SUSTAINABLE Energy Paths for the Caribbean

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2020

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Sustainable Energy

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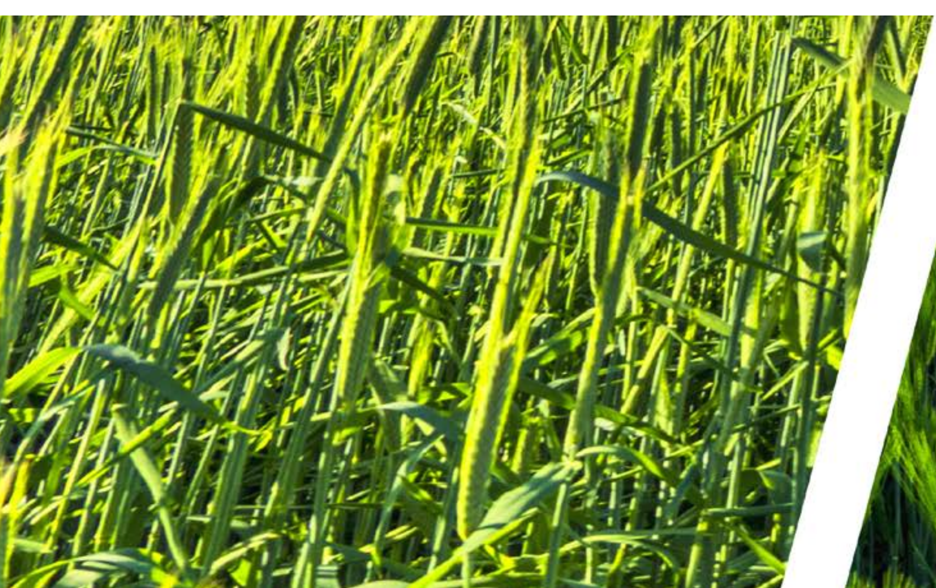


Abbreviations and Acronyms

AC	Alternating Current
CAPEX	Capital Expenditure
CARICOM	Governments of the Caribbean Community
CHENACT	Caribbean Hotel Energy Efficiency Action Programme
ECM	Electronically Commutated Motors
EOL	End of Life
ESCOs	Energy Service Companies
GDP	Gross Domestic Product
HFO	Heavy Fuel Oil
IPP	Independent Power Producer
IRP	Integrated Resource Plan
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized Cost of Electricity
LED	Light Emitting Diode
LEED	Leadership in Energy and Environment Design
LNG	Liquefied Natural Gas
MH/HPS	Metal Halide and High Pressure Sodium
MW	Megawatt
MWh	Megawatt-hour
NOAA	National Oceanic and Atmospheric Administration
PPA	Power Purchase Agreement
PSC	Permanent Split Capacitor
PV	Photovoltaic
RE	Renewable Energy
VOLL	Value of Lost Load
VGF	Viability Gap Funding
vRE	Variable Renewable Energy
VRF	Variable Refrigerant Flow

INTRODUCTION

Recent technological changes create an opportunity to transform Caribbean energy systems. Sustainable energy interventions in the Caribbean are becoming both cheaper and cleaner because of rapidly increasing efficiencies in solar PV, wind, battery storage, and renewable distributed generation. As prices continue to drop, the uptake of sustainable energy measures is expected to increase significantly. At the same time, climate change is increasing the risk of hurricanes and other natural disasters, meaning that investing in more resilient energy systems is essential.

While moving to sustainable energy has strong positive financial and economic returns as well as social and environmental benefits, governments in CARICOM face challenges.[1] Governments will need to implement the appropriate policy and regulatory measures to manage the transformation and attract the capital required.

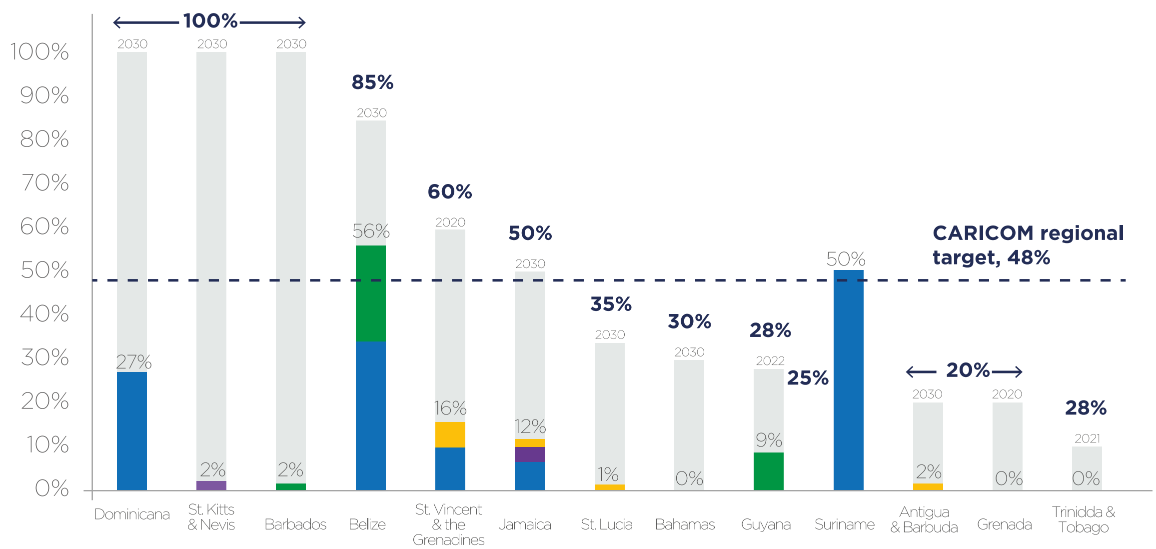
Governments in the Caribbean Community (CARICOM) have set both regional and national targets to make their energy sectors more sustainable. However, progress against these targets has been relatively slow. Figure 1.1 shows countries' progress against renewable generation targets.

1. For the purpose of this study, the CARICOM countries considered are: Antigua and Barbuda, The Bahamas, Barbados, Belize, Dominica, Grenada, Guyana, Jamaica, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, and Trinidad and Tobago.

Figure 1.1: Progress Against Renewable Energy Targets in CARICOM

Notes: The years at the top of each bar indicate the target year set by the country to reach their renewable energy target.

Source: UNFCCC 2016, Castalia 2019.



Rapid technological and other changes can transform energy sectors Solar PV and wind technologies have improved to the point that renewable generation costs less than the fuel cost of conventional generation in most CARICOM countries. Recent power purchase agreements (PPA) in Jamaica have reached the US$0.09 per kWh range for solar and US$0.12 cents per kWh range for wind, and falling prices are expected to continue (New Energy Events 2018, Powell 2016).[2]

Battery storage technologies are also improving and becoming cheaper, with prices for lithium-ion batteries expected to drop 43 percent from current prices by 2023, reaching US$100 per kWh (J.P. Morgan 2018). Battery storage provides system stability, allowing for higher levels of variable renewable energy (vRE) such as solar PV and wind.

Batteries can also 'time-shift' solar power from the daytime hours it is generated to serve load at night. For many CARICOM countries, solar (or wind) power plus storage can provide reliable power for up to 14 hours a day at an average of US$0.17 per kWh. This is cheaper than conventional heavy fuel oil (HFO) or diesel power plants (Lazard 2017).[3]

2. The solar power PPA refers to the Paradise Park solar plant, which became operational in 2018. The wind power PPA refers to the Blue Mountain Renewables wind farm.

3. Storage cost estimates are based on the following assumptions for lithium-ion batteries: CAPEX: US$315 per kWh and US$50 per kW; 4-hour duration; 90 percent round-trip efficiency.

That said, battery costs have not yet fallen to the level that would make batteries viable for power supply throughout the night. Countries need dispatchable power sources that meet the following criteria:

Controllable: the generation source can operate to its maximum capacity, or anywhere in between depending on the needs of the system

Firm: there is confidence that the generation source will be available when it is needed

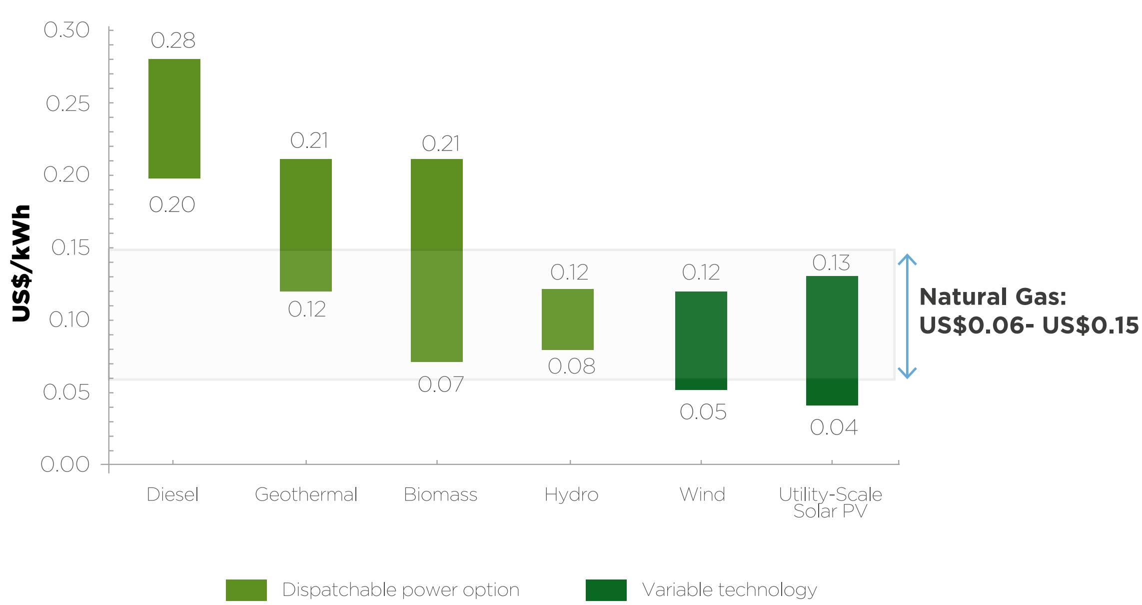
Flexible: the generation source can ramp up or down quickly to adapt to fluctuations in demand (AEMO 2018).

CARICOM countries that want to quickly eliminate the use of HFO and diesel but lack dispatchable renewable options such as geothermal and hydro, may choose to use natural gas to achieve lower emissions and cleaner power at costs which are affordable. As the number of electric vehicles increases in the future, vehicle-to-grid functionality may become another option for nighttime power supply.

The price of natural gas supply to the region has fallen, thanks to technological advances in natural gas extraction and the transportation and re-gasification of liquified natural gas (LNG) at small scale, as shown in Figure 1.2. These trends mean that LNG can displace HFO or diesel as a cheaper and cleaner fuel option for some CARICOM countries.

Figure 1.2: Natural Gas Can Be Cheaper Than Other Dispatchable Power Options

Source: IRENA 2018, Lazard 2017, Lazard 2018.



Options for energy efficiency are also improving because of technological change, such as the advent of light-emitting diode (LED) lighting, which uses up to 75 percent less electricity than conventional lighting (US DOE 2019). Energy efficiency gains in lighting, cooling, and manufacturing can reduce costs, greenhouse gas emissions, and dependence on fuel imports. Demand-side energy efficiency measures present large untapped potential in the region as return on investment can be high and can reduce the total amount of electricity generation required.

At the same time, climate change is increasing the risk of hurricanes and other severe weather events in the Caribbean, making sector-wide resilience planning essential. Options to increase resilience include:

Strengthening generation plants to withstand extreme weather

Undergrounding critical parts of electricity networks (where flooding is not a risk)

Using distributed generation and batteries in microgrids that can supply energy during power outages on the main grid.

Potential benefits of a sustainable energy transformation

Recent developments in the sustainable energy market create opportunities that could yield US$16 billion in net economic benefits to CARICOM countries over the next 20 years. Table 1.1 shows the net benefits from a "sustainable energy pathway" scenario designed to maximize net economic benefits from renewable energy, energy efficiency, and resilience.

Table 1.1: Summary of Net Economic Benefits in a Sustainable Energy Pathway (2020–2040)

Sustainable energy measure	Value (present value US$ billion)
Net benefits from reducing costs by using renewable power	5.7
Net benefits from increased efficiency in electricity use	6.1
Net benefits from increased resilience in the electricity system	4.3
Total net economic benefits	**16.1**

Need for finance

To realize these benefits, CARICOM countries will need to invest an estimated US$11 billion over the next 10 years. The investment needed can be broken down by specific sustainable intervention type, as shown in Table 1.2.

Table 1.2: CAPEX Needed for Sustainable Energy Pathways (2020–2030)

Investment type	CAPEX (US$ billon)
Renewable energy	3.3
Natural gas generation	1.1
Conventional generation	0.3
Battery storage for grid support	0.7
Energy efficiency in electricity	1.4
System resilience	4.1
Total	**10.9**

Note: CAPEX values are total sums needed for the period 2020–2030.
See Appendix A and Appendix B for the assumptions used for energy efficiency and electricity generation, respectively. See Table 4.1 for the assumptions used for energy resilience.

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The sustainable energy pathways designed to maximize net economic benefits were prepared for each CARICOM country and then aggregated to give a regional perspective. The results are presented for:

Increasing energy efficiency (Section 2)

Scaling up renewable energy generation and adding battery storage technologies to provide grid stability for increased vRE penetration (Section 3), and

Improving system resilience (Section 4).

Barriers to uptake of the sustainable energy measures are discussed in each section. Policy and regulatory measures to overcome these barriers are presented in Section 5.

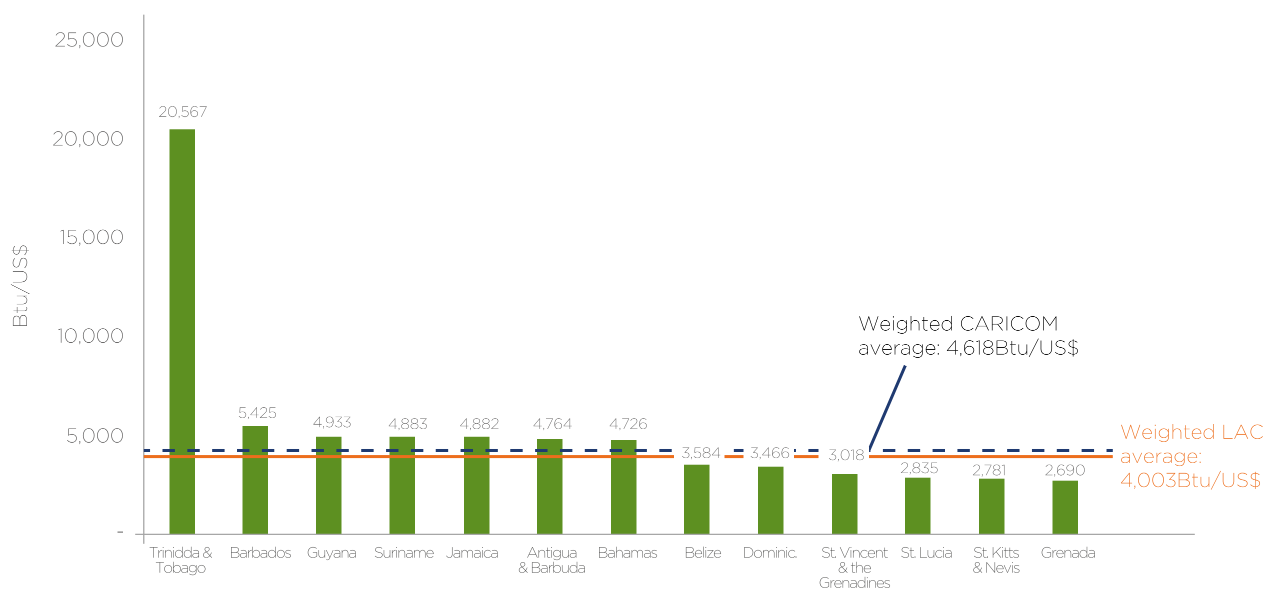
ENERGY EFFICIENCY

Despite high energy costs, CARICOM countries are relatively inefficient in their energy use. CARICOM economies have a higher average energy intensity (4,618Btu per US$ of GDP) than the average of other economies in Latin America and the Caribbean (4,003Btu per US$ of GDP). Each CARICOM economy's energy intensity is shown in Figure 2.1. Trinidad and Tobago—as a hydro-carbon producing country—has a highly energy intensive economy. However, energy importers such as Barbados, Jamaica and the Bahamas are also more energy intensive than the average for other countries in the region.

Figure 2.1: Energy Intensity in CARICOM (2016)

Note: Energy intensity measures the energy inputs (primary energy consumption in Btu) divided by economic output (measured by GDP).

Source: US EIA 2020.

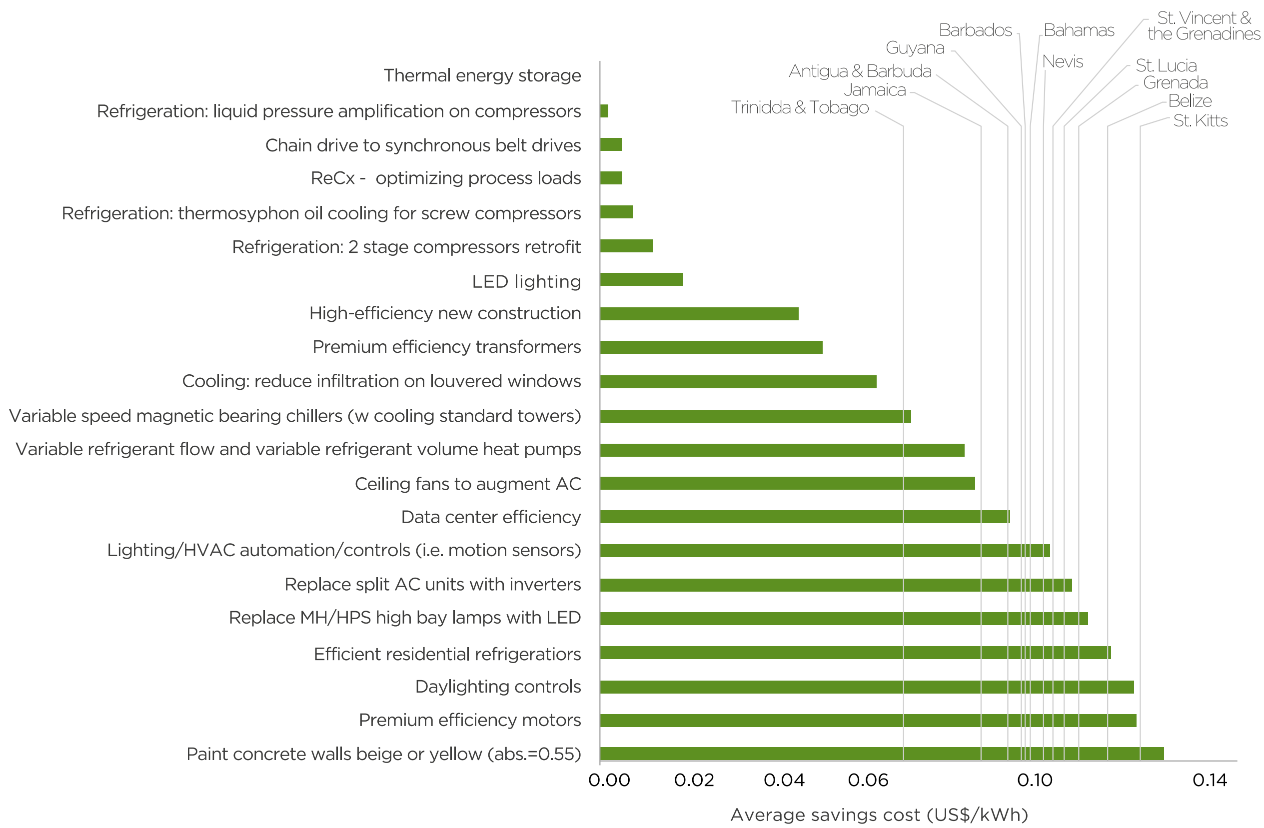


Modeling indicates that investing in energy efficiency could yield US$6.1 billion in net economic benefits over the next 20 years. Investments in energy efficiency are economically viable when the cost of saving a unit of energy is less than the cost of producing that unit (generation cost). The cost of saving a unit of energy is estimated from the cost and useful life of each investment.

Figure 2.1 shows the economics of typical energy efficiency investments for CARICOM countries, comparing the cost of saving a kWh with the cost of producing a kWh in each country.

Figure 2.2: Economic Viability of Energy Efficiency Measures

Note: The cost of each measure is annualized and then divided by the expected saving per year over its lifetime. A 10% discount rate is assumed. See Appendix A for the complete assumptions used for this analysis.



Energy efficiency options for CARICOM countries to consider

The economic analysis shows that CARICOM countries have many options to save money by investing in energy efficiency, as described in Table 2.1. Measures that are economically viable in most CARICOM countries are shaded in green; those that are not viable in most CARICOM countries are shaded in red.

Table 2.1: Descriptions of Energy Efficiency Measures

Energy Efficiency Measure	Description
Refrigeration: liquid pressure amplification on compressors	Upgrade high-capacity industrial compressors with variable loads to models including liquid pressure amplification pumps. These increase liquid refrigerant pressure from the condenser to the expansion valve, allowing compressor discharge pressure to be reduced and reducing electricity consumption by the compressor by 20–40%
Chain drive to synchronous belt drives	For systems that use a belt to transmit energy from a motor to the associated drive (fan, pump, or industrial application), replace less efficient belts (including chain drives or V-belts) with synchronous (notched) belts to increase efficiency.
ReCx: optimizing process loads	Investigate and optimize process loads (e.g. industrial equipment, maintenance operations, lab exhaust, kitchens)
Refrigeration: thermosyphon oil cooling for screw compressors	Upgrade high-capacity industrial refrigeration compressors with thermosyphon oil cooling. This is a passive means of cooling compressor oil using refrigerant condensate returning from the condenser, eliminating oil pumps and/or loss of compressor capacity associated with active oil cooling systems.
Refrigeration: two-stage compressors retrofit	Upgrade sub-zero industrial refrigeration units to two-stage compressor units, increasing efficiency at part loads.
LED lighting	Replace incandescent, fluorescent, or compact fluorescent light fixtures and bulbs with high-efficiency LED lightbulbs.
High-efficiency new construction	When constructing new buildings, incorporate passive (e.g. daylight autonomy, passive ventilation) and active (high-efficiency cooling, displacement ventilation) high-efficiency design elements to improve total building performance.
Premium efficiency transformers	Upgrade industrial transformers to premium efficiency transformers.
Cooling: reduce infiltration on louvered windows	Apply air sealing to reduce infiltration on louvered windows (or leaky doors/windows) to reduce cooling energy and peak air-conditioning load.
Variable speed magnetic bearing chillers (w cooling standard towers)	Replace standard chillers with high-efficiency models that use variable speed drives and magnetic bearings, maintaining standard cooling towers.
Variable refrigerant flow and variable refrigerant volume heat pumps	Replace conventional cooling systems with multi-split variable refrigerant flow (VRF) heat pumps. These take advantage of well-designed control systems, inverter-controlled compressors, and ECM fans to create an integrated building-level solution with better efficiency than either stand-alone air-conditioning units or chilled water systems in many applications.
Ceiling fans to augment AC	Install ceiling fans to improve human comfort at higher indoor air temperatures, reducing air-conditioning energy consumption.
Data center efficiency	Implement operational, maintenance, and capital measures to reduce cooling requirements, improve delivery of cooling to racks, and enhance energy efficiency of cooling systems serving data centers.
Lighting/HVAC automation/ controls (i.e. motion sensors)	Install sensors and controls to efficiently operate lighting and HVAC systems depending on occupancy (i.e. using occupancy sensors or motion sensors); automate lighting and HVAC schedules.
Replace split AC units with inverters	Replace split air-conditioning units with higher-efficiency units at end of life. (Higher-efficiency models use inverters to speed-control the air-conditioning compressor, and use higher-efficiency electro-commutated motors for the evaporator and condenser fans).
Replace MH/HPS high bay lamps with LED	Replace metal halide and high-pressure sodium (MH/HPS) high bay lamps with LED options to reduce lighting power use and air-conditioning energy use.
Efficient residential refrigerators	Replace conventional residential freezers and refrigerators with Energy Star-certified models.
Daylighting controls	Install sensors and controls to make efficient use of daylight to reduce electric lighting.
Premium efficiency motors	Upgrade standard efficiency motors for fans, pumps, and industrial equipment to premium efficiency motors (IE3 type as defined by the International Electrotechnical Commission).
Paint concrete walls beige or yellow (abs. = 0.55)	Paint exterior concrete walls with low-albedo paint (usually beige or yellow, with solar absorption <0.55) to reduce cooling energy and peak air-conditioning load

By adopting economically viable energy efficiency measures, CARICOM countries could meet demand for energy services while consuming 18 percent less electricity over the next 20 years (see Figure 2.2).

Figure 2.3: Impact of Energy Efficiency Measures in CARICOM (2020–2040)

Source: Castalia's CARICOM Energy Model.

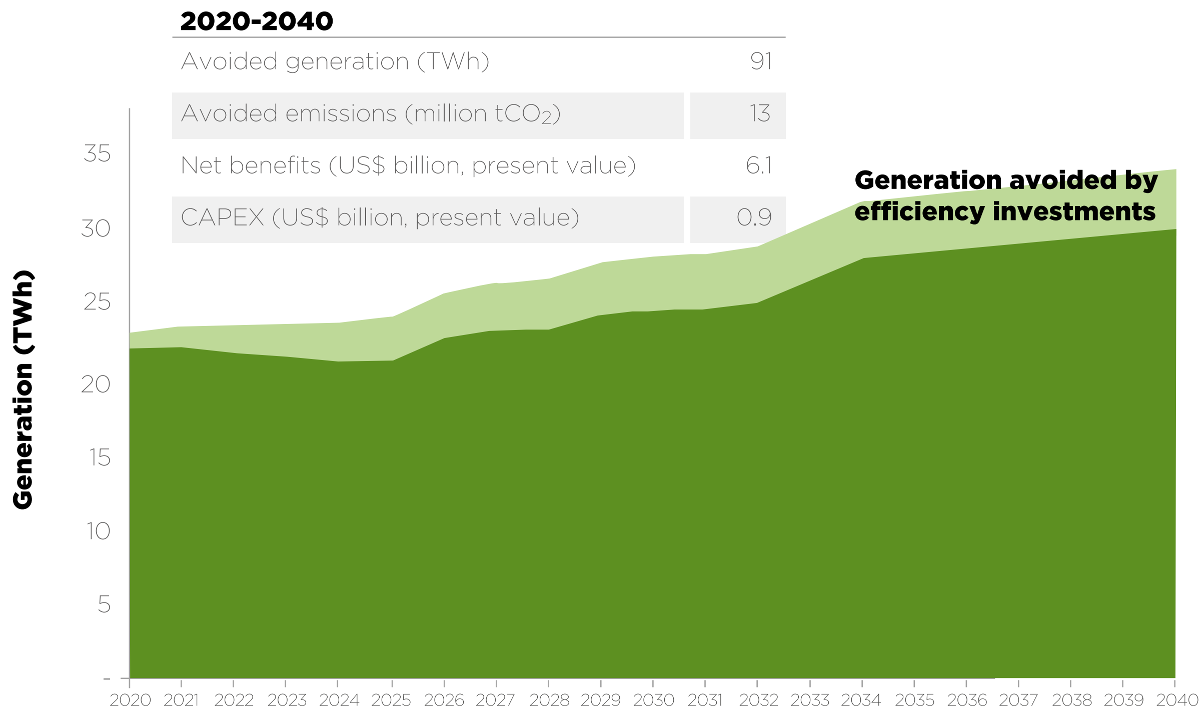


Table 2.2 compares a 'business-as-usual scenario' with a scenario in which economically viable energy efficiency measures are implemented across CARICOM. As the table shows, while nearly $1 billion would need to be invested in energy efficiency, the resulting savings in generation costs have a present value of around US$7 billion, yielding net benefits with a present value of around US$6 billion.

Table 2.2: Calculations for Net Economic Benefits of Energy Efficiency (2020–2040)

Note: All vales are in present value terms. Present values are calculated for the period 2020 to 2040, using an assumed social discount rate of 10%.

Source: Castalia's CARICOM Energy Model.

Metric	Business-as-usual (US$ billion)	Energy efficient scenario (US$ billion)
Generation cost	25.8	18.8
CAPEX	0	0.9
Net economic benefits		**6.1**

Energy efficiency targets

Some CARICOM countries have set national energy efficiency targets. Progress toward these targets has been limited. Different countries use different indicators, making it difficult to measure or compare energy efficiency progress across the region. The most common energy efficiency targets set by countries relate to electricity consumption, energy intensity, and system losses, as shown in

Table 2.3:

Source: Data compiled from national energy policies and the nationally determined contributions under the Paris Agreement (Worldwatch Institute 2015, UNFCCC 2016).

Country	Energy Efficiency Target(s)
Antigua & Barbuda	10% reduction in energy intensity from 2010 levels by 2023
The Bahamas	None
Barbados	22% reduction in electricity consumption compared to a BAU scenario in 2029
Belize	30% reduction in energy intensity per capita from 2011 levels by 2033 Reduce transmission and distribution losses to 7% by 2030
Dominica	Reduce system losses to 10% by 2020 20% reduction in public sector electricity consumption by 2020
Grenada	None
Guyana	None
Jamaica	71% reduction in energy intensity from BAU scenario by 2030
Saint Kitts & Nevis	20% reduction in peak demand
Saint Lucia	20% reduction in public sector consumption by 2020
Saint Vincent & the Grenadines	15% reduction in electricity generation from BAU scenario by 2025 5% reduction in system losses by 2020
Suriname	None
Trinidad & Tobago	None

Barriers to investing in energy efficiency

What is preventing consumers, businesses, and governments from realizing gains from investing in energy efficiency? Barriers include:

Financing constraints

A limited and uncompetitive supply of equipment

Incomplete information, and

Agency problems.

Lack of policy and regulatory frameworks for energy efficiency is a barrier in some countries.

As shown in Table 2.4, CARICOM countries can overcome these barriers by adopting appropriate policies and standards, and developing innovative financing mechanisms to promote[4] energy efficiency. Removing these barriers will reduce electricity costs, improving competitiveness and productivity.

Table 2.4: Potential Solutions to Overcome Barriers to Investing in Energy Efficiency for CARICOM

Barrier	Description	Potential Solutions
Financing constraints	In some cases, consumers and producers may need to borrow money to afford energy efficiency equipment. Terms may be unfavorable: high interest rates, short lending tenors, and high collateral requirements. Banks may also not be accustomed to providing financing for energy efficiency equipment and may not have experience appraising interventions	▪ Establish a consumer finance instrument for viable energy efficiency technologies on terms that make them attractive ▪ Provide concessional loans and financing for energy efficiency investments that are technically and financially viable
Limited and uncompetitive supply of equipment	Some energy efficiency equipment has limited availability. It can be relatively difficult to purchase and is often sold at uncompetitive prices.	▪ Establish financial instruments to create a critical mass of key equipment on the supply side and jump-start the market for them. Such measure may include: grants for promoting LEDs; a “cash for clunkers” trade-in program for efficient air conditioners; low-interest financing options for small and medium businesses to invest in energy efficiency. ▪ Governments to take the lead in introducing energy efficiency technologies using energy service companies (ESCOs) ▪ Establish technical standards for technologies and use them to establish eligibility for tax and customs incentives
Incomplete information	In places where a technology is not widely used, people may not know its benefits. People may not be aware of new technologies until they are widespread, and lack of awareness can prevent uptake. Policymakers may also not be familiar with the benefits of energy efficiency, which may prevent them from pursuing energy efficiency.	▪ Provide credible information that will orient the purchase of equipment towards efficient technologies ▪ Establish a standards and certification scheme to disclose information that is credible and easy for consumers to understand (such as. Energy Star ratings)5 ▪ Enforce standards by banning the import of sub-standard equipment and consider phasing out incandescent lights
Agency problems	Agency problems take place when the person who should invest in the equipment is not the same person who uses it. Most commonly, this happens in the public sector, in the development of new construction, and in leased buildings	▪ Implement audits and retrofits for public sector buildings under aperformance contracting scheme using ESCOs ▪ Mandate energy efficiency in building codes

4. See Section 5 for details on the recommended policies and regulations to increase energy efficiency.

5. The Energy Star rating program was launched by the US Environmental Protection Agency to promote energy efficiency and help consumers and businesses identify energy efficient products with the Energy Star label. The Energy Star rating provides credible and unbiased information on the energy efficiency of household appliances, heating and cooling units, lighting, and buildings.

RENEWABLE ENERGY

If CARICOM countries invest optimally in renewable electricity generation, they could save US$5.7 billion in generation costs from 2020 to 2040. increasing the share of renewable generation by a factor of almost four, while reducing electricity costs, oil imports, and CO2 emissions.

To develop sustainable pathways for electricity generation the least-cost generation matrices for each country were estimated by assessing the full range of energy sources, including renewables, battery storage, natural gas, and conventional HFO and diesel generation based. The following factors were considered:

> Electricity demand, calculated as the sales for each customer category plus system losses. Electricity sales are based on historic data, assuming an annual growth rate based on the growth rate of the preceding 3 years
>
> Required dispatchable capacity, calculated as the forecast peak demand plus a reserve margin.
>
> Installed capacity, projected on the basis of existing installed capacity, planned decommissioning dates, refurbishment options, and planned projects already committed.

The gap between installed capacity and required capacity is then filled in the model using the most economically viable technology.

To assess the economic viability of the generation technologies, the levelized cost of electricity (LCOE) of each technology is compared to a benchmark. The benchmark used depends on whether the technology provides dispatchable or variable power, and if it is applied at the utility or distributed-scale. If the LCOE of the generation source is lower than its relevant benchmark, the technology is considered economically viable.

The benchmarks vary by country depending on country-specific differences, such as fuel costs and grid-usage costs. Dispatchable power sources such as biomass, geothermal, energy from municipal solid waste, and natural gas would typically replace generation from heavy fuel oil (HFO) or diesel plants. Thus, to assess the viability of dispatchable power sources, the benchmark used is the estimated LCOE of heavy fuel oil (HFO) or diesel-based generation, depending on which fuel is more commonly used in each country.

The benchmark for utility-scale variable generation sources (solar PV, wind, and run-of-river hydro) is the average variable generation cost in each country. For distributed generation technologies, the benchmark is the average variable generation cost plus the distribution losses in each country. Table 3.1 shows the benchmarks used for each country.

Table 3.1: Country Benchmarks for Economic Viability of Generation Options

Source: Castalia's CARICOM Energy Model.

Country	LCOE HFO (US$/kWh)	LCOE Diesel (US$/kWh)	Average Variable Generation Cost (US$/kWh)	Average Variable Generation Cost + Losses (US$/kWh)
Antigua & Barbuda*	N/A	0.21	0.11	0.16
Bahamas*	0.17	0.25	0.11	0.13
Barbados	0.21	N/A	0.11	0.12
Belize*	0.17	N/A	0.11	0.12
Dominica	N/A	0.16	0.09	0.10
Grenada	N/A	0.10	0.11	0.12
Guyana	0.22	N/A	0.13	0.18
Jamaica	0.15	N/A	0.10	0.13
St. Kitts & Nevis*	N/A	0.21	0.13	0.15
St. Lucia	N/A	0.21	0.13	0.14
St. Vincent & the Grenadines*	N/A	0.21	0.11	0.12
Suriname	0.17	0.20	0.10	0.11
Trinidad & Tobago	N/A	N/A	0.07	0.07

* Country-specific data on the diesel or HFO costs were unavailable. For countries with diesel-generation, the diesel LCOE was assumed to be US$0.2105/kWh. For countries with HFO-based generation, the HFO LCOE was assumed to be US$0.1738/kWh.

Generation from diesel and HFO is not applicable in Trinidad and Tobago, as the country uses natural gas for generation.

To determine the least-cost generation mix in each country, the benchmarks above are compared to the estimated LCOEs presented in Table 3.2.

Table 3.2: Estimated LCOEs by Generation Technology

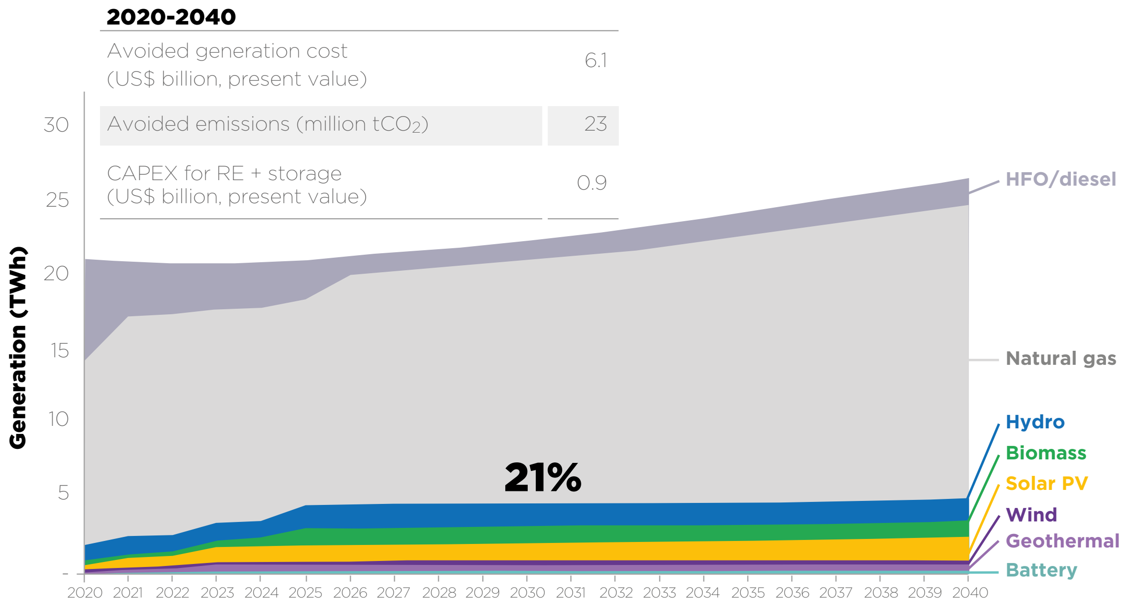
Note: LCOE calculations use a 10% discount rate. The values above are regional averages. The LCOEs for natural gas, HFO, and diesel are calculated using the projected fuel costs in each country.

Generation Technology	Average LCOE (US$/kWh)
Dispatchable utility - scale	
Conventional combustion turbine (natural gas)	0.10
Combined cycle gas turbine	0.15
Geothermal	0.12
Biomass	0.17
Energy from municipal solid waste	0.23
Battery storage plus vRE	0.21
Utility - scale variable renewable generation	
Run-of-river hydro	0.08
Solar PV	0.11
Wind	0.11
Distributed generation	
Residential solar PV	0.25

Modeling using these benchmarks and LCOEs indicates that CARICOM countries could reduce generation costs by 24 percent over the next 20 years if they invest in least-cost sustainable energy pathways. The least-cost sustainable energy pathway for the region is shown in Figure 3.1.

Figure 3.1: Sustainable Energy Pathway Projected Generation Mix (2020–2040)

Source: Castalia's CARICOM Energy Model.



CARICOM reaches 21 percent renewable energy in 2030 under the sustainable energy path, more than four times current levels. The share of renewable generation reaches 37 percent in 2030 if Trinidad and Tobago is excluded as an outlier, because of its natural gas resources and relatively high energy consumption.

Benefits from least-cost renewable energy investment

Investments in renewable energy as shown in Figure 3.1 would generate US$5.7 billion in net economic benefits.[6] In addition, CARICOM's exposure to fuel price volatility. Over the past 15 years, the standard deviation of the spot price of oil using the West Texas Intermediate (WTI) benchmark was US$3.75 per MMBtu and the standard deviation of natural gas spot prices using Henry Hub was US$2.40 per MMBtu.[7]

Further, CARICOM countries could reduce fuel oil imports by 260 million barrels and reduce CO2 emissions by 26 percent (41 million tonnes) between 2020 and 2040.

Storage and renewable technologies expected

The projected increase in renewable energy is made possible by investing in renewable generation sources and interventions that support grid stability. Grid stability investments (such as battery storage) allow for a

6. In present value terms, assuming a social discount rate of 10 percent.

7. Standard deviation is commonly used to measure price volatility as it represents the average amount a price has differed from the mean over a period of time. In this case, the standard deviation was calculated from the average quarterly spot prices for WTI and Henry Hub for the period between 2005 and 2019.

higher penetration of vRE sources, such as solar PV and wind. By 2040, generation from solar PV will reach an estimated 1,570TWh annually under the sustainable energy pathway, compared to only 79GWh in a business-as-usual scenario. Wind generation is expected to be double the amount projected in a business-as-usual scenario, by 2040.

In addition to solar PV and wind, renewable generation could be increased by using geothermal, biomass, and, to a lesser extent, hydro. These technologies are important because they produce reliable, flexible, and resilient power from renewable sources. Generation from geothermal is possible in eastern Caribbean countries and could eventually allow countries with surplus geothermal power to export renewable energy to other islands. Generation from biomass is expected to increase five times as much in the sustainable energy pathway projections as in the business-as-usual scenario. Hydro, on the other hand, is expected to remain close to current levels, as most of the hydro potential has already been developed.

Blended finance can increase renewable generation even more

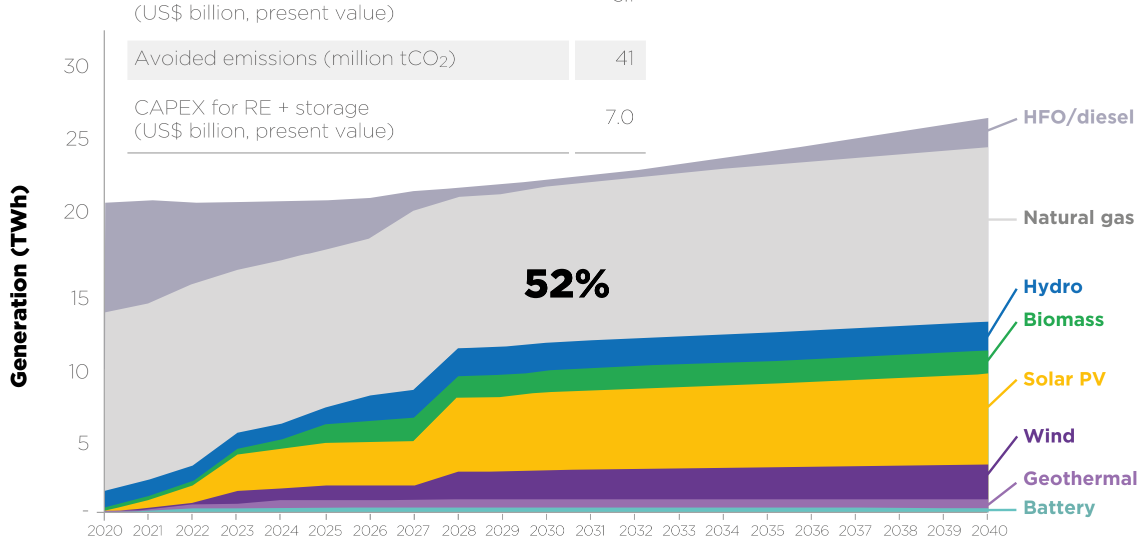
If CARICOM used blended finance for viability gap funding (VGF), it could increase its share of renewable generation even more and achieve its target of 48 percent by 2027. Meeting this target would require about US$10 billion of investment over the next 10 years, more than two times the amount needed to implement a sustainable energy pathway intended to only minimize generation costs.

Figure 3.2 shows the projected generation mix from 2020 to 2040 with an additional US$405 million of viability gap funding.

Figure 3.2: Projected Generation Mix to Achieve CARICOM Renewable Generation Target (2020–2040)

Source: Castalia's CARICOM Energy Model

2020-2040	
Avoided generation cost (US$ billion, present value)	3.1
Avoided emissions (million tCO_2)	41
CAPEX for RE + storage (US$ billion, present value)	7.0



BUILDING ENERGY RESILIENCE

Energy resilience refers to energy infrastructure's ability to withstand, and recover quickly from, a major disruption. In the Caribbean, hurricanes, floods, and earthquakes are among the greatest disruption risks (Willis and Loa 2015). Measures to improve a system's ability to withstand, and recover from, a natural disaster include: improving system architecture; burying distribution lines (where flooding is not a risk), and strengthening solar installations by using vibration-resistant modules and incorporating lateral racking supports.

Although resilient infrastructure involves upfront capital costs, investing in resilience in CARICOM now could result in net economic benefits worth US$4.3 billion over the next 20 years.

The devastation caused by hurricanes in recent years, and global climate trends, have increased the urgency in CARICOM countries to invest in energy resilience. The United States National Oceanic and Atmospheric Administration (NOAA) predicts that hurricanes' destructive potential is likely to increase due to:

Rising sea levels, which cause larger storm surges

More rainfall during hurricanes, increasing an average of 10–15 percent

More frequent category 4 and category 5 hurricanes (NOAA 2020).

Hurricanes damage generation, transmission, and distribution infrastructure, all of which is expensive to rebuild. Damage to energy infrastructure causes power outages for customers and lost revenue for utilities.

In 2017, Hurricanes Maria and Irma devastated islands across the Caribbean. When Hurricane Maria hit Dominica, it caused damage equivalent to 224 percent of GDP. Damage to its electricity infrastructure was costed at US$33 million, with the utility losing US$34 million in revenue while electricity services were down (Government of the Commonwealth of Dominica 2018). In Puerto Rico, Hurricane Maria wiped out 90 percent of the island's electricity grid and caused damage costing more than US$90 billion (Uria 2018).

Hurricane Irma caused similar devastation in the region, destroying 95 percent of homes and infrastructure on Barbuda, including the entire electricity grid (Burgess and Locke 2017). In the British Virgin Islands, 645km of transmission and distribution lines were wiped out (Malo 2018). CARICOM countries will need to consider the long-term economic costs and benefits to determine whether investing in resilience is worthwhile. Modeling suggests that CARICOM is likely to benefit from burying distribution lines in selected areas and strengthening generation facilities to withstand extreme weather conditions.

Undergrounding distribution lines

Burying distribution lines protects the infrastructure from damage and reduces duration of power outages. Undergrounding lines costs more, at US$650,000 to US$2 million per kilometer depending on the terrain, vegetation, and existing structures (Pacific Gas and Electric Company 2017, Kury 2017), compared to about US$90,000 per kilometer for standard overhead lines. However, in selected areas, the benefits of undergrounding exceed the costs.

As part of Puerto Rico's plan to rebuild after Hurricane Maria, the Puerto Rico Energy Resiliency Working Group has recommended undergrounding distribution lines in selected areas, at an estimated cost of US$35 million (Puerto Rico Energy Resiliency Working Group and Navigant Consulting 2017).

CARICOM countries should similarly consider undergrounding (or otherwise protecting) critical parts of the network. Deciding to underground will depend on geotechnical conditions (which affect the cost of undergrounding) and the risk of flooding (which can make undergrounding counter-productive, as well as the value of the load served by the portion of the network in question.

Improving the resilience of solar PV and wind generation assets
Infrastructure for solar PV and wind generation is particularly vulnerable to hurricanes. Repairing all the damage to solar and wind facilities in Puerto Rico took a year. Damage caused to one wind farm alone was estimated at US$25 million. Damage to various solar facilities was estimated at US$40 million.

Some CARICOM countries have invested in building more resilient generation facilities: Jamaica's 28MW Content Solar facility was built to withstand category 4 hurricanes. Flood and wind surveys ensured that climate risks were considered before construction started. The project's racking was designed with screw piles constructed to withstand severe weather conditions (WRB Enterprises 2018).

CARICOM countries should consider the CAPEX and the potential risks of direct and indirect damage caused by hurricanes. This will help them determine whether investing in energy resilience is justified. The most obvious impact from hurricanes is damage to the infrastructure itself, such as overhead power lines blown down and generation plants destroyed.

8. This figure is assumed to apply to just a fraction of the CARICOM loads—for example, for areas of business, tourism, financial services, and critical infrastructure. This is why it is recommended to strengthen only a fraction of the distribution network—the assumption being that it would be the high-value loads which are protected, while more rural or isolated areas would not require as much protection.

Economic benefits of keeping the power on

While the cost of rebuilding infrastructure seems massive, it may only be around 10 percent of the total economic cost of hurricane damage to electricity systems. In a business-as-usual scenario, 90 percent of the economic cost comes from power outages, which can last months. Without power, businesses cannot operate, vital services cannot be provided, and people's daily lives become more difficult.

Economists have measured the cost to society of power outages, using an indicator called value of lost load (VOLL) (London Economics International LLC 2013). This is the loss of economic output and convenience caused by every MWh of demand for energy that could not be met. Estimates for VOLL range from US$2,000 to US$250,000 per MWh, depending on factors such as the GDP of the country and the composition of customers (Schröder and Kuckshinrichs 2015).[8] A typical VOLL is estimated to be US$10,000 per MWh not supplied (Sioshansi and Pfaffenberger 2007).

Each country is different and each network is different, so countries need a detailed analysis to determine what resilience investments are cost-benefit justified. In one scenario, CARICOM countries were assumed to invest in resilient solar PV and wind projects (increasing CAPEX by 20 percent compared to a standard project). Countries were also assumed to underground 25 percent of total distribution lines over the next 10 years. The analysis suggests that if all CARICOM countries made these resilience investments now, net economic benefits would have a present value of around US$4 billion over the next 20 years.[9] Table 4.1 shows how these benefits were calculated.

9. In present value terms, assuming a social discount rate of 10 percent.

Table 4.1: Estimated Costs and Benefits of Energy Resilience (2020–2040)

Costs and benefits	Non-resilient scenario (US$ millon)	Resilient scenario (US$ millon)	Difference (US$ millon)
CAPEX to underground distribution lines	0	2,491	(2,491)
Estimated damage to distribution lines	1,087	917	170
Net costs of undergrounding			**(2,321)**
CAPEX to strengthen solar PV and wind assets	0	46	(46)
Total estimated damage to solar PV and wind generation	139	82	57
Net cost for hurricane -resistant RE			**11**
Economic loss caused by power outage	11,394	4,769	6,625
Avoided cost of economic loss due to power outages			**6,625**
Total net benefits			**4,315**

Note: All values are in present value terms calculated using an assumed social discount rate of 10%. Resilience benefits are assumed to be for investments in the centralized grid.
Assumptions are: cost to underground power lines: US$650,000/km; VOLL: US$10,000/MWh; 25% of power lines are assumed to be buried over the next 10 years; Capital cost to strengthen wind and solar assets is 20% higher than standard non-resilient assets.
Guyana, Suriname, and Trinidad and Tobago are not included as they have no significant hurricane threat.
Source: Castalia's CARICOM Energy Model.

5 RECOMMENDATIONS FOR ADOPTING SUSTAINABLE ENERGY PATHWAYS

By transitioning to the sustainable energy pathways shown in this report, CARICOM countries could reap US$16 billion in net economic benefits over the next 20 years. Because the policy, regulatory, and financial measures needed are common to most Caribbean countries, a regionally integrated approach makes sense. Developing standard tools together will reduce costs. Common approaches across the region will lower learning and transaction costs for private suppliers and investors, broadening the market, increasing competition, and benefiting Caribbean consumers.
Set sustainable energy targets based on energy sector plans that achieve policy objectives

Set sustainable energy targets based on energy sector plans that achieve policy objectives

Governments in CARICOM should set sustainable energy targets that are consistent with policy intentions and strategic objectives. Targets should be set for:

- Renewable electricity generation
- Energy efficiency
- Energy resilience.

These targets should be based on energy plans—including Integrated Resource Plans (IRPs) in electricity. The targets should be designed to achieve governments' objectives of affordable, resilient, and sustainable energy supplies, to ensure that the targets are consistent with national objectives. CARICOM's regional renewable energy targets should be set at a level consistent with national targets. CARICOM should also consider creating a regional energy efficiency target that is consistent with national targets. This is not a simple task, as common energy efficiency indicators reflect the structure of a country's economy to a considerable extent.

For example, energy intensity is defined as the primary energy consumption divided by economic output. Countries in which energy-intensive sectors make up a large portion of their economy, such as Trinidad and Tobago, have a higher energy intensity than other CARICOM countries (CIA 2020). Uniform indicators such energy intensity can be valuable, bearing in mind caveats regarding economic structures.

To track performance and set suitable targets, CARICOM should create a standardized set of indicators for the sustainable energy transition. CARICOM could also develop and manage a regional reporting system that contains all the national and regional targets, and tracks progress against those targets. In addition, CARICOM should consider creating an assessment tool to help countries evaluate investment options in energy efficiency and renewable energy to maximize benefits.

Set standards that promote energy efficiency and resilience

Governments in CARICOM should adopt national building codes that set energy standards for buildings, manage building design, installed equipment, and construction materials. National building codes should be aligned with the Regional Energy Efficiency Building Code, which establishes a regional framework for energy efficiency in CARICOM countries.

Building codes can help CARICOM countries overcome agency problems. The Regional Energy Efficiency Building Code framework covers building envelope and wall construction requirements, as well as minimum equipment performance standards for lighting, heating, ventilation, and air conditioning (CARICOM 2017).

Governments can also encourage voluntary building certification for energy efficiency. For example, the Leadership in Energy and Environmental Design (known internationally as LEED) is the most widely used green building rating system in the world. Voluntary certification can represent a new standard for energy-efficient buildings and can help owners to attract tenants looking for more efficient buildings. Governments can use technical standards for technologies to establish eligibility for tax and customs incentives.

CARICOM should establish a regional scheme certifying the energy efficiency of appliances. In CARICOM countries, appliances are generally sold without information about their energy efficiency. Energy efficiency certification can help to establish minimum performance standards for appliances, and ensure that energy efficiency levels are disclosed to the public. CARICOM should consider adapting the existing Minimum Energy Performance Standards into this regional certification scheme.

Governments in CARICOM should also establish resilience ratings for energy infrastructure, based on its ability to withstand hurricanes and other natural disasters. Governments, utilities, and customers all want to know how resilient their energy systems are, and a resilience rating system would help achieve this.

Establish regulatory frameworks that encourage investment in resilient energy systems

Governments in CARICOM should set resilience requirements and include these in the national IRP and grid codes. This approach is being used to prepare what are being called, ‘Integrated Resource and Resilience Plans’ in Barbados, Belize, Guyana, and Trinidad and Tobago.

Resilience requirements include a security of supply requirement, which sets a reliability standard for the system. The security of supply requirement is calculated using a loss of load probability, which represents the hours each year in which demand cannot be met. Because the region is vulnerable to natural disasters, CARICOM countries should incorporate this risk into the loss of load probability used for IRPs. IRPs will then be able to more accurately reflect the specific risks and needs of each country.

CARICOM should develop models for revenue mechanisms that enable utilities to recover the cost of investing in energy resilience. Regulators in hurricane-prone countries can require utilities to invest in energy resilience. If utilities are allowed to include the additional costs for resilience in their rate base, they can recover their costs through tariffs. This will ultimately cost less than having non-resilient systems.

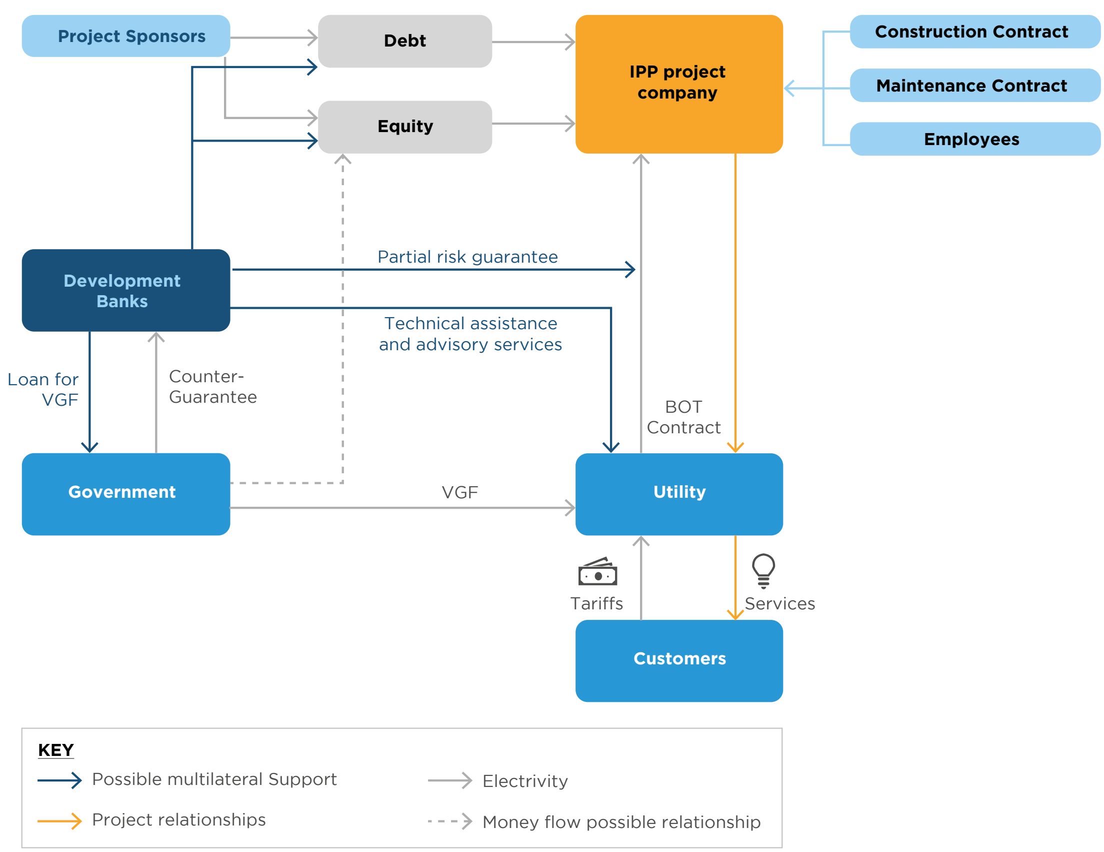
Develop financing mechanisms that attract private finance for sustainable energy investments

Blended finance provides opportunities for CARICOM countries to raise capital for renewable energy, battery storage, energy efficiency, and resilience. To attract private capital, projects should be well structured, using financial instruments such as VGF, credit-risk guarantees, and other credit-enhancement tools.

Figure 5.1 shows an example of a possible independent power producer (IPP) project using blended finance mechanisms.

Figure 5.1: Example of Project Structure in IPP Model

Note: Engineering, Procurement, Construction (EPC). Build-operate-transfer (BOT).



CARICOM should consider establishing a donor-supported regional fund that offers concessional loans and/or credit-enhancement mechanisms for sustainable energy and resilience projects. Credit enhancement tools may offset risks such as off-taker credit risk.

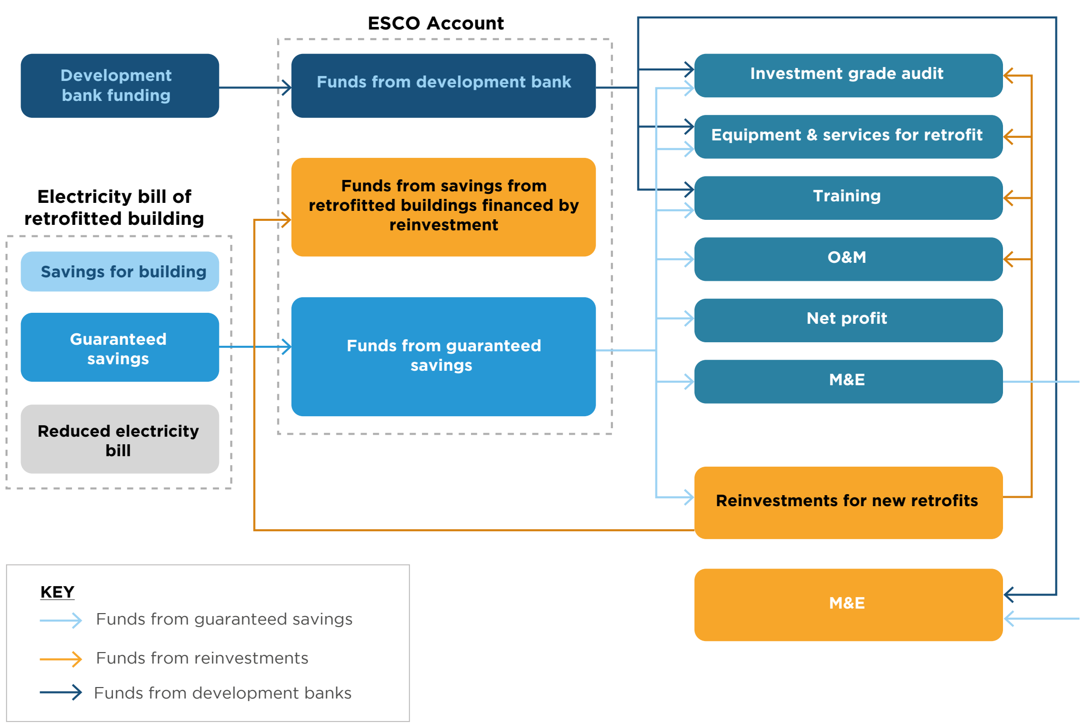
Similarly, CARICOM should consider establishing a regional revolving fund to finance energy efficiency retrofits of public buildings under an ESCO model. In this model, private energy service companies (ESCOs) are procured under performance-based contracts. A revolving fund allows savings generated from one retrofitted building to be reinvested into retrofitting more buildings.

Figure 5.2 shows the flow of funds in such an energy efficiency revolving fund scheme.

Figure 5.2: Overview of Energy Efficiency Revolving Fund Model

Note: Monitoring and evaluation (M&E).

Source: Adaptation from IDB n.d.



The IDB is implementing this model in Barbados under the Smart Fund II. In this case, the IDB will provide seed capital for the revolving fund and will gradually decline annual contributions each year, over 5 years.

CARICOM should also consider a regional initiative that channels donor money to help fund energy audits for large consumers. Such an initiative could be used to demonstrate potential gains from energy efficiency. Other regional-level initiatives have proven successful. For example, the Caribbean Hotel Energy Efficiency Action Programme (CHENACT) has supported more than 200 energy efficiency audits in small and medium-sized hotels across CARICOM (CHENACT 2019). In Barbados, these audits estimated a savings potential of 18GWh per year, which represents 14 percent of the country's total energy consumption (IDB 2019, IDB 2019). Additionally, CARICOM should consider establishing a donor-supported consumer finance instrument that channels financing through local commercial banks for energy efficiency and distributed generation investments. Innovative financing mechanisms could use low-interest loans and/or grants to support the uptake of energy efficiency measures and renewable distributed generation. These mechanisms could be replicated at the regional level, drawing on experience from successful cases such Barbados' Energy Smart Fund.

Box 5.1: Barbados' Energy Smart Fund: An Innovative Approach for Energy Efficiency and Distributed Renewable Generation

Since 2011, the IDB-funded Smart Fund in Barbados has provided US$10 million in loans disbursed and technical assistance for energy efficiency and renewable energy investments. Projects supported by the Smart Fund have resulted in an estimated 4GWh of energy saved annually, and 1.9MW of installed renewable energy capacity. The Smart Fund's five core financing mechanisms are:

Technical assistance facility—provides grants for executing pre-investment audits and studies. So far, 28 grants have been approved through the Smart Fund

Energy efficiency retrofit and renewable energy finance facility—provides concessional financing to implement renewable energy and energy efficiency projects that are financially and technically viable. This has resulted in 22 loan requests being approved for US$8 million

Pilot consumer finance facility—provides interest rate rebates or purchase price rebates to retailers that have experience in "hire-purchase" and sell renewable energy and energy efficiency equipment. This allows retailers to offer customers reduced interest rates or prices. More than 2,500 households have benefited from rebates in Barbados

Energy efficiency lighting distribution facility—provides grants to selected retailers to purchase energy efficient lights and distribute them to residential customers based on a voucher system. Over 30,000 lights have been distributed

Discretionary grant facility—provides institutional support to execute the Smart Fund's operations. This facility has led a nationwide media awareness campaign and conducted external energy evaluations and audits in Barbados.

This model could be replicated in other CARICOM countries, or at the regional level.

Source: (Castalia 2019)

Develop replicable business models for sustainable energy investments

Utilities in CARICOM should establish programs to procure renewable IPPs competitively. Having a well-defined procurement program, rather than a series of unpredictable and one-off transactions, helps to build both market interest and public sector capacity. Experience from Jamaica and globally indicates that success is most likely when the following elements are in place:

A capable public entity to run competitive procurement

International standard transaction documentation, including a bankable power purchase agreement

Clearly defined and transparent procurement processes

Well-designed qualification and evaluation criteria.

IPPs allow the private sector to bear some of the risks that governments or utilities might not be willing to take. On the energy efficiency side, governments can hire energy service companies (ESCO) to develop, implement, manage, and finance energy efficiency measures that guarantee energy and cost savings through performance-based contracts. Under these arrangements, the ESCO gets paid a share of the savings achieved. ESCOs can finance energy efficiency measures, reducing the need for governments and businesses to make large capital investments up front.

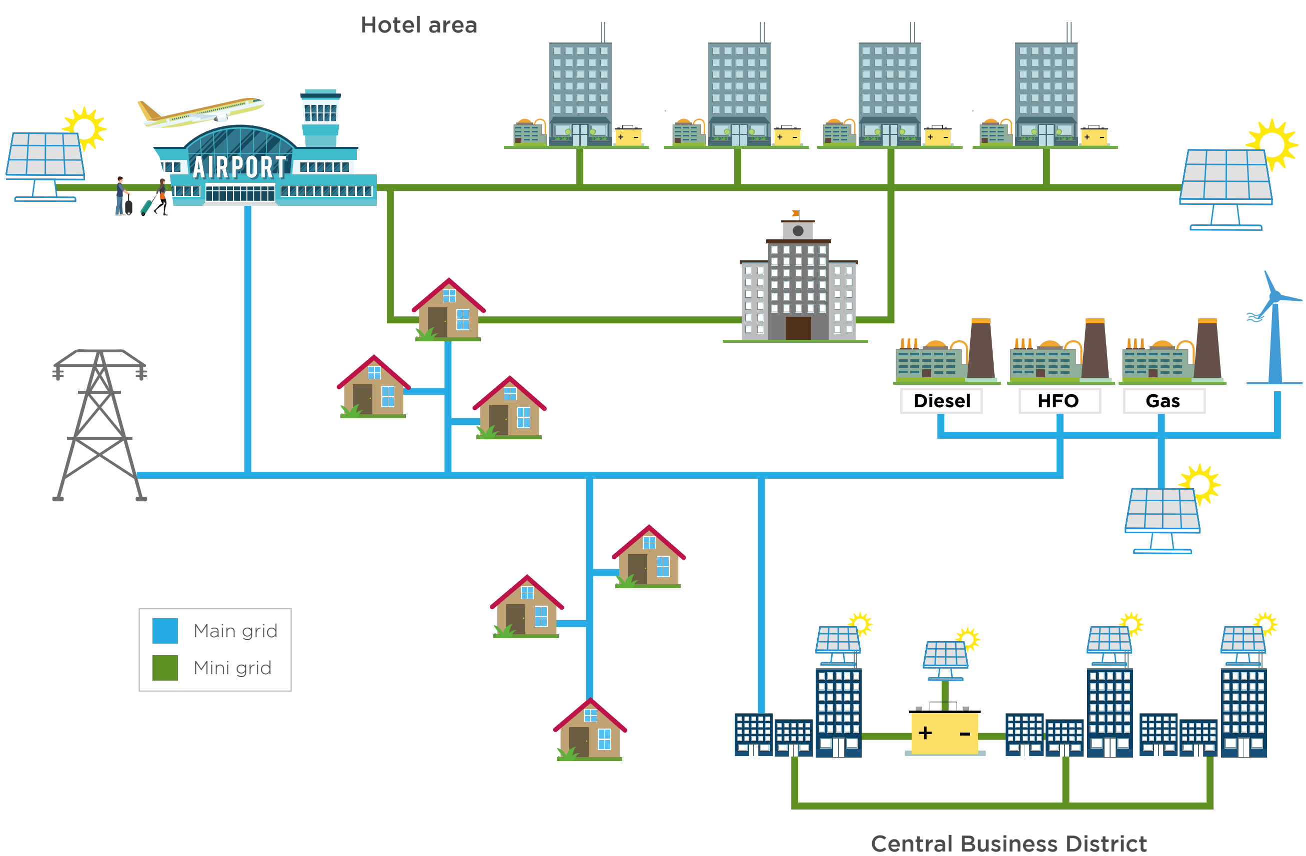
CARICOM countries vulnerable to hurricanes should develop 'build-it-back-better' plans so they are prepared to rebuild energy systems with resilient infrastructure after hurricane damage. These plans should be developed before a hurricane strikes. Governments should 'design in' resilience to new infrastructure: building a resilient facility is usually cheaper than retrofitting an existing facility to make it more resilient.

To support countries in resilience planning, CARICOM should develop a regional "resilience toolkit" that provides governments with the technical tools to plan and design resilient energy systems. The toolkit should include examples of delivery models, and financing and regulatory arrangements to build mini grids that can operate in isolation from the main grid.

In addition to undergrounding critical parts of distribution networks and strengthening generation assets, CARICOM governments should consider innovative delivery models to improve resilience. Governments are increasingly looking to distributed energy resources located close to the end-users. Small-scale renewable generation, battery storage, and microgrids can operate in "island mode" when the main grid goes down. Electricity service would therefore be able to continue in at least some areas after a hurricane.

Jamaican utilities have considered using microgrids in high-value areas, such as the business district in New Kingston and top-end hotels in resorts on the North Coast. Puerto Rico plans to rebuild its power system as a set of interconnected mini grids to increase resilience (Puerto Rico Energy Resiliency Working Group and Navigant Consulting 2017). An example of this model is shown in Figure 5.3.

Figure 5.3: Example of a Resilient Grid Using Microgrids



Strengthen institutions where necessary to enable optimal planning for sustainable energy measures

Utilities and governments in CARICOM should have institutions with the capacity to plan and implement renewable generation and energy efficiency projects. Many CARICOM countries are designating entities to develop the studies needed before they can decide to scale up renewable generation, while maintaining system stability.

Resource assessments are the first step in identifying the most promising types of renewable sources available, based on country-specific conditions. Utilities and project developers should use resource assessments to estimate the potential of generation options, and to determine the technical specifications for projects.

Drawing from resource assessments, IRPs provide roadmaps to meet forecast electricity demand in the most cost-effective way. As part of the IRPs, vRE integration studies determine the limits to vRE penetration, how fast-acting reserves and other measures can change these limits, and the cost implications. Entities responsible for system planning in CARICOM should use vRE integration studies to determine the grid investments needed to achieve the optimal amount of vRE without jeopardizing grid stability.

To maximize gains from technological developments in renewable energy and energy efficiency, CARICOM governments and utilities will need to share knowledge and experience. CARICOM should consider developing a regional, donor-supported program to achieve economies of scale in IRP development. The program would use a combined approach to procure suitable power system planning software, Caribbean-specific datasets for technology costs, consulting support, and capacity building.

Government officials, regulators, and utilities should be offered training in planning and managing for resilience. CARICOM should promote regional workshops and training initiatives to inform utilities, regulators, and governments about sustainable energy measures.

APPENDIX A:
ENERGY EFFICIENCY ASSUMPTIONS

Table A.1:Assumptions for Energy Efficiency Calculations

Energy Efficiency Measure	Installed Capacity kW	Lifetime years	Savings vs Typical Baseline %	Electr-icity Savings kWh/year	Simple Payback years	Unit Capital Cost US$	Additional O&M Cost US$/ year	Annualized Capital Cost US$/ year	Annualized Capital Cost Recovery Factor US$/kWh	O&M Cost US$/ kWh	Annualized Savings Cost US$/ kWh
Refrigeration: liquid pressure amplification on compressors	400.0	15	20%	876,000	0.1	$13,307	$0	$1,750	$0.00	$0.00	**$0.00**
Chain drive to synchronous belt drives	32.4	15	6%	13,895	0.1	$530	$0	$70	$0.01	$0.00	**$0.01**
ReCx: optimizing process loads		21	7%	4		$1	$0	$0	$0.02	$0.02	**$0.01**
Refrigeration: thermosyphon oil cooling for screw compressors	119.5	15	27%	385,390	0.2	$22,421	$0	$2,948	$0.01	$0.00	**$0.01**
Refrigeration: two-stage compressors retrofit	165.0	20	18%	294,000	0.4	$30,291	$0	$3,558	$0.01	$0.00	**$0.01**
LED lighting		20		697,500	4.5	$310,615	$23,400	$36,485	$0.05	$0.03	**$0.02**
High-efficiency new construction		30		325	8.0	$195	$6	$21	$0.06	$0.02	**$0.04**
Premium efficiency transformers	212.3	20	2%	28,641	1.7	$12,205	$0	$1,434	$0.05	$0.00	**$0.05**
Cooling: reduce infiltration on louvered windows	32.3	25	2%	1,074	2.2	$607	$0	$67	$0.06	$0.00	**$0.06**
Variable speed magnetic bearing chillers (w cooling standard towers)		25	30%	751,920	10.0	$456,030	$2,500	$50.240	$0.07	$0.00	**$0.07**
Variable refrigerant flow and variable refrigerant volume heat pumps		15		5		$3	$0	$0	$0.08	$0.00	**$0.08**
Ceiling fans to augment AC		13		500		$300	$0	$42	$0.08	$0.00	**$0.08**
Data center efficiency	37.0	5		397,000	5.5	$138,582	$0	$36,558	$0.09	$0.00	**$0.09**
Lighting/HVAC automation/ controls (i.e. motion sensors)		12		40,000		$26,283	$200	$3,857	$0.10	$0.01	**$0.10**
Replace split AC units with inverters	1.4	15	25%	937	3.2	$758	$0	$100	$0.11	$0.00	**$0.11**
Replace MH/HPS high bay lamps with LED	0.1	11	65%	1,927	2.9	$1,450	$7	$219	$0.11	$0.00	**$0.11**
Efficient residential refrigerators	0.1	15	32%	255	3.4	$223	$0	$29	$0.12	$0.00	**$0.12**
Daylighting controls		12		120,000		$95,574	$400	$14,027	$0.12	$0.00	**$0.12**
Premium efficiency motors	0.8	20	6%	393	4.0	$404	$0	$47	$0.12	$0.00	**$0.12**
Paint concrete walls beige or yellow (abs.=0.55)	31.0	15	3%	2,209	3.8	$2,132	$0	$280	$0.13	$0.00	**$0.13**
Water conservation (Low flow fixtures, DHW reduction)		20		220		$266	$0	$31	$0.14	$0.00	**$0.14**
Replace Window AC Units with Inverter Split Systems	1.1	15	51%	2,222	4.7	$2,689	$0	$354	$0.16	$0.00	**$0.16**
Variable Frequency Drives	0.7	10	17%	596	1.4	$214	$61	$35	$0.06	$0.10	**$0.16**
Paint Concrete Walls w/ Cool Roof White (Abs. = 0.25)	25.9	15	14%	8,388	5.2	$11,208	$0	$1,474	$0.18	$0.00	**$0.18**

APPENDIX B:
RENEWABLE ENERGY ASSUMPTIONS

Table B.1: Assumptions for Generation Technologies for LCOE Calculations

		Conventional Technologies		Intermittent Renewable Sources			Dispatchable Renewable Sources			Natural Gas Technologies	
Assumption	**Units**	**HFO**	**Diesel**	**Solar PV Utility**	**Wind Onshore**	**Hydro (run-of-river)**	**Biomass**	**Energy from-MSW**	**Geo-thermal**	**CCGT**	**CT**
Capacity Type		Dispatch-able	Dispatch-able	Variable	Variable	Variable	Dispatch-able	Dispatch-able	Dispatch-able	Dispatch-able	Dispatch-able
Capacity	MW	10	10	10	10	25	15	15	10	10	10
Unit capital cost	US$M/MW	1.98	0.63	2.40	1.42	4.32	3.68	5.33	12.90	6.53	1.16
Lifetime	Years	20	20	20	20	25	25	25	30	20	20
Capacity Factor	%	85%	85%	23%	30%	50%	84%	85%	85%	85%	85%
Fixed O&M	US$/kW-yr	18.00	30.00	45.0	33.30	42.5	142.28	457.16	41.22	7.54	17.80
Variable O&M	US$/MWh	9.00	6.0	0	7.505	0	8.05	11.71	21	2.99	8.49
Unit cost of the resource	US$/MMbtu	13.55	23.93	0	0	0	3.91	-2.41	0	11.35	11.35
Heat rate	Btu/kWh	9,500	7,962	N/A	N/A	N/A	15,857	15,819	N/A	6,517	9,783

Note: Unit capital cost include interest during construction.

Municipal solid waste (MSW); Combined cycle gas turbine (CCGT); Combustion turbine (CT)

Source: Lazard 2017, Lazard 2018, IRENA 2018, US EIA 2017, Castalia 2019.

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