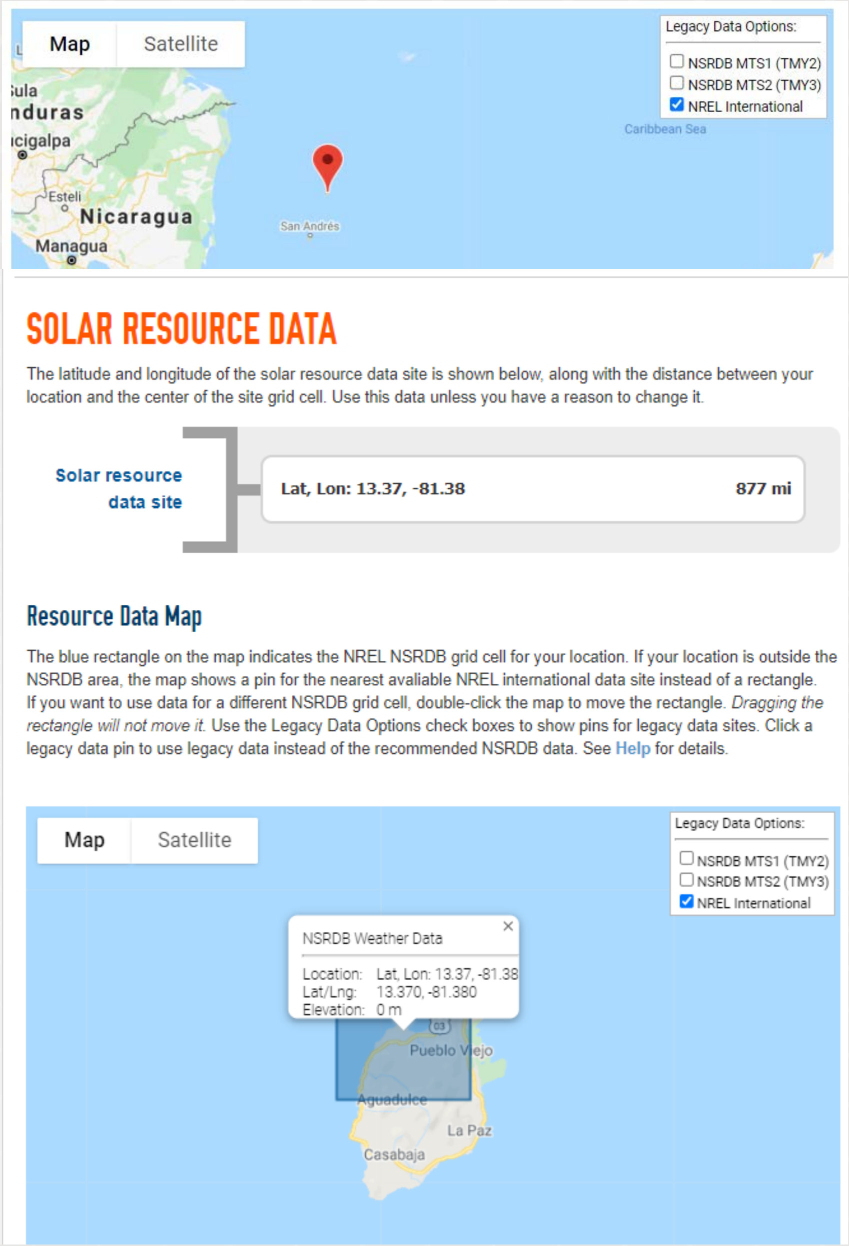
ELECTRICAL SYSTEM INFRASTRUCTURE

- A supervisory controller will be required to dispatch the diesel generators, battery, and potentially to control the centralized PV plant(s).
  - A fixed cost of $250,000 is assumed as representative.[1,2]
- Upgrades to the diesel plant switchgear are assumed to be required to allow automated operation.
  - A fixed cost of $100,000 is assumed.[1]

1. NEMA. 2016. *Powering Microgrids for the 21st-Century Electrical System.*
2. Giraldez, Julieta, Francisco Flores-Espino, Sara MacAlpine, and Peter Asmus. 2018. *Phase I Microgrid Cost Study: Data Collection and Analysis of Microgrid Costs in the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-67821. https://www.nrel.gov/docs/fy19osti/67821.pdf.

PV PRODUCTION MODEL

- NREL's PVWatts® production profile for a typical meteorological year was used in the HOMER model to estimate PV performance.
- 1.2 DC-to-AC ratio
- South-facing, 15-degree tilt
- Specific annual energy production:
  - 1,918 kWh/kW-AC, Year 1
  - 1,598 kWh/kW-DC, Year 1.
- Assuming 0.5% per-year degradation.



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