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Harnessing Distributed Solar Energy to Reduce Belize's Dependence on Imported Energy: A Preliminary Review of Solar's Potential

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This paper provides a preliminary review on the potential of solar distributed generation in Belize to reduce imported electricity from Mexico. It was found that power generation from solar sources can supply significant installed capacity on Belizean rooftops. However, rooftop solar generates energy at costs higher than conventional power-generating sources, except for fuel generators, but lower than the retail rate. Additionally, due to integration challenges and costs, curtailment will restrict rooftop market potential to credibly reduce electricity imports over the medium term. Launching an effective distributed rooftop segment that can decrease the country's dependence on imported electricity depends on internal and external factors. Scaling up rooftop solar generation will require striking a balance between clean energy targets and least-cost planning.

Author Note:

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Keywords: Photovoltaic, GHI, PVOUT, Constant-value method, LCOE.
JEL Classification: L9, L94

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Glossary

Ancillary services: are the variety of operations on the electricity networks that are required to balance supply and demand over all time scales, while maintaining voltage and frequency within safe limits and preventing overload of grid infrastructure.

Photovoltaic power production potential (PVOUT): represents the expected lifetime average electricity production (in kWh) produced per kilowatt of installed photovoltaic DC capacity considering solar radiation, air temperature, and terrain to simulate the energy conversion and losses in the PV modules.

Distributed generation: Term applied to a variety of small power supplies (eg. solar) located near the point where the power is used. Opposite of central power.

Electrical Grid: An integrated system of electricity distribution, usually covering a large area.

Hosting capacity: The limit on the amount of PV that can be integrated in a distribution grid without any grid impacts is called the PV hosting capacity.

Installed Capacity: Sometimes termed peak installed capacity or rated capacity, means the capacity of the facility (expressed in MW) were it to be operated on a continual basis at the maximum capacity possible without causing damage to it.

Irradiance: The direct, diffuse, and reflected solar radiation that strikes a surface. Usually expressed in kilowatts per square meter. Irradiance multiplied by time equals insolation.

Kilowatt (kW): A standard unit of electrical power equal to 1000 watts, or to the energy consumption at a rate of 1000 joules per second.

Load: The demand on an energy producing system; the energy consumption or requirement of a piece or group of equipment. Usually expressed in terms of amperes or watts in reference to electricity.

MW (MW): 1,000 kilowatts, or 1 million watts; standard measure of electric power plant generating capacity.

Photovoltaic: Photovoltaic (PV) technology converts sunlight into electricity. Often referred to as PV for short, photo means ‘light’ and ‘voltaic’ means electric.

Photovoltaic (PV) System: A complete set of components for converting sunlight into electricity by the photovoltaic process, including the array and balance of system components.

Peak Demand/Load: The maximum energy demand or load in a specified period.

Prosumer: A prosumer is an individual who both consumes and produces.

PV Array: A group of PV (photovoltaic) modules (also called panels) arranged to produce the voltage and power desired.

Rooftop Orientation: Also known as azimuth, orientation refers to a roof’s position relative to the sun.

Tilt Angle: The angle at which a photovoltaic array is set to face the sun relative to a horizontal position. The tilt angle can be set or adjusted to maximize seasonal or annual energy collection.

Utility-scale facility: one which generates solar power and feeds it into the grid, supplying a utility with energy. Utility-scale solar facility typically has a power purchase Agreement (PPA) with a utility, guaranteeing a market for its energy for a fixed term of time.

1.0 Executive Summary

This paper provides a preliminary review of the potential of solar distributed generation (DG) in Belize to reduce the volume of imported electricity from Mexico. Solar DG, defined as energy generated close to the point of consumption, is poised to be a disruptive force to Belize's traditional centralised electricity infrastructure.

Social acceptance of solar DG in Belize has heightened as solar photovoltaic (PV) module costs have trended downward. Concurrently, the policy community's interest has intensified with the rise in environmental awareness and the volatility of energy import prices. Since there are various technical studies yet to be done on the deployment of DG, including the Belize Electricity Limited's (BEL) Least Cost Expansion Plan Study that commenced in 2021[1], this study will provide an initial exploration and insight into solar DG's potential to displace electricity imports and the challenges associated with increasing the share of this resource in the energy mix.

1.1 The Problem

Although Belize is one of the largest renewable energy producers in the Caribbean, a significant portion of the country's electricity mix stems from imported electricity and fuel to power diesel-fired turbines. From 2017-2021, approximately 44%[2] of Belize's electricity production was sourced from renewable hydro and biomass (bagasse) sources combined. The remaining 56% was either imported from a Mexican state-owned electric utility, Comisión Federal de Electricidad (CFE) (47%), or sourced from diesel-fired turbines (9%) situated in Belize. On average, Belize spends 3.7% of its GDP on electricity-related foreign exchange payments[3], which amounts to a sizeable leakage of hard currency. BEL's Annual Report (2021, p. 6) stated that the cost of power continues to be the "most significant and variable element of overall cost," underscoring the need to increase in-country generation through investment in solar energy to reduce the impact of volatile price fluctuations and decrease reliance on fossil fuels.

The Government of Belize, along with other governments across the Caribbean, acknowledged that heavy dependence on fuel-fired electricity generation widen the region's carbon footprint, contributing to the associated climate change effects. In response, the governments of all 15 CARICOM member states signed the CARICOM Energy Policy in 2013, committing to increasing their renewable energy power capacity over time. Wyllie et al. (2018) noted that CARICOM states agreed to increase their renewable energy output as follows: (i) 20% by 2017, (ii) 28% by 2022, and (iii) 47% by 2027. Belize and Suriname are the only states that have already achieved the long-term target of 47% in 2022. Belize went a step further by committing to promote rooftop solar and setting a more ambitious national renewable target of at least 75% by 2030, in line with their commitments in Glasgow at COP26 (Annual Tariff Review Proceeding, 2022).

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[1] BEL 2021 Annual Report.

[2] Percentage sourced from renewables increases to almost 50% when 2019's drought year is excluded.

[3] 0.4% represents fuel imports for generators, 1.4% for CFE electricity imports and 1.9% represents a contractual payment in foreign currency for a portion of domestic electricity production.

According to Bunker et al. (2018), Belize's 75% renewable target is achievable through a mix of hydro, solar, and biomass sources. At the same time, reports by Electrowatt-Ekono (2006) and OLADE (2019) recognised the relevance of hydro for Belize but acknowledged its limited expansion possibilities. Given this, any power supply expansion plan to meet rising electricity demand should include renewable sources, such as utility and solar DG (OLADE, 2019).

1.2 Objectives

This study focuses only on grid-connected solar PV systems on residential rooftops with no battery storage. Therefore, this paper uses DG, solar DG, and rooftop solar interchangeably. The study seeks to answer the following questions:

- What is Belize's solar resource potential?
- What is the technical potential of rooftop solar generation?
- Is this technical potential of rooftop solar achievable, considering:
    - policy curtailment,
    - grid-integration challenges,
    - the economic and commercial viability of rooftop solar, and
    - existing barriers?

Understanding Belize's potential in solar DG generation and its associated challenges should help improve the likelihood of utilising this renewable generation source to reduce electricity imports.

1.3 Results of Analysis

The study found that power generation from Belize's natural solar resource is physically capable of supplying significant installed capacity on Belizean rooftops. An estimated total installed PV capacity of 169MW can be deployed on rooftops throughout the country. Based on Belize's average daily solar radiation of 5kWh/m^2, this instalment could generate approximately 221,659MWh of solar electricity annually. Therefore, rooftop solar power can save around US$40.2mn in electricity import costs annually.

However, the achievement of this technical potential is hampered by the possible curtailment of this intermittent source in the absence of storage. Currently, there is no official cap assigned to distributed renewable energy sources. Preliminary discussions recorded in previous sources have proposed 10% of peak demand for non-firm renewable sources with a tentative allocation of 5MW for solar distribution. Whatever curtailment is approved by the Public Utilities Commission (PUC) in the future it will impact the potential to reduce imports.

The financial viability of widespread DG applications is mixed. On the one hand, rooftop solar generates energy at BZ$0.34 cents, which is higher than conventional wholesale power-generating sources, except for fuel generators. On the other hand, between 10:00 a.m. and 1:00 p.m. on weekdays when solar is at its maximum generation capacity, CFE prices are typically (but not always) higher than BZ$0.34 cents. Additionally, from the average customer's perspective, the payback period is also lengthy at 12.3 years. However, BEL's Solar PV Programs could alleviate the initial investment costs, making it more attractive to customers. Under this third-party ownership scheme, the customer would allow BEL to install a solar PV system on their roof, and any surplus generation would be credited towards future consumption. Among other things, the customer would benefit from a reduction in their monthly electric bill.

Furthermore, increased penetration of solar DG would bring significant integration challenges and costs, restricting rooftop solar production potential to reduce electricity imports significantly over the short and medium term.

1.4 Recommendations

Launching an effective distributed rooftop segment that can decrease the country's dependence on imported electricity depends on:
(i) **external factors:** such as, the continued decline in costs for solar panels and batteries; and
(ii) **internal factors:** such as, the elimination of import duties on solar hardware and batteries; increased investments to make the electricity system more flexible; implementation of supportive compensation policies, rate structures, and interconnection standards; and reasonable financing options.

For Belize, which already has a good mix of renewable energy in its supply portfolio, a wider scale-up of rooftop solar PV will need to find that balance between clean energy targets and least-cost planning.

2.0 Methodology

To provide preliminary insights into Belize's solar potential, this study was guided by the descriptive-analytical framework proposed by the U.S. National Renewable Energy Laboratory (NREL) (Brown et al., 2016) and the World Bank Group – ESMAP (2019).

2.1 Technical Potential Analysis

In this study, "technical potential" measures the maximum possible solar energy production given the availability of roof surfaces. The constant-value methodology was used to estimate the maximum PV generation capacity for residential rooftops[4] based on the suitable rooftop area for PV installation. A constant-value analysis is a simple method using the total number of housing units and estimated floor space. This data is used alongside several rule-of-thumb assumptions for rooftop orientation, tilt angle, and shading to calculate total roof space. According to Kurdgelashvili et al. (2019), although the constant value method is simple, it can accurately estimate technical PV potential for large geographical areas.

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[4] Rooftop PV potential studies can be categorised into constant-value methodology or Geographic Information Systems (GIS) based methodology.

2.1.1 Data Inputs and Calculations for Technical Potential

The main data inputs to assess technical PV potential are:

- average daily shortwave solar radiation (GHI) received by a horizontal surface (kWh/ m^2),
- PV power production potential (PVOUT),
- total number of houses and type of structure,
- total gross roof space, and
- total PV array area (available area of the roof).

2.1.2 Rooftop Technical Production Method

Step 1: Calculate gross roof space. According to Belize's 2019 Labour Force Survey, the number of single-family detached, single-family attached, and apartments was 86,671 units. Using the 2010 Belize Census report as a guide, an estimated 63% of housing units had wooden, cement, or mixed structures that supported appropriate roofing material[5] for PV installation. Furthermore, before calculating the total rooftop area for residential buildings, the average square footage of the different house types was assumed to be 800 square feet.[6] All housing unit types are assumed to have pitched roofs with an average tilt angle of 20 degrees. Using these factors, the total gross roof space of the residential buildings can be calculated as follows:

Gross Roof Space = Total Number of Housing Units * Average Housing Roof Size (1)

Step 2: Calculate the total area for the PV array. The available area of pitched roofs for PV installation can be reduced by shading from trees, other obstructions, and roof orientation. Therefore, an access factor was applied for residential roofs to account for losses and other constraints. The literature[7] on rooftop PV potential provides reference values for the access factor. Following Kurdgelashvili et al. (2019), an access factor of 24.3% for hot climates was used. The total area for PV arrays that can be installed was calculated as follows:

Total PV Array Space (Tilted Residential Roof) = Gross Roof Space * Access Factor * (2) Geometric Factor

Where,

$$\text{Geometric Factor} = 1/\cos(\text{Tilt}) \qquad (3)$$

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[5] 100% of concrete housing units were assumed to have suitable roofing and a third of wooden and mixed houses were assumed to have appropriate roofing to support PV installation.

[6] Approximated based on a typical two-bedroom house plan provided by Belize Central Building Authority. Square footage of typical low-income house category ranges between 800 - 1000 square footage.

[7] Chaudhari et al. 2004. Denholm and Margolis 2008, Frantzis et al. 2007, Paidipati et al. 2000, Kurdgelashvili et al., 2019, estimate access factors of 22% - 27% for residential rooftop area suitable for PV installation.

Step 3: Estimate total residential PV production. The total residential PV potential[8] was estimated by converting the total available PV array roof space values from square footage to square meters and multiplying this estimated total PV array area with the assumed solar system power density (W/m^2), which is determined by panel efficiency (here, assumed at a conservative 15%). This calculation is displayed below.

$$\text{Technical PV Potential (MW)} = \text{Total PV Area} * \text{Power Density} \quad (4)$$

Where,

$$\text{Power Density under Standard Test Condition} = 1000W/m^2 * \text{Panel Efficiency} \quad (5)$$

2.2 Economic Potential Analysis

The study also assessed the economic PV potential via a simplified levelized cost of energy (LCOE) and payback period analysis. The LCOE indicator employed simple assumptions about installation and maintenance expenses to estimate how much it would cost to produce a unit of energy (ESMAP, 2020). This metric permits the comparison of solar energy to other energy generation technologies.

2.2.1 Calculations for Economic Potential

The methods to assess economic potential are:

- Simplified levelized cost of energy (LCOE)
- Payback period time estimation

LCOE[9] is the product of all the lifetime costs associated with installation and operation of the PV system divided by the electricity produced during this lifetime, represented by the following formula:

$$LCOE = \frac{Total\ Life\ Cycle\ Cost}{Total\ Lifetime\ Power\ Produced} = \frac{\sum_{t=1}^{n}\left(\frac{CAPEX_t + OPEX_t}{(1+d)^t}\right)}{\sum_{t=1}^{n}\left(\frac{PVOUT_t}{(1+d)^t}\right)} \quad (6)$$

In which, LCOE = the average lifetime levelized cost of electricity generation, $CAPEX_t$ = investment expenditures in the year t, $OPEX_t$ = operations and maintenance costs in the year t, $PVOUT_t$ = electricity generation in the year t, d = discount rate, and n = lifetime of the PV system in years.

Meanwhile, the payback period is a simple indicator that gives the number of years it takes to break even from undertaking the initial expenditure. It is used to evaluate the feasibility of a given project and is measured as follows:

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[8] Similar to Kurdgelashvili et al. (2019), the final technical potential estimation in this study represents a restrained ceteris paribus result, as the panel efficiency and housing stock is static and does not allow for either efficiency gains due to innovation or housing unit expansions.

[9] It must be noted that this LCOE calculation is just an approximate calculation that may differ at the real generation level due to various intricate factors such as grid infrastructure, and soft costs such as installation design and other balance of system costs..

Payback Period = Initial Investment / Estimated Annual Net Cash Inflow (7)

2.3 Interviews

The existing constraints and challenges of a solar rooftop segment were gleaned through semi-structured interviews with representatives from the Belize Electricity Limited (BEL), the Public Utilities Commission (PUC), and the Energy Unit in the Ministry of Public Utilities. Additionally, a consumer and two suppliers of solar modules were interviewed.

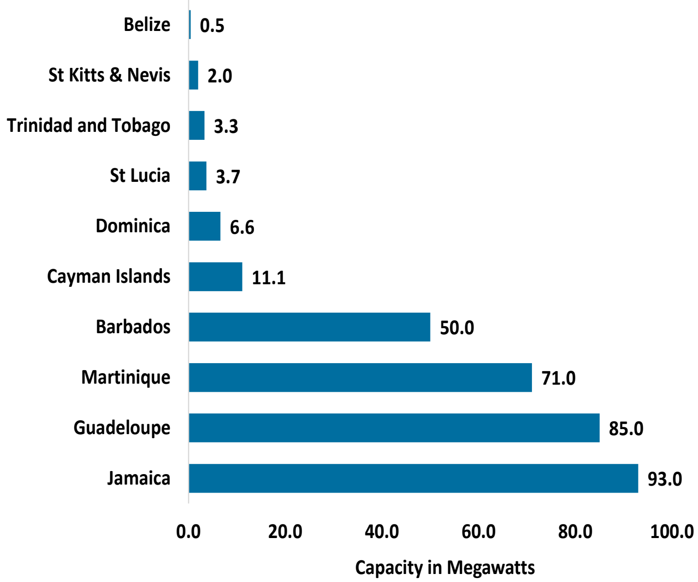
3.0 Belize's Electricity Landscape

3.1 Energy Supply System

In Belize, BEL is the sole distributor of electricity. It purchases electricity from several domestic, independent power producers[10] (IPPs) and a Mexican state-owned electric utility, CFE. Hydropower and imported electricity purchased on the spot market from Mexico's CFE are Belize's primary energy sources, followed by biomass. However, the share of solar energy is negligible. When it comes to installed solar PV capacity, Belize lags most of its Caribbean counterparts (see Figure 1).

In 2020 and 2021, the primary energy consumer was the commercial sector, followed closely by the residential sector. Installed capacity was approximately 178.2MW in 2020, with peak demand of 102.7MW. Table 1 provides an overall picture of Belize's energy supply system at the end of 2020 and 2021.

Figure 1: Installed Solar PV Capacity in the Caribbean (2020)



Note: Adapted From "Latin America and the Caribbean: solar PV capacity 2020, by country", by B. Alves, 2021. Copyright 2022 by Statista

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[10] IIPs include Belcogen and Santander (bagasse), Mollejon, Vaca, Challilo, Hydro Maya (hydro), Blair Athol Power Company (Heavy Fuel Oil (HFO))

Table 1: Belize’s Electricity Production, Demand, and Average Unit Cost of Electricity

	2020	2021
Annual Energy Consumption (MWH)	539,269	560,793
Peak Demand (MW)	102.7	103.5
Annual Net Generation (MWh)	613,681	646,034
Hydro production	241,986	157,326
Imports from Mexico	270,239	380,195
Biomass production (bagasse fired)	81,332	57,508
Solar production	568	595
Fuel Plant production (HFO/deisel)	19,555	50,409
Mean Electricity Rate (US$/kWh)	0.211	0.204
Annual Average Unit Cost of Power (US$/kWh)	0.110	0.121
Average unit cost imported from Mexico (US$/kWh)	0.069	0.085
Average unit cost of Hydro (US$/kWh)	0.126	0.105

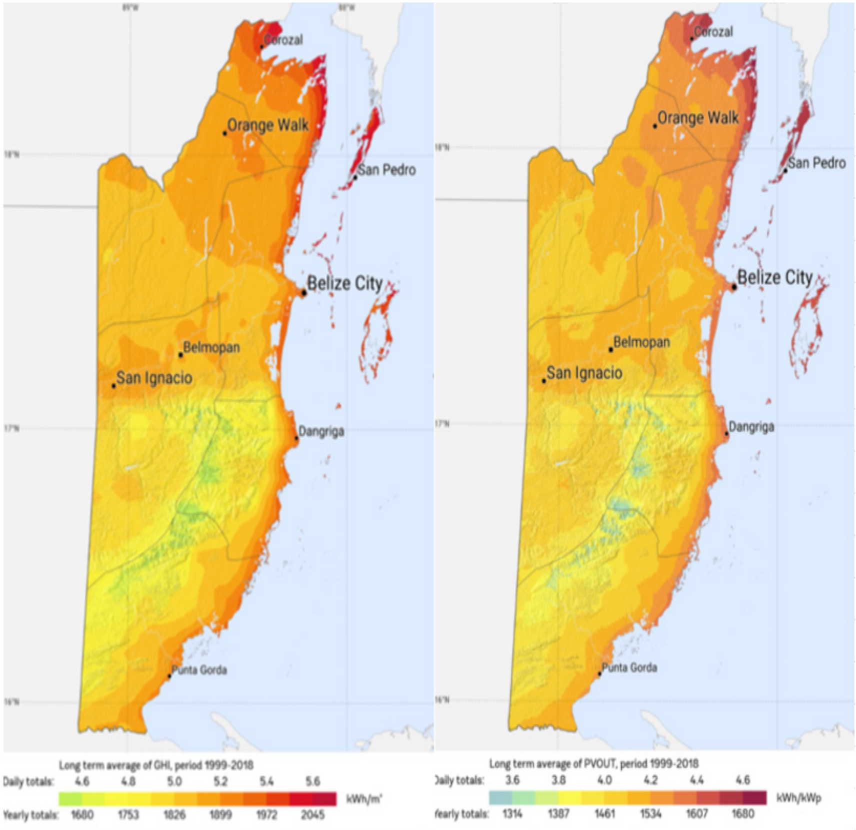
Note: Taken from BEL Annual Report 2021 and BEL’s Letter to PUC regarding Cost of Power and Related Matters for September 2021. Public Domain.

3.2 Regulatory and Policy Context

In Belize, the PUC is the primary entity responsible for oversight of the electricity sector. The Commission was formed under the Public Utilities Commission Act with the responsibility of ensuring that: i) the services (namely potable water, telecommunications, and electricity) offered by public utility providers are satisfactory and provided at a reasonable cost; and ii) the interest of consumers is protected, pertaining to tariffs, continuity, and quality of supply.

Over the years, Belize has enacted and signed on to several policies to encourage using renewable energy technologies to lower the nation’s carbon footprint (see Appendix Table A1). Although several Caribbean countries have implemented some form of policy mechanism to support and incentivise the implementation of solar DG (see Appendix Table A2), Belize has no regulations to guide the development of the distributed solar market. However, the legal and regulatory framework to include DG is being developed by the PUC and BEL (BEL, 2021). In the proposed Electricity Byelaws 2017, BEL must develop interconnection standards for energy trading with customers operating distributed renewable sources. Additionally, bye-laws on new class licenses for DG that will guide purchase agreements and compensation mechanisms are currently being developed. Furthermore, in 2022’s Annual Tariff Review Proceeding (ARP), the PUC began to lay the foundation for developing a DG market by recommending that BEL install a battery energy storage system at the Belize City and San Pedro Substations, respectively, by September 2023. They viewed the “introduction of battery storage as a precursor to the uptake of DG and utility-scale intermittent renewables” (ARP, 2022, p. 8).

Figure 2: Belize's Global Horizontal Irradiance (RHS) and Photovoltaic Power Potential (LHS)



Note: From Global Solar Atlas 2.0, Solar resource data: Solargis. Copyright by the World Bank CC BY 4.0

4.0 Analysis of Solar Energy's Resource and Technical Potential

Any analysis of solar DG begins with a look at the long-term energy availability of the country's solar resource or theoretical resource potential. The next section contains an assessment of solar's technical potential.

4.1 Theoretical Resource Potential

Solar resource potential is characterised by the amount of sun's energy that Belize receives over a certain time. Countries near the equator or in a tropical climate, such as Belize, generally experience higher levels of solar radiation than in temperate climactic zones. Figure 2 (left-hand side, LHS) is an irradiance map of Belize. It shows that some regions in Belize experience values of up to 5.6 kWh/m^2, with most of the country receiving daily totals above 5kWh/m^2. When accounting for climatic and geographic effects and PV system configuration, the theoretical solar output for Belize dips from an average of 5.2kWh/m^2 (Figure 2 LHS) to a practical photovoltaic power potential (PVOUT) of approximately 4kWh/kWp (Figure 2 right-hand side, RHS). Most countries fall between a PV potential of 3.0 and 5.0 kWh/kWp, with only 70 countries having an average daily output that exceeds 4.5kWh/kWp (ESMAP, 2020).

4.2 Technical Potential

4.2.1 Technical Generation Potential

In addition to solar radiation, the roof area available for PV installation will directly determine energy generation capacity. Using the constant-value approach, the total roof space for PV deployment for all residential units in Belize was estimated at 46.4mn ft^2 (Appendix Table A3).

Accounting for the access factor and roof tilt, the total roof space was transformed into 1.1mn m^2 of useable rooftop space for PV array installation. Assuming a conservative module efficiency of 15%, an estimated total installed PV capacity of 169 MW can be deployed on rooftops throughout the country (see Table A4). Based on Belize's average solar radiation, this instalment could generate[11] approximately 221,659MWh of solar electricity annually. Rooftop solar power has the potential to cover 40.0% of total electricity sales, calculated as average sales over the period 2019-2021, and 90.3% of residential electricity consumption, based on a three-year average of residential sales.[12]

5.0 Is the Technical Potential for Rooftop Solar Achievable?

Belize has significant technical potential for rooftop solar energy. However, considerable effort will be needed to achieve Belize's technical potential when accounting for the myriad of barriers facing rooftop solar power generation, including regulatory, economic, and grid challenges.

The development of Belize's rooftop segment will be influenced by its perceived financial viability, the distribution grid configuration and costs, and any future policy curtailment of intermittent solar generation. Chiefly, applying any generation cap could limit the rooftop segment and influence the reduction of CFE imports over the medium term. This section will explore the key challenges and constraints of the solar rooftop market under current technical, economic, and regulatory conditions, namely:

- distribution grid challenges,
- economic and commercial viability of rooftop solar,
- rooftop PV curtailment policies, and
- barriers to solar rooftop development.

5.1 Distribution Grid Challenges

Integrating rooftop solar generation within the existing network is expected to create issues relating to power quality, infrastructure requirements, and technical performance. Incorporating rooftop solar systems necessitates a more active distribution network than what currently exists in Belize.

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[11] Generation estimates are an approximation based on average GHI or 'peak sun hours' available per day over 300days for the year due to cloud coverage, and an estimated tilt factor of 1.1 resulting from optimum orientation of PV module. A rule of thumb performance ratio of 0.75 was applied that considers deduction of energy loss e.g., conduction loss.

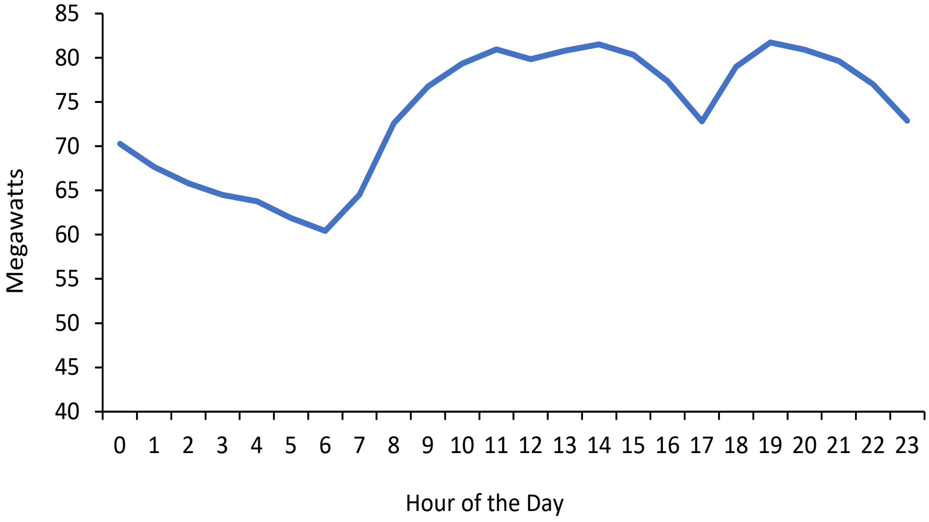
[12] Residential sales were 245,265MWh in 2020 (BEL Annual Report, 2020).

5.1.1 Hosting Capacity Challenges

Distributed rooftop solar PV systems are designed to export surplus energy to the distribution grid, where power flows from customers back to the network. However, Belize's grid network is not designed to handle this feedback. Brown et al. (2014) posited that reviewing the associated costs of integrating PV in the distribution grid is critical for evaluating the effectiveness of solar integration and, thus, the future development of the distributed market. Installing more solar PV than the circuit's hosting capacity[13] can cause adverse effects, such as overvoltage, line-loading violations, and other overcurrent protection-related problems in the system (Jothibasu et al., 2016). Presently in Belize, current meters can only support small systems, and these meters cannot effectively track what the prosumer will provide back to the grid. Additionally, with higher PV deployment, there will be a need for grid-side and operational measures such as, scheduling and dispatch coordination, and new technologies and system upgrades to keep the system stable. These measures will certainly bring additional network costs. Customer-sided solutions such as smart inverters and battery storage to modulate power exports based on the time of the day, will also be needed to accommodate more PV than the hosting capacity (IEA, 2019).

Preliminary surveys by BEL, the main distributor, have indicated that the grid can support an overall hosting capacity of approximately 24-40% of peak load demand, given the current configuration. However, hosting capacity depends on location, is time varying, and is unique to specific feeders, or main power lines. Therefore, BEL's hosting capacity estimate will vary depending on the specific location on a distribution circuit. Accommodating high penetrations of solar PV going forward

Figure 3: Belize's Average Hourly Load Profile 2021



Note: Demonstrates the daily demand for electricity that is served by available generation.
Sourced from BEL

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[13] The limit on the amount of PV that can be integrated in a distribution grid without any grid impacts is called the PV hosting capacity (Jothibasu et al., 2016).

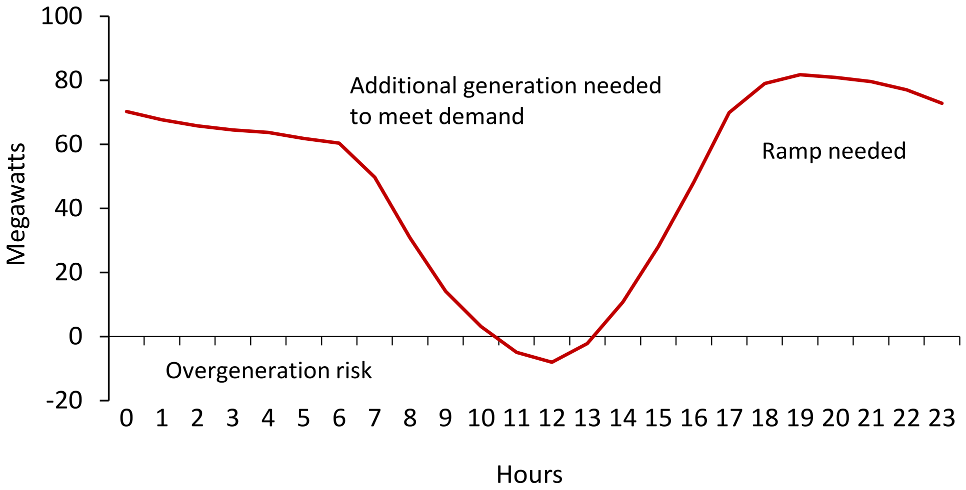
will require BEL to execute hosting capacity analysis reports. These studies would help to guide interconnection roll-out plans by pinpointing the suitable locations (feeder and/or substations) for the smooth integration of solar PV and the unsuitable locations that would need some impact mitigation strategies to increase hosting capacity.

5.1.2 Grid Flexibility Challenges

Figure 3 shows Belize's average hourly load profile for 2021. This curve approximates the actual demand for electricity throughout the day. The load graph indicates that Belize's first ramp period is around 6:00 a.m., which peaks and levels off around 10:00 a.m. The second ramp period comes as the sun sets around 6:00 p.m. Under growing solar penetration on the grid, solar production would coincide with peak demand between 10:00 a.m. and 3:00 p.m., saving hydro resources during peak PV generation hours for evening peak power generation when demand increases and PV generation stops altogether.

Figure 4 approximates the residual load if Belize's full technical potential is generated. The residual load curve is derived by subtracting the potential technical supply of rooftop solar (adjusted by a ratio of hourly solar irradiation) from power demand over a 24 hour period. The residual curve provides insight into three challenges concerning variability and correlation of power demand with rooftop solar supply (Ueckerdt et al., 2011). First, the full-load hours of dispatchable generation capacities will be reduced. In turn, this will require ramping flexibility and the ability of these sources to start and stop multiple times per day. Second, rooftop solar provides low-capacity credit, defined as the "amount of additional load that can be served due to the addition of the generating unit while maintaining existing reliability" (Alabadi, 2020). Solar can meet Belize's first peak hours without battery storage between 11:00 a.m. and 1:00 p.m.

Figure 4: Estimation of Belize's Residual Load Curve



Note: Demonstrates the amount of load remaining to be served by non-solar generation after loads have been served with all available rooftop solar generation at its technical potential. Authors's estimation.

However, without battery storage, adding more rooftop installations will not meet the second peak demand given solar's diarnal pattern of generation. Third, the overproduction during the early afternoon will need to be curtailed in the absence of storage or the ability to transmit it.

The need for flexible power output would redefine Belize's future power purchase agreements to include ramping flexibility. Presently, each of Belize's energy supply sources has "different characteristics of cost, level, and type of capacity, reliability, location on the grid, and purchase arrangements with BEL" (Mencias, 2021, p. 2). For example, in the case of CFE, energy, subject to availability, must be purchased two days ahead of actual dispatch, compared to purchases from BECOL, where BEL must ensure that it purchases all energy by this facility or pay for the remainder not taken up (Mencias, 2021). If solar is added to Belize's energy mix, another "must-take" supply source is added, where solar energy must be taken up during the main hours of 10:00 a.m. to 1:00 p.m. This calls for active power and timing balance, alongside adjustments to BEL's dispatch models to ensure the pursuit of the most economical dispatch.

In Belize's energy mix, hydro and diesel generation plants offer flexible reaction times. Biomass is used for baseload when online and, therefore, does not have this capability. CFE also has the potential to be flexible through an ancillary service contract. Currently, "if BEL takes more than it had contracted to in any hour on the day of dispatch, it will pay the spot price on any additional amounts it purchases" (Mencias, 2021, p. 2). BEL is working on an ancillary service contract to fix this issue. With CFE providing ancillary services to mitigate the variability and uncertainty of PV, higher solar penetration might reduce CFE imports but not eliminate them. Tillet et al. (2012) pointed out that energy independence and resiliency are often incorrectly viewed as interchangeable. Belize's energy policy does not advocate for independence but rather for resiliency and sustainability through a diversified energy supply portfolio with least-cost considerations.

5.2 Economic and Commercial Viability of Rooftop Solar

We now assess the economic and commercial viability of rooftop solar using our principal metrics of LCOE and the payback period. If this technology is commercially viable, customers will choose to install a rooftop solar system, that is, if their solar system can pay for itself within a reasonable time and their monthly electricity bill is reduced. Economic viability is achieved if the cost of generating 1 kWh of rooftop solar generation is lower than the cost of wholesale power (Gischler and Janson, 2011) and a unit of imported electricity. Achieving economic viability will reduce the cost of electricity to the country or at least not increase it.

5.2.1 Economic Viability

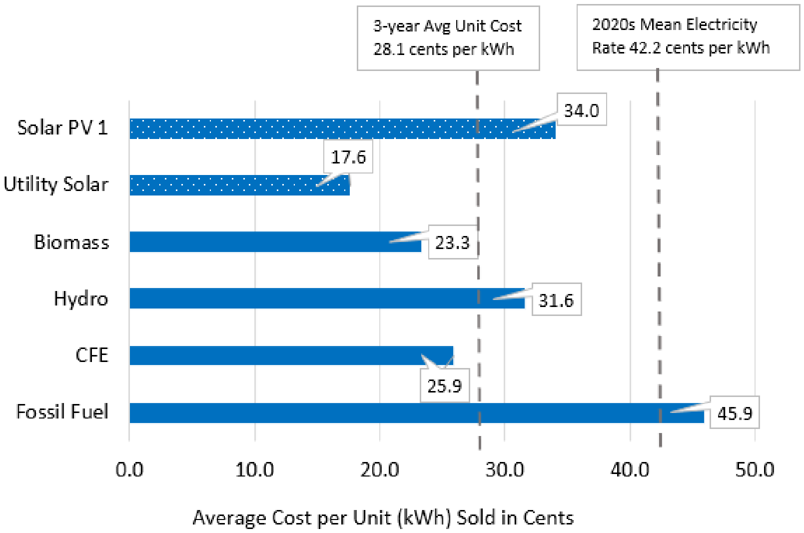
The LCOE was calculated on the following assumptions:

- a 3kW solar system,
- system cost of US$6,000,

- operational life is 25 years,
- annual maintenance costs at 2% of the initial system cost, and
- discount rate[14] of 6% , and
- system efficiency of 15%.

These assumptions lead to solar DG production costs of 0.34 BZD/kWh

Figure 5: Solar PV compared to 5-yr average wholesale power cost and 2021's retail mean electricity rate ($BZD)



Note: The unit cost of power for respective utility sources and CFE are based on the average annual unit cost 2016-2020, BEL. Public domain

Except for the fuel-powered facilities, distributed solar generation costs are higher than other power sources in Belize at BZD 0.34 cents per kWh (Figure 5). Figure 5 also shows that solar PV generates energy at a cost less than the retail rate. This aspect suggests that rooftop PV could deliver substantial economic benefits to host customers if some form of feed-in-tariff policy was in place in Belize. Compared to the US minimum and maximum residential 2021 LCOE benchmarks (Lazard, 2021), Belize's rooftop solar LCOE lies within the range (see Figure 6).

Having economic viability reduces the cost of electricity to the country or at least does not increase it. Presently, BEL's dispatch model pursues the "most economic dispatch" (Mencias, 2021), and thus, operational modes are primarily tied to CFE prices and BECOL's reservoir levels. CFE prices are generally lower early in the mornings and for extended periods through Saturday and Sunday. Figure 7 shows CFE prices for a weekend and weekday in October 2021. The grey area of Figure 7 shows the "must take" period of the day, where rooftop solar must be dispatched without batteries or the ability to transmit it. Accounting for the

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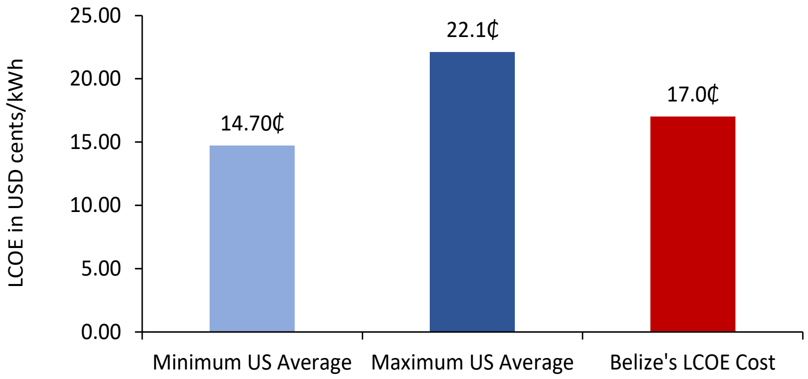
[14] The discount rate represents the opportunity cost of capital, which is foregone elsewhere by committing to a solar PV investment. There are economic and non-economic factors that can influence a decision to get rooftop solar, and therefore it is difficult to set a discount factor (Doluweera, et al., 2020). Therefore, this study calculates the LCOE values using two discount rates.

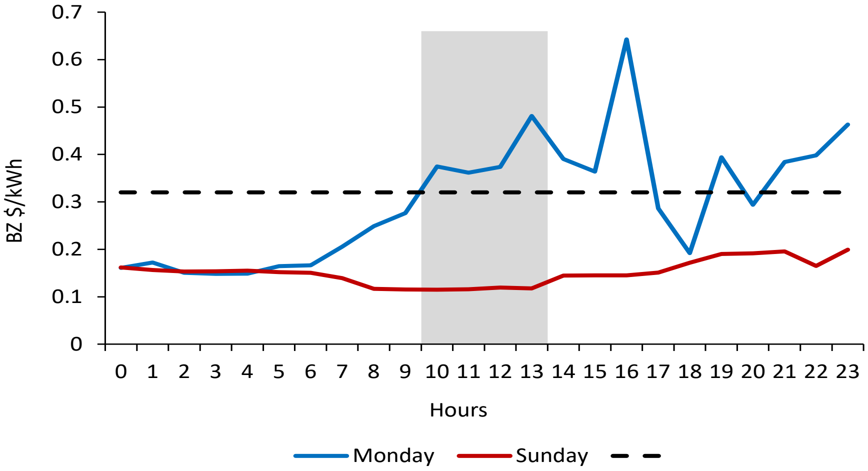
Figure 6: Comparative Look at LCOEs for US Residential PV and Belize Residential PV (USD)



Note: Adapted From "Levelized Cost of Energy (LCOE) analysis version 15.0 for Energy," by Lazard, 2021. Copyright 2021 by Lazard; and Author's calculation.

solar rooftop's estimated LCOE of BZD$0.34, there is the possibility of cost-savings during the solar peak period of 10:00 a.m. to 1:00 p.m. during weekdays. However, these savings are offset on the weekends, when CFE prices are typically at their lowest. For Belize, which already has a good mix of renewable energy in its supply portfolio, a wider scale-up of rooftop solar PV will need to find that balance between clean energy targets and least-cost planning.

Figure 7: CFE Hourly Prices Compared to Solar PV LCOE Cost



Note: Taken from Letter Re. "*Cost of Power and Related Matters*", John Mencias, 2021. Public Domain.

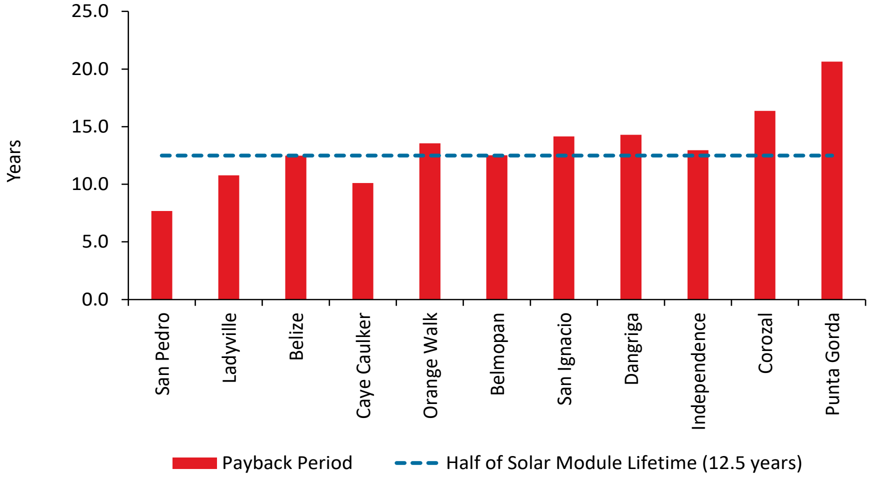
5.2.2 Commercial Viability

Regarding commercial viability, the payback period for a small solar PV rooftop system is lengthy at 12.3 years. This result is based on the following assumptions: a 3kW system, daily electricity use of 8.2 units or kWh/day, an average monthly electricity bill of BZD 107.38, an approximate electricity bill savings of BZD 80.09 per month, and initial investment sourced out-of-pocket.

Photovoltaic solar panels are designed to last at least 25 years. A payback below half the lifetime may be acceptable for some prosumers, but Darghouth et al. (2020) suggested that payback periods closer to 5-7 years were more likely to stimulate the expansion of solar markets.

However, the electricity usage and bill will vary across individual customers and districts (see Figure 8). For example, San Pedro, Caye Caulker, and Ladyville displayed the highest average residential demand and electricity usage, and therefore, payback periods for these regions were 7.7, 10.1 and 10.8 years, respectively. Districts with the lowest average electricity bills had the highest payback periods. These districts were Punta Gorda and Corozal, with estimated payback periods of 20.6 years and 16.4 years, respectively.

Figure 8: Payback Periods by Region



Note: Author's estimation of the payback period for an average Belizean consumer by region.

The upfront cost of solar systems is burdensome for the average Belizean, particularly for lower-income households. Combined with a long payback period, the commercial incentive is practically eliminated. This would lead to slow gains in market share and, thus, impact the pace at which rooftop solar can lower imports. At the same time, many landlords might be reluctant to invest in an installation from which the tenant will benefit. However, BEL's "rent-a-roof" model, where BEL incurs the upfront installation costs while the customer reaps the benefit of lower monthly bills, would help to stimulate uptake.

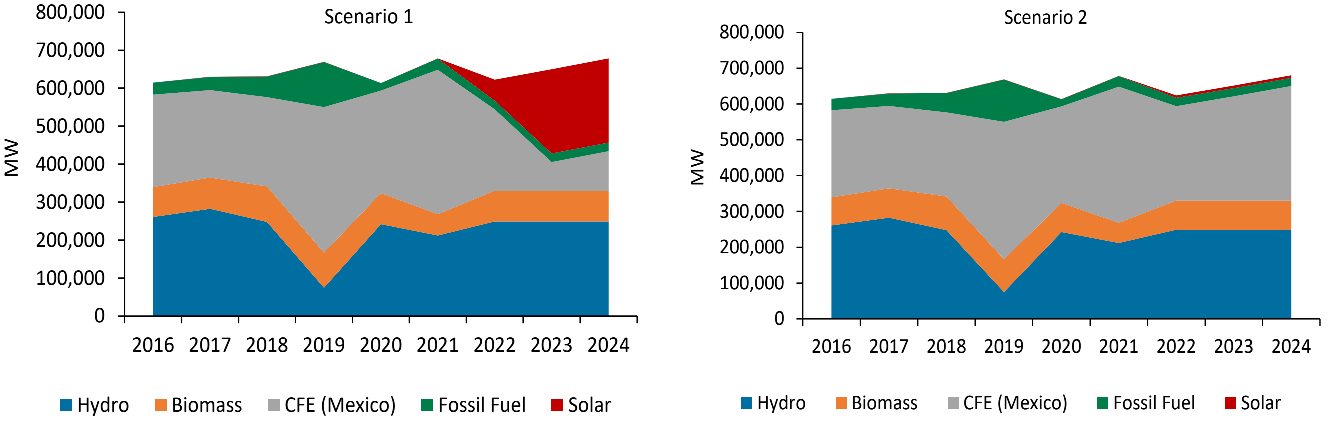
5.3 Curtailment Challenges

Based on the technical potential of rooftop generation, solar DG is sufficient to reduce electricity imports. However, a policy-induced curtailment of solar DG is very likely given solar's intermittent nature and the absence of storage. According to the PUC's 2013 initial draft proposal, the cap for non-firm renewable generation sources was set at approximately 10% of peak demand capacity (Belize Technology Needs Assessment, 2017, p. 152). A smaller system distributed generation cap was also set within this overall cap. In 2017, the Belize Technology Needs Assessment Report (2017, p. 152) provided an estimated cap of 5MW for small distributed solar energy generation that regulatory stakeholders tentatively proposed. Nonetheless, these proposed caps have not been officially endorsed by the PUC, and there are ongoing discussions to finalise the optimal curtailment of rooftop distributed solar PV and other non-firm renewable generation sources.

Two scenarios were used to gauge how an overall rooftop DG cap could affect the reduction in imports. Scenario 1 assumes that the technical potential generation of 221,659MW is reached in 2023 and 2024, while scenario 2 assumes that a 5MW cap is applied to rooftop solar. Thus, solar DG electricity generation is only 6,560MWh.

- In scenario 1, import savings of BZ$80.4mn[15] are realised from 2022-2024 (Figure 9, RHS). Imports are reduced to accommodate increasing PV output.
- Under scenario 2, no import savings are realised, as the much lower solar generation is insufficient to fill the energy requirements to supply additional demand growth (see Figure 9, RHS).

Figure 9: Projected Reduction in CFE Imports based on Technical Potential and Curtailment of Rooftop Solar PV Generation[16]



Note. Projection scenario 1 of how rooftop solar reduces CFE in the electricity mix using the technical potential generation. From BEL and Author's Estimation.

Note: Projection scenario 2 of how rooftop solar reduces CFE in the electricity mix with the cap on solar generation. From BEL and Author's Estimation.

5.3.1 Import Intensity of Solar PV Investments

Additional consideration must also be given to the significant import content of solar PV investments. A local supplier stated that imports accounted for 80-90% of solar installation costs. Tillet et al. (2012) referred to Belize's "dependency dilemma" in their study, where solar energy had the potential to decrease the imports of electricity and fuel but simultaneously increase solar equipment importation. Recently, suppliers imported an average of $1.5mn in solar equipment

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[15] Import savings measured using average CFE unit cost of power for period 2016-2021.

[16] These two comparative projection scenarios do not account for the approximate 15MW of solar utility that is planned for. This analysis focuses only on distributed solar PV rooftop segment. Also, any extra demand growth in both scenarios is supplied by CFE or solar as the assumption is that biomass and hydro's future expansion possibilities are limited. Therefore, projections for these two sources are kept at their 5-year averages over the projection period. Projection of demand growth based on BEL's projections over this period.

over the last five years. This amount is negligible. However, solar equipment imports will likely increase with future growth in the rooftop solar PV market, with a likelihood of offsetting CFE's import reductions.

5.4 Barriers to Solar Rooftop Development in Belize

Furthermore, as part of the assessment, several barriers to achieving solar PV rooftop market development were identified based on literature and interviews with energy stakeholders and solar suppliers. They included:

- regulatory and procedural barriers,
- financial Barriers, and
- technical Barriers.

These barriers are outlined below.

5.4.1 Regulatory and Procedural Barriers

- **Lack of compensation mechanisms**: The absence of incentive schemes such as Standard Offer Contracts for small-scale energy installers is a barrier for this nascent market.
- **Inability to connect to the grid to sell power**: Grid rules are not designed to accommodate DG.
- **Lack of regulations and technical standards**: The lack of standards/regulatory framework was identified as a significant barrier, including the non-availability of standards for products, workmanship, grid connection, and installation. According to the PUC, bylaws and standards will be released soon. There will be a Power Purchase and Procurement Bye-law to clarify and present price-clearing mechanisms and detail the trade of power, including feed-in tariffs with volume-control mechanisms. Also, interconnection licensing will focus on establishing technical and international standards and physical interfaces.
- **Inflexibility of tariff structure**: Flexibility is needed to facilitate new business models by BEL, the only distributor who would want to participate in the rooftop solar market. Any new regulations or tariff structure need to be fair to relevant stakeholders, ensuring that the country can accommodate rooftop PV on an appropriate level. However, according to the PUC, addressing the flexibility of the tariff structure to accommodate rooftop solar PV sales to the grid will likely not be resolved in the near term. The last tariff structure review was in 2005, and since then, the cost of servicing residential buildings has gone up, whereas industrial has gone down. However, plans are underway to categorise new prosumers accounts to apply a suitable pricing design that will recover applicable network costs, allowing a net billing market-based compensation scheme at the wholesale price.
- **Lack of knowledge and awareness by consumers**: Consumers lack knowledge of the technical aspects, costs, and benefits of solar PV systems. For example, stakeholders pointed out that many solar owners believe their solar panels will give them power during an outage. Many mistakenly view their grid-tied panels on their homes as microgrids when they do not have this capability unless they invest in storage and smart inverter technologies that allow islanding.

5.4.2 Financial Barriers

- **High import taxes**: Suppliers identified import tax as a barrier to developing the solar PV DG market. Though solar panels are only charged a 3% environmental tax, battery components are taxed at a 35% import tax rate plus 12.5% general sales tax (GST) and a 3% environmental tax. All other system components are taxed at the same GST and environmental tax rates with a 5% import tax. This makes an already costly project even more expensive, thus making the employment of solar PV models less attractive, especially for those who may not be able to access credit.
- **Economies of Scale**: Belize is a relatively small market compared to other nations worldwide undertaking solar energy initiatives. For comparison, Belize consumed 539GWh of electricity in 2020, whereas Germany, a country that employs solar DG energy heavily, consumed 557.5TWh in 2020 (Alves, 2021). With such a large demand market, these countries can obtain economies of scale within their rooftop solar market segment, which drives down costs for the customer. There is simply not enough demand for electricity in Belize. Therefore, costs will be passed down to the consumers when the relatively more expensive solar source is added to the energy mix.
- **Theft**: A consumer mentioned that theft of their panels was a challenge they faced. Solar PV panels are mounted on rooftops, making them especially vulnerable to theft if not properly installed.

5.4.3 Technical Barriers

- **Solar Panel Intermittency**: Solar power output is variable because of the solar cycle and clouds. The intermittency of solar panels can be eliminated by using batteries that can expand dispatch capabilities. However, the cost of storage technology remains high. This was identified as a significant barrier to faster growth of the rooftop segment.
- **Inspection and Maintenance Capacity Constraints**: With the growth in the rooftop solar market, the demand for skilled technicians to inspect premises will increase. The limited capacity of skilled technicians to conduct inspections could be a potential bottleneck to market development.

6.0 Risks, Opportunities, and Recommendations

6.1 Risks and Opportunities

The challenges and risks outlined in section 5 and Table 2 are not specific to Belize and have led many countries to prioritise utility-scale solar over rooftop solar generation (SolarPower Europe, 2021; Amarawardhana et al., 2019; Tsuchida et al., 2015). These risks exist despite the opportunities that can be exploited with a rooftop segment. One such risk is where higher income households are more likely to install PV, and any subsidisation of this segment could be regressive and increase energy inequality (Lukanov and Krieger, 2019). Additionally, when consumption of BEL's power decreases with distributed solar, the company's fixed costs will not change and, thus, must be distributed over a smaller volume of sales, penalising those that do not have installed solar. Similar risks are tied to the supportive mechanisms that can become burdensome to the government, depending on the policy incentive mix they choose.

Table 2 outlines the main risks and opportunities of rooftop solar based on literature and interviews with energy stakeholders.

Table 2: Risks and Opportunities of Rooftop Solar PV

Levels		Scope/Stakeholder	Risks	Opportunities
1.	**Macro**	**1.1** Climate Change Mitigation	Rebound effect Disposability of solar panels	Clean energy targets
		1.2 Economy	Lower tax revenue Increase energy inequality	Capital Investments Creation of employment Technological spill overs Balance of Payments (lower energy imports)
2.	**Electricity System**	**2.1** Consumers	Higher retail prices Increase in energy inequality	Lower wholesale prices Lower electricity bill Empowered prosumers
		2.2 Producers/ Distributors	Lower wholesale prices Erosion of customer base Revenue loss Rise in network costs	New business models Improve integration and cooperation between CFE and BEL - balancing services
		2.3 System	Higher Integration costs Grid instability	Lower peak demand Diversification and resilience

Note. Adapted from “Photovoltaic Self-consumption is now Popular in Spain: Effects of New Regulation on Prosumers’ Internal Rate of Return,” by J. L. Prol and K. W. Steininger, 2020, https://doi.org/10.1016/j.enpol.2020.111793, Creative commons license. Also taken from interviews with Belizean Energy Stakeholders.

6.2 Recommendations

The following recommendations address these challenges and risks. This section proposes seven recommendations to promote rooftop solar growth, with the understanding that deployment of this renewable source is appropriate where it is commercially viable for small residential applications and economically viable for the country.

1. Ensure a well-designed and coordinated distributed energy policy with adequate grid rules, technical standards, and installation codes, including customer requirements for installing advanced smart inverters for grid support and flexibility.
2. Eliminate administrative barriers by streamlining the permit procedure. An energy stakeholder mentioned that Belize’s permit costs are reasonable, but the wait could be long.
3. Foster long-term planning and resiliency of the rooftop market segment through suited building codes and city-planning procedures.
4. Improve power system flexibility and operational efficiency to support grid integration of renewables, enabling future power purchase agreements and business models to build that flexibility in their daily supply management.
5. Launch a coordinated public awareness programme to educate prosumers about their impact on the grid and energy management.

6. Eliminate import duties on solar hardware and batteries.
7. Develop further technical and economic studies so sector authorities can make informed decisions.

7.0 Conclusion

Will developing a distributed PV rooftop segment in Belize reduce foreign importation of electricity? Belize has the solar resource potential and suitable rooftop space to install 169MW of solar capacity on rooftops. This has the potential to supply 94% of the residential market and bring an average import savings of USD 40.2mn a year through the reduction in CFE imports.

However, closing the gap between what is technically possible and realistically achievable will demand significant effort to alter BEL's business model to include: smart-grid technologies and interconnection standards, changing regulatory policies, and compensation mechanisms allowing energy to flow back to BEL so customers gain some economic benefits. Bridging the gap between what is achievable and technically feasible will also entail increasing the commercial viability of this rooftop investment, since a 3kW rooftop solar installation for a typical BEL customer would incur a lengthy payback period of 12.3 years. However, third-party ownership schemes, like BEL's proposed programme, might increase social acceptance and speed solar uptake.

Integrating solar will also bring challenges for Belize's electric grid system. Rooftop solar PV at low penetrations is much easier to integrate than at higher levels. Given BEL's current grid configuration, hosting a significant penetration of rooftop solar will need new technologies and system upgrades. This hosting capacity challenge will not be solved in the near term and will require future investments to make the electric system flexible. Further investments in long-term energy storage will be needed, as recommended in 2022's ARP. Based on solar's intermittent nature, generation will likely be curtailed. Whatever cap is approved in the future by PUC, it will impact the potential to reduce imports significantly. Finally, without policies to support clean energy, such as: lowering import duties on solar hardware and batteries, fostering the ability to sell power back to the grid, creating policy mechanisms such as net billing, and fostering integrated long-term planning for both networks and administrative operations, the development of rooftop solar segment will be slow and electricity imports will continue to grow to meet rising demand.

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9.0 Appendix

Table A1: Policies and Frameworks Surrounding Renewable Energy Implementation in Belize

Policy	Year	Key Points	Targets/Recommendations
National Development Framework for Belize- Horizon 2010-2030	2010-2030	Details the vision for Belize to be achieved by 2030 under which the promotion of green energy is emphasized.	* Create an institutional framework for providing a viable energy policy. * Provide incentives to encourage investment in renewable energy sources. * Educate the public on renewable energy technologies. * Provide tax and other incentives to encourage households to invest.
National Energy Policy Framework	2011	To mitigate the effects of energy price volatility and the environmentally damaging effects of fossil fuel use, it was acknowledged that Belize needed to tap into its renewable energy potential. The national energy policy framework was drafted with the goal of creating a plan geared at achieving energy efficiency, stability, and security over the next 30 years.	* Shift from electric to solar lighting in the residential sector, 60% Electric and 40% Solar by 2040. * Eliminate electricity water heating in the commercial sector by 2040 with a goal of LPG water heating (10%), solar water heating (70%) and geothermal water heating (20%). * Dispatch maximum energy obtainable under the BECOL, Hydro Maya, and BELCOGEN PPAs after 2010.
Belize Sustainable Energy Strategy	2012	The strategic consultancy firm, Castalia was contracted by the Inter-American Development Bank to advise the Ministry of Energy, Science, Technology and Public Utilities on how the country can expand its use of underutilized renewable resources.	* Create building codes to facilitate the installation of energy efficient technologies. * Initiate public awareness campaign. * Collaborate with neighbouring countries to create a labelling system and performance standards for EE technologies. * Provide personnel training. * Introduce consumer finance scheme especially for bulk purchases of EE technologies.
CARICOM Energy Policy	2013	Was developed with the intension of ensuring access to clean, affordable, and renewable energy for all citizens of CARICOM to facilitate the development of member states and consolidation of CARICOM.	* Increase renewable energy capacity to 20% by 2017, 28% by 2022, and 47% by 2027.
The Intended Nationally Determined Contribution	2015	The Paris Agreement was signed by virtually every country in the world with the goal of keeping global warming well below 2 degrees Celsius. To achieve this, every country that signed on was asked to formulate their own goals called Nationally Determined Contributions (NDCs).	* Increase renewable energy production to 85% by 2030. * Reduce transmission and disruption losses from 12% to 7% by 2030. * Reduce conventional transportation fuel by 2030.
Growth and Sustainable Development Strategy	2016-2019	Builds upon the 2010-2030 Horizon plan by 'providing an action plan for our vision'.	* Establish the National Climate Change Office. * Launch a study on the appropriate green technology options that can be used in Belize in both the short term and long term * Design programmes to facilitate and incentivize green technology investment by way of the MOF. * Design disincentives for use of environmentally unfriendly technologies by way of the MOF. * Review incentive regime – tax and non-tax.

Table A2: Renewable Energy Generation Policies in Selected Caribbean States

Country	Policy Mechanism	On-site Consumption?	Program Cap	Compensation Structure
Barbados	Renewable Energy Rider	Yes	9MW	Under 2kW: Cash payment for metered output. Over 2kW: Cash payment for 100% of power.
Cayman Islands	CORE Tariff	No	2MW	Cash payment for 100% of power.
Grenada	Renewable Standard Offer	No	2.5% of annual electricity demand	Cash payment for 100% of power.
Jamaica	Net Billing Standard Offer	Yes	2% of peak demand	Cash payment for metered output.
St. Vincent and the Grenadines	Net Billing	Yes	5% of peak demand	Cash payment for 100% of power.
US Virgin Islands	Net Metering	Yes	15MW	Generation credited to utility account.
Belize	No Policy and Compensation Structure. Policy expected in 2022			

Note: Adapted from “Solar PV in the Caribbean: Opportunities and Challenges”, GTM Research-Meister Consultant Group, 2015 https://www.ctc-n.org/sites/www.ctc-n.org/files/resources/solar-pv-in-the-caribbean.pdf

Table A 3: Number of House Units and Horizontal Roof Space

Number of Suitable Housing Units	Assumed Average Unit Size (Ft2 per unit)	Calculated Total Square Footage of Floor space (million)	Gross Horizontal Roof Space Ft2 (million)
54,551	800	43.6	46.4

Note: Author’s estimation. Average house size is an approx imationbased on a typical two-bedroom room house plan provided by Belize Central Building Authority. Square footage of typical low-income house category ranges between 800 – 1000 square footage. Additionally, to measure the gross horizontal roof space, a pitch calculation was used to convert total square footage of floor space to roof space.

Table A4: Estimated Rooftop PV Technical Potential for Residential Units in Belize

District	Total Roof Area Suitable for PV Deployment (m^2)	Installed Capacity (MW)	Estimated Annual Generation (MWh/year)	Annual Generation Potential (% of Residential Sales)
Corozal	0.12	18.8	24,707	111.7
Orange Walk	0.13	19.4	25,445	90.9
Belize	0.38	57.8	75,868	75.3
Cayo	0.26	38.8	50,834	93.4
Stann Creek	0.13	19.7	25,814	77.9
Toledo	0.1	14.5	18,991	280
Total Country	1.12	169.0	221,659	90.3

Note: author’s estimation