Options for achieving Cape Verde's 100% renewable electricity goal: a review

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Abstract: The government of Cape Verde, an archipelagic Small Island Developing State (SIDS) off the coast of Senegal, has established a goal to achieve 100% of its electricity from renewable sources by 2025. Several islands in the archipelago have suitable wind and solar resources and nationally these compose about 25% of the electricity output. However, not all islands are equally endowed with these resources and the lack of grid connections among islands poses challenges for integrating additional variable energy generation. Integrating desalination and storage (pumped hydro or battery) could enable greater penetration of wind and solar energy. Ocean thermal energy conversion (OTEC) is an emerging technology that could be suitable for Cape Verde. Microgrids and self-generation could prove to be more cost effective than grid connections outside of the large cities. Achieving the 100% renewable energy goal would require a US$1 billion investment. Cape Verde has a variety of resources that can contribute to achieving its 100% renewable electricity goal but combining them in manageable and cost-effective way remains a challenge. The options, opportunities, and challenges encountered by Cape Verde are applicable to other countries, especially small island developing states and archipelagos around the world.

Keywords: Africa, Cape Verde, renewable energy, Small Island Developing States (SIDS) solar energy, sustainable development, wind energy

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1. Introduction

Small island developing states (SIDS) share common challenges in the energy sector including limited access to resources for power generation, manufacturing, and transportation; a lack of generating capacity; aging infrastructure; and limitations for grid-based electricity (Shah et al., 2016). SIDS also tend to be physically vulnerable to the effects of climate change, although at least one study suggests that SIDS score relatively high on measures of adaptive and implementation capacities (Barr et al., 2010). Cape Verde (also known as Cabo Verde), like many other SIDS, has adopted energy policies that address both of these challenges (Republic of Cape Verde, 2010, 2016). The policies encourage the development of domestically-available, renewable, and low-carbon energy sources to reduce its dependence on expensive, imported fossil fuels. This investment will modernize the electricity grid and could reduce electricity prices and price volatility while expanding electricity access. Investments in low-carbon, renewable energy infrastructure also help Cape Verde meet its Nationally Determined Contribution (NDC) under the Paris Climate Agreement (Republic of Cape Verde, 2016). These energy policies, therefore, may both mitigate future climate change by reducing emissions and reduce vulnerability to unavoidable climate events by improving living standards and resilience (Kelman, 2014; Kelman & West, 2009).

Figure 1: Cape Verde lies about 650 km west of Senegal. ©E. Nordman in ArcGIS.

Cape Verde, an archipelago of small islands about 650 km (400 miles) west of Senegal (Figure 1), depends primarily on imported fossil fuels for its electricity production. The African Development Bank (2014) noted that Cape Verde's reliance on imported petroleum is a heavy burden on the national economy and the high price of electricity constrains its progress toward inclusive, green growth. Its remote location and lack of infrastructure leave it vulnerable to the effects of climate change especially regarding water management, agriculture, forestry, and coastal development (including tourism). The African Development Bank stated, however, that Cape Verde has substantial renewable energy resources, including wind and solar energy. Cape Verde's 2008 National Energy Policy set a goal of obtaining one-half of its electricity from renewable sources by 2020. It has since raised the goal to obtain 100% of its electricity from renewable sources by 2025 and make a concerted effort to achieve it by 2020 (Republic of Cape Verde, 2016). In doing so, Cape Verde will continue its progress toward achieving Sustainable Development Goal #7: Ensure access to affordable, reliable, sustainable and modern energy for all (United Nations, 2018).

Cape Verde is one of 15 SIDS with 100% renewable energy goals. Some of these countries are, like Cape Verde, archipelagos (REN21, 2018). Creating clean, renewable, and reliable energy systems on archipelagos composed of small islands can be more challenging than creating a system for a single larger island or continental land mass. Unless the islands are linked, a costly endeavor, each island's electrical grid will stand alone and will be unable to achieve the economies of scale associated with continental systems. Other countries, especially but not limited to SIDS, can learn from Cape Verde's successes and challenges in aiming for an electricity system based on 100% renewable energy.

This paper grew out of a project for the United States Department of State's Virtual Fellows Program in which professionals, in this case an academic team, provide consultative services on a pro-bono basis. The research team investigated the following questions:

1. What is the potential for exploiting solar, wind, water pumping, waves/ocean, biomass, and geothermal energy sources and technologies in addition to the thermal, wind, and solar resources that currently meet Cape Verde's energy needs?
2. How many more megawatts (MW) of capacity is the goal for 2025, what energy sources are to be tapped in what proportions, and what is the estimated cost?

Additionally, the team critically analyzed the potential for Cape Verde to reach its goal of an electricity system based entirely on renewable energy sources given the technical, economic, and social constraints.

The team answered these questions using publicly available information supplemented with applications to Cape Verde when possible. This included reviewing the peer-reviewed literature on island energy systems including the particular social, economic, and technical challenges faced by islands and archipelagos. Additional sources of information included technical reports from Cape Verdean industries and utilities and conversations with a Cape Verdean energy expert. The paper begins with a brief literature review of social, economic, and technical challenges of island energy systems in general, followed by a demographic profile of Cape Verde and description of its renewable energy goals. Each renewable energy technology is then described and evaluated for its feasibility in Cape Verde. The team synthesized the results to suggest options for Cape Verde's energy development.

This paper presents and assesses a wide range of options that Cape Verde may choose to use to reach its renewable energy goals. However, it is not prescriptive or recommends detailed plans about how Cape Verde should move forward in its energy transition.

2. Sustainable energy planning in Small Island Developing States

Cape Verde is not alone among SIDS in pursuing a goal to source 100% of its electricity from renewable sources. More than 50 countries, many of which are SIDS, have such a goal (REN21, 2018). These energy transitions are more than simple changes in technology, especially on islands. Harrison and Popke (2018, p. 167) used the idea of the "island energy metabolism" to describe and integrate a re-engineering of "new material substances that interact with existing social, political-economic, and infrastructure networks, and doing so in particular geographic locales." The authors attempt to move beyond the narrow roadmap of techno-economic energy analysis and toward a more holistic vision of energy transitions in the Caribbean. A successful and just energy transition will necessarily include island-specific challenges of territoriality, small markets, and archipelagic island sovereignties.

Harrison and Popke (2018) note that islands are often seen as laboratories of experimentation and sustainable development. But they also cite Grydehøj and Kelman's (2017) 'eco-island trap' of conspicuous sustainability. SIDS may adopt ambitious renewable energy or sustainability goals for a variety of reasons unrelated to climate change or infrastructure improvements. These alternative motives range from gaining competitive advantage to distracting from government failures. Investments in 'eco-island' initiatives may ultimately misallocate resources from more pressing needs or raise costs for residents. Islands can then be trapped as exemplars that fail to meet unrealistic expectations. The authors call for a more realistic approach that truly benefits islanders.

In a similar vein, Dornan and Shah (2016) investigate the strategic reasons why many SIDS adopt ambitious renewable energy goals. They suggest that SIDS adopt these goals, in part, to attract development assistance which is often available for capital-intensive renewable energy projects but not for operational fossil fuel costs. Another common reason for the ambitious goals is that SIDS are most vulnerable to the effects of climate change, from erratic weather patterns to sea-level rise. The goals give less-powerful SIDS some leverage in advocating for wider adoption of low-carbon energy sources. Energy-related development assistance, when coordinated, can improve infrastructure and leverage technical expertise. However, Dornan and Shah (2016) note that uncoordinated action can lead to suboptimal results. It is therefore critical to facilitate coordination among the local governments and utilities, multilateral banks, and the international donor community to ensure that the benefits of energy-related development assistance are maximized.

The International Renewable Energy Agency (2018) launched its SIDS Lighthouses Initiative in 2014 to facilitate energy transitions on islands. Cape Verde is a partnering country. The Lighthouses Initiative identified seven key actions to enhance the adoption of renewable energy solutions in SIDS:

1. Institutional Frameworks: Support government leadership and policies to accelerate renewable energy transitions.
2. Knowledge Base: Create a repository of best practices and appropriate technologies.
3. Transition Planning: Develop comprehensive transition plans including market design and regulatory frameworks.
4. Financing: Design and implement energy transition roadmaps and develop bankable proposals.
5. Renewable Energy Deployment and Operation: Select technologies, establish local contractor and project management capability.
6. Human Capacity Building: Enhance human and institutional capacity for energy transitions.
7. Regional and International Co-operation: Increase collaboration among utilities, academia, regulators, and others (International Renewable Energy Agency, 2018).

Cape Verde is making progress on these key actions. Its institutional frameworks support the renewable energy transition as, for example, described in its NDC document. Cape Verde has developed a robust knowledge base including at least five renewable energy feasibility studies. It has worked with consultants to develop transition plans and technical roadmaps for 50% and 100% renewable electricity scenarios (see Section 6: Energy systems modeling).

3. Current state of Cape Verde and its energy system

3.1 Demographic and energy profile

Cape Verde was discovered and colonized by Portugal, as were other Atlantic islands such as Madéira and São Tomé. Unlike those islands, however, Cape Verde could not produce valuable export crops like sugar, wine, coffee, or cacao. The islands' desert and semi-desert climates limited their economic development. Early in its history, Cape Verde's main economic activity was selling slaves, meat, cloth, and services to passing ships (Garfield, 2015).

Cape Verde is now recognized as a model for sustainable economic development. It graduated from the United Nations' list of Least Developed Countries in 2007. Tourism is now the main driver of economic development but the African Development Bank (2014) recommends diversification for sustained growth.

Cape Verde's estimated population of 550,000 (2019) is concentrated on the island of Santiago, especially in the capital city of Praia (Table 1, Figure 2). Most Cape Verdeans (62%) live in cities (Instituto Nacional de Estatistica, 2016).

Table 1: Cape Verde's estimated population, by island (Instituto Nacional de Estatistica, 2016).

Island	Island population (2019 est.)	Percent of total population	Percent urban (based on 2010 census)
Boa Vista	18,795	3.41	58.88
Brava	5,463	0.99	18.81
Fogo	35,015	6.36	33.40
Maio	7,351	1.34	42.91
Sal	39,696	7.21	92.49
Santiago (São Tiago)	309,633	56.25	60.82
Santo Antão	38,194	6.94	34.92
São Nicolau	12,107	2.20	44.14
São Vicente	84,229	15.30	92.65
Total	**550,483**	**100**	**61.79**

Figure 2: Cape Verde comprises nine major islands. ©US Central Intelligence Agency, 2018.

Cape Verdeans enjoy a high rate of electricity access (95%), but about 35% still cook with traditional fuels, namely firewood. Nationally, renewable energy accounts for about 25% of total electricity production and 23% of installed capacity (35 MW of 150 MW in 2015). The electricity system, however, is composed of nine different grids on each of the inhabited islands (Costa, 2015). This presents a barrier to achieving economies of scale associated with centralized energy systems but offers an opportunity for distributed energy systems.

Cape Verde's energy portfolio comprises four main sources: petroleum products for transportation and electricity production; wind and solar for electricity production; and butane gas and firewood for cooking. The National Electricity and Water Company (Electra) is the supplier of grid electricity on the islands. Electra generated approximately 400 GWh of electricity in 2015. With a population of about 550,000, per capita electricity consumption is about 727 kWh/person/year. This is higher than the Sub-Saharan Africa average of 488 kWh/person/year (World Bank, 2017).

Electricity in Cape Verde, as in most small island states, is expensive. Most of Cape Verde's electricity production comes from diesel generators so the electricity price reflects the price of imported oil. Electricity prices for the end consumer have fluctuated from more than €0.30/kWh in 2012 to €0.25/kWh in 2017 (Hove, 2018).

Cape Verde has taken advantage of the renewable resources on the islands to provide residents locally-generated power. It first installed wind turbines in 1994 and has worked to expand wind energy production across four islands (Table 2) (Hove, 2018; Monteiro Alves et al., 2000). Between 2012 and 2017, the 25.5 MW of turbines produced between 60 and 80 GWh of electricity per year with capacity factors ranging from 26% on Sal to 39% on Santiago. Wind accounted for about 22% of the country's total electricity consumption during that time. This electricity production avoided the consumption of 15 million liters of imported fuel oil (Reiche et al., 2017). Graça (2017, p. 10) noted that between 2011 and 2016, the 0.5 MW wind farm on Santo Antão "already allowed financial savings in fuel costs equivalent to 166% of the project investment cost." The value of the total fuel savings exceeded €1.5 million.

Table 2: Wind farm production statistics, 2017 (Hove, 2018).

Island	Installed wind capacity (MW)	Electricity produced (MWh)	Wind speed (m/s)
Santiago	9.35	31,383	8.2
São Vicente	5.95	19,507	9.6
Sal	7.65	16,541	8.8
Boa Vista	2.55	7,959	8.9
Total	**25.50**	**75,291**	**8.9 (average)**

The wind farms accounted for 17% of total electricity production in 2017, down slightly from previous years. The reduced penetration was due in part because the electric utility-imposed technical restrictions on wind generation. The electric utility only absorbed 75% of the electricity that could have been produced by the wind farms. This was especially pronounced on the island of Sal where 54% of wind-generated electricity was put on to the grid and the remaining 46% was wasted (Hove, 2018). This curtailment of wind power highlights the lack of energy storage capacity to fully use the available intermittent energy resources.

In addition to wind turbines, Cape Verde also has solar photovoltaic (PV) installations including two large-scale solar farms built in 2010: a 5 MW PV array on Santiago and a 2.5 MW PV array on Sal (CapeVerde.com, 2011). This accounts for roughly 5% of the total 150 MW of installed capacity (Costa, 2015).

3.2 Cape Verde's renewable energy vision

Cape Verde has engaged in energy policy and planning to create a sustainable energy system (African Development Bank, 2014; Republic of Cape Verde, 2016). Its most recent energy planning document is Cape Verde's Nationally Determined Contribution (NDC) under the United Nations Framework Convention on Climate Change (Republic of Cape Verde, 2016).

Cape Verde made two unconditional commitments in its NDC: 1) "to achieve 100% grid access by 2017" and 2) "to achieve a 30% renewable energy penetration rate into the electric grid by 2025." As a small island developing state, Cape Verde seeks international support to achieve more ambitious goals. The conditional goal is to "increase the renewable energy uptake in electricity to 100% by 2025, with best efforts to achieve this goal by 2020, in accordance with the following indicative trajectory:

- 35% RE [renewable energy] penetration rate in 2016-2018;
- 50% RE penetration rate in 2018-2020;
- 100% RE penetration rate in 2020-2025" (Republic of Cape Verde, 2016).

The condition for achieving the 100% renewable energy penetration rate is obtaining international financial support. The NDC document described several key measures to achieve the goals, such as smart grids across the nine independent island energy networks; energy storage; microgrids; household-scale electricity systems; and solar hot water heaters. The NDC included additional commitments for energy efficiency, afforestation and reforestation; and waste management (Republic of Cape Verde, 2016).

Achieving these goals requires substantial investments in energy infrastructure not only to replace the existing diesel generators but also to keep up with population growth and increasing electricity consumption. Gesto Energy (2011) estimated the demand for electricity in 2020 to be about 670 GWh per year. Total electricity consumption in Cape Verde in 2017 was more than 424 GWh (Electra SA, 2018) so new generation sources will need to cover as much as 250 GWh of additional electricity consumption in the coming years.

Each of Cape Verde's constituent islands is a separate electricity grid. The islands are separated by considerable distances, ranging from 10 km to more than 100 km. These distances are similar to those of the Hawaiian archipelago. Solomon and Wellstead (2018) reported that linking the Hawaiian Islands via submarine transmission cables would be too expensive. It is likely that linking Cape Verde's islands would be similarly infeasible.

The next section describes a range of technology options, some readily deployable and others on the cusp of commercialization, that could contribute toward Cape Verde's 100% renewable electricity goal. Addressing the full social implications of Cape Verde's energy transition is beyond the scope of this report. However, we recognize that the technological shifts occur through and are mediated by social, political, and economic forces.

4. Options for renewable electricity generation

The menu of renewable energy options continues to expand as technologies and business models evolve. This section provides a brief description of various renewable-based electricity-generating options and an assessment of their feasibility for Cape Verde.

4.1 Wind

Cape Verde lies in the path of the northeasterly trade winds. Cabeólica reported average hub-height wind speeds of between 8.3 m/s and 9.9 m/s at the four wind farms it owns (Monteiro, 2017). These factors make Cape Verde an excellent candidate for wind energy production. Gesto Energy (2011) estimated that the nine islands could potentially support 241 MW of wind energy capacity at a levelized cost of electricity of around €0.05/kWh. This is greater than the entire existing electricity grid (150 MW). Cabeólica currently sells its wind-generated electricity at about €0.14/kWh (€140/MWh) (Hove, 2018).

Cape Verde has significant offshore wind resources as well. The entire region has offshore wind speeds greater than 8 m/s which are highly suitable for energy production (Figure 3) (US National Renewable Energy Laboratory, 2014). Cape Verde's offshore wind resource is similar to that of Fuertaventura in the Canary Islands, which was deemed suitable for offshore wind energy development (Veigas et al., 2014). Conventional offshore wind turbines are fixed to the sea bed and are limited in practice to depths less than 30 m. Ocean depth increases quickly with distance from shore around most of Cape Verde's islands rendering them unsuitable for conventional offshore wind energy. There are small areas of suitable depth to the southeast of São Nicolau and between Boa Vista and Maio (Figure 4). Floating offshore wind turbines are an emerging technology that could be appropriate for the deep waters off Cape Verde. A Spanish analysis of floating deep-water wind turbines estimated the levelized cost of electricity (LCOE) to be €75-215/MWh (Castro-Santos et al., 2016).

The challenge, however, for additional wind development on the four islands with existing wind farms is the high degree of wind penetration – about 20-25% (Table 2). The utility Electra curtailed a substantial portion of wind generation, up to 46% on the island of Sal, in order manage the grid load (Hove, 2018; Reiche et al., 2017). Additional wind energy development on those four islands will likely require additional investments in grid management and electricity storage solutions. Integrating desalination and pumped storage could make the system more efficient by reducing curtailments (see sections 5.2 and 6 for further discussion of storage and energy system modeling).

4.2 Solar photovoltaic energy

Cape Verde lies only 16° north of the equator and its potential for photovoltaic (PV) solar power is quite promising. Gesto Energy (2011) estimated that 315 MW of solar PV projects are feasible in Cape Verde with most of the potential development on Santiago. They estimated the levelized cost at about €0.25/kWh but solar PV costs have dropped significantly since 2011. Currently only 7.5 MW of solar PV capacity has been installed. The 315 MW of potential solar PV could produce as much as 471 GWh of electricity based on estimates using the PVGIS for Africa and Asia (Joint Research Centre, 2012). That is more than the 400 GWh of electricity produced by the Electra utility from all sources in 2015. This additional PV electricity would be more than sufficient to cover the increased demand through 2020 and beyond – if it could be integrated into the electricity grid.

Energy storage, including combining storage with solar PV, is discussed in Section 5.2.

4.3 Hydropower and marine kinetic energy

Marine and hydrokinetic energy captures energy from rivers, ocean currents, waves, and tides (US Department of Energy, 2016). The capture of energy from flowing water, known as hydropower, is not a viable option for Cape Verde because there is insufficient surface water. Likewise, Cape Verde has a relatively small tidal range of about one meter, making it inadequate for tidal energy (Ocean Energy Systems, 2017). Cape Verde is exploring other marine energy resources.

Wave energy harnesses energy from either surface waves or below-surface pressure fluctuations (US Bureau of Ocean Energy Management, 2018). The optimal power density for wave energy is 40-60 kW/m (Kempener & Neumann, 2014) but most sites in Cape Verde have power densities of about 20 kW/m. The northwestern islands, notably Santo Antão, have wave resources of up to 27 kW/m during the winter (December-March) (Bernardino et al., 2017). Resolute Marine Energy is developing a wave-powered desalination system off the coast of Praia, Cape Verde's most populated city (Freyberg, 2016).

Wave energy is less variable than, and complementary to, wind and solar energy. However, the cost of wave energy is high. A review of estimates from the US, Europe, and Australia reported an average of US$0.24/kWh (von Jouanne & K.A. Brekken, 2017). Others estimated a considerably higher cost at about US$1.00-1.5/kWh for a 10 MW system (Jenne et al., 2015) – more than four times the current price of electricity in Cape Verde. Resolute Marine Energy's wave-powered desalination system is expected to produce electricity and drinking water at levelized costs of US$0.21/kWh and US$1.44/m^3, although this is a generic estimate and is not specific to Cape Verde (Reavis & Zuckerman, 2014). Combining wave power with offshore wind could potentially result in more efficient use of fixed-cost resources, as suggested by Veigas et al. (2014) in the Canary Islands.

4.4 Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) uses the difference between warm surface water and cold deep ocean water to produce electricity. OTEC is particularly attractive because it provides dispatchable (baseload) power. A US$5 million, 105 kW pilot-scale OTEC plant is now operating in Hawaii. Several pilot-scale projects exist at other locations around the world, but OTEC has not yet been developed at a commercial scale (Vyawahare, 2015).

OTEC works best when there is at least a 20° C temperature difference between surface and deep water. These conditions exist along equatorial latitudes (Vyawahare, 2015). Cape Verde is only about one hundred miles north of the boundary of these ideal conditions. Coarse-scale assessments show that the southernmost tip of Santiago has a temperature difference of 19.5° C, which warrants site-specific investigations (Ocean Energy Systems, 2017). Ocean thermal energy should be investigated more thoroughly for suitable sites around Cape Verde.

OTEC is an emerging, but promising, technology so cost estimates are mostly speculative. Some expect the costs to fall to US$0.10-0.18/kWh as the technology matures (von Jouanne & K.A. Brekken, 2017). A conceptual design for a 5 MW system in the Oman Sea with a 22° C temperature difference had an expected LCOE of US$0.12/kWh (Hamedi & Sadeghzadeh, 2017). A LCOE in this range could be economically feasible for Cape Verde.

4.5 Geothermal

As a volcanic archipelago, Cape Verde has potential to exploit geothermal energy, particularly on the island of Fogo. Gesto Energy (2011) used a wide arrange of services to assess geothermal potential on Fogo. They found a potential geothermal reservoir on Fogo with a total capacity of 3 MW (Global CCS Institute, 2015). If the reservoir remains at a consistent temperature annually, this would benefit the island of Fogo. Even though 3 MW is a small compared to other large-scale projects, geothermal energy can still provide 2% of Cape Verde's current total capacity. More importantly, geothermal energy is not variable and can provide critical baseload power to complement variable sources like wind and solar. However, water samples have caused skepticism as to whether a reservoir with proper geothermal potential exists (Global CCS Institute, 2015). Geothermal systems typically have LCOEs of US$0.03-0.15/kWh (von Jouanne & K.A. Brekken, 2017). Gesto's (2011) estimate was €0.175/kWh.

5. Delivery of energy services

The way in which energy services are delivered has a considerable effect on improvements in living conditions (including health), electricity price, and grid stability. This section addresses options to deliver improved energy services for electricity generation.

5.1 Grids, microgrids and self-generation

Several groups have drafted renewable energy 'roadmaps' for Cape Verde (Gesto Energy, 2011; Heck et al., 2013) which relied substantially on centralized, grid-based renewable energy. But as noted by Dr. Anildo Costa (personal communication), the Cape Verdean government has not formally adopted a renewable energy roadmap to achieve its goals, and more distributed generation is being connected to the grid. While not a resource itself, microgrids and self-generation offer an alternative to large, grid-based electricity generation and delivery.

Solar household systems are standalone systems whereas microgrids, as the name suggests, connect many houses. An economic analysis of the two found that a standalone solar household system has a lower annual user cost than a microgrid in small or dispersed villages.

The microgrid is an economically viable option if there are at least 180 households that are relatively close together (Chaurey & Kandpal, 2010). Electric utilities can offer a range of services across the 'energy ladder' continuum, from solar household systems to microgrids to full grid-connected electricity (Stanton & Nordman, 2017).

Although diesel-based microgrids have been used in many rural areas, including in Cape Verde, Ranaboldo et al. (2014) designed a microgrid using wind and solar energy for three Cape Verdean communities. They found that the hybrid wind-solar microgrid had a lower life-cycle cost than either a pure diesel microgrid or a wind-solar-diesel hybrid, although it was unclear if future values were discounted. The analysis did not monetize the environmental and health benefits of non-polluting renewable energy sources which would make the renewable microgrid even more favorable.

The intersection of distributed energy technologies, mobile communications, and mobile banking has revolutionized the delivery of off-grid electricity services. The cost of solar panels and LED lights has fallen tremendously, yet the systems' capital costs still put them out of reach for many households. With advances in mobile phones, households are now able to connect to energy companies in real time. Mobile banking enables the easy and reliable transfer of money via SMS. Pay-as-you-go energy systems integrate these three capabilities and allow households to purchase solar household systems or similar systems and pay the cost over time. Kenya and Tanzania have emerged as leaders in this sector. Development finance institutions can encourage local banks to provide financing for pay-as-you-go energy systems by providing loan guarantees and lines of credit (Sanyal et al., 2016). Such pay-as-you-go systems could enable Cape Verde to step closer to its renewable energy goals without the large capital investments of centralized systems.

5.2 Energy storage

Conventional electricity sources, like fuel oil, coal, and natural gas, are 'dispatchable'. That is, they can be turned on and off (with various degrees of ease) to meet consumer demand. But most renewable sources, like wind and solar energy, are 'non-dispatchable'. Grid operators have no control over when the wind blows or when the sun shines. As more non-dispatchable renewable energy (wind and solar) is connected to the grid, especially as penetrations approach 50%, more electricity production will be curtailed when supply exceeds demand. In Cape Verde, renewable energy curtailments range from 2% on Santiago to 46% on Sal (Hove, 2018; Mostert et al., 2014). Curtailments can be reduced by either storing excess energy or facilitating the timely alignment of demand and supply.

Storing energy from non-dispatchable sources enables electricity supply to match the timing of electricity demand on various temporal scales from minutes to months. Numerous storage technologies currently exist, such as pumped hydropower, phase change materials such as ice and molten salts, sensible heat thermal energy storage, underground thermal storage, and batteries.

Gesto Energy (2011) noted that there is an opportunity to develop pumped storage facilities in which seawater is pumped to high-elevation reservoirs when electricity supply exceeds demand. When demand increases, the water is released from the reservoirs and spins a turbine as it flows back to the sea. Pumped storage can augment variable energy resources, particularly wind, which tends to blow more strongly at night when demand is low. Such pumped storage facilities can reduce the curtailment of intermittent energy sources like wind. Gesto Energy (2011) proposed three pumped storage reservoirs on Santiago at an estimated cost of €40 million each.

The consulting firm MWH led a consortium of technical analysts in an economic assessment of pumped storage reservoirs in Cape Verde. Pumped storage's cost effectiveness is highly sensitive to the type of financing and associated interest rates. The cost of generation using pumped storage ranged from €83/MWh for publicly-financed projects to €240/MWh for privately financed projects. By comparison, the team estimated the variable cost of diesel power at €174/MWh, suggesting that a publicly-financed pumped storage project would be a cost-effective investment (Mostert et al., 2014).

Segurado et al. (2011) analyzed the integration of wind energy and desalination on São Vicente in Cape Verde. One of the challenges of increasing the proportion of intermittent energy sources is that supply and demand do not always align. If wind turbines are generating electricity at times of low demand, the electricity may be rejected. Coupling the wind turbines to the desalination systems, on which São Vicente depends entirely for its drinking water, optimizes the use of wind-generated electricity. Pumping the freshwater into a high-elevation pumped-storage reservoir would enable storage of both water and energy. This would further optimize the use of renewable energy in desalination although it is unclear whether a suitable site exists for the hypothetical pumped storage reservoir. Segurado et al. (2015) further explored the coupling of electricity, pumped storage, and desalination in a PhD thesis. Integrating these systems in São Vicente could allow for renewable energy penetrations of up to 84%. In the reference case, they estimated the cost of electricity production at €0.273/kWh. In the optimized scenario with 53.3% wind power and 22.5% pumped storage, the electricity production cost falls to €0.145/kWh. They estimated the system's capital cost at €22 million.

Evidence from other parts of Africa show that solar PV with battery storage can be cost effective. Lai and McCulloch (2017) modeled a hypothetical Kenyan solar system with and without electrical energy storage. The base-case scenario, including a 2.5 MW system sized to match a 1.9 MW load without storage, had a levelized cost of electricity of US$0.093/kWh. The alternative case also featured a 1.9 MW load, but was sized to 5 MW and included battery storage. The levelized cost of electricity from the solar with storage system ranged between US$0.15/kWh and US$0.20/kWh depending on the choice of discount rate. The results suggest that PV with battery storage could be a cost-effective option for Cape Verde to integrate more variable PV into the grid while balancing the load.

'Vehicle-to-grid' systems, conceptually at least, date back to the early 2000s (Letendre & Kempton, 2002). Electric vehicles are not merely electricity consumers – they also store large amounts of energy in batteries and, under certain conditions, can feed power back on to the grid. This requires a connection from the vehicle to the grid, some type of control that regulates the flow, and a reliable meter inside the vehicle. Electric vehicles can then charge when (renewable) electricity supply is high and discharge when demand is high and supply is low. This ability is economically valuable to grid operators (Letendre & Kempton, 2002).

Island power systems are less responsive to shocks and more vulnerable to grid instability compared to larger continental systems (Díaz et al., 2015). Díaz et al. (2015) analyzed the potential of electric vehicles to provide energy storage in the Canary Islands, particularly the island of Tenerife. Their simulation included various levels of renewable energy up to 25% penetration (402 MW wind and 151 MW PV) and levels of electric vehicles (10,000-50,000). In the optimal scenario, the vehicle-to-grid vehicle fleet reduced curtailments from more than 25% to 10-15%. The bank UBS predicts that the cost of electric vehicles could reach parity with gas vehicles in Europe by 2018 (Campbell, 2017). If so, the transition to an electric fleet could happen relatively quickly. The vehicle-to-grid scenario proposed at the turn of the century may soon be feasible.

6. Energy system modeling

A team of European and Cape Verdean researchers proposed a highly detailed plan for Cape Verde to reach its 100% renewable electricity goal. Heck et al. (2013) analyzed the energy supply options for Cape Verde, including wind, solar, and municipal solid waste, and alternatives to store energy to address both short-term and long-term fluctuations. They provided several case studies in renewable energy and efficiency applications in the agricultural, food preparation, and hospitality industries. The team also proposed a detailed mechanism to finance the transition to a renewable energy system.

Heck et al. (2013) proposed a renewable generation system based on solar PV and wind with energy storage. The proposed system was highly centralized for each island with utility-scale generating sources serving many households. The optimal energy mix included 347 MW of solar PV, 196 MW of wind, 66 MW of battery storage, and 13,520 MWh of seasonal storage (pumped hydropower systems). The total capital cost of the system was €1,272 million (Table 3). The team estimated that demand among all the islands would total 671 GWh per year and the system would produce 1,223 GWh per year. The excess electricity would need to be stored, used for desalination or electric vehicle charging, or converted into cooking gas. The estimated levelized cost of electricity ranged from €0.104/kWh to €0.189/kWh. This is lower than the recent (highly variable) electricity prices of €0.25-0.30/kWh.

The Heck team's plan, however, was not adopted by the government and is not being implemented. The plan relied heavily on centralized energy sources whereas the local trend is toward distributed generation (A. Costa, personal communication).

Table 3: An optimized mix for 100% renewable electricity. Adapted from Heck et al. (2013).

Island	Solar PV (MW)	Wind (MW)	Battery storage (MW)	Seasonal storage (MWh)	Total installed capacity (MW)	Total capital cost (€), in millions
Boavista	42	28	9	1,600	70	164
Fogo	10	7	2	550	17	42
Maio	10	3	1	280	13	27
Sal	36	24	9	2,100	60	162
Santiago	168	112	30	7,700	280	660
Santo Antão	12	3	3	250	15	36
São Nicolau	3	2	1	70	5	12
São Vicente	64	16	10	900	80	160
Total installed power	347 MW	196 MW	66 MW	13,520 MWh	543 MW	
Total capital cost	€418 million	€332 million	€119 million	€404 million		€1,272 million

Jacobson et al. (2018) evaluated 100% wind-water-solar energy supply, storage, and transmission scenarios for 139 countries aggregated into 20 regions. End uses included not only electricity, but also transportation, heating and cooling, industry, agriculture, forestry, and fishing. The scenarios envisioned the transition to 100% wind-water-solar by 2050. Cape Verde was not among the countries analyzed, but they did evaluate several Caribbean islands. They found that "the actual price paid for BAU [business as usual] electricity on islands, such as in the Caribbean is currently a mean of ~33¢/kWh, much higher than the estimated costs found here (in Case A) of replacing BAU electricity in Haiti-Dominican Republic (9.25¢/kWh), Cuba (~10.8¢/kWh), or Jamaica (9.76¢/kWh)." The study supports the previous analyses in concluding that a 100% renewable scenario is technically possible and cost effective for islands – and possibly for Cape Verde. However, Cape Verde's goal has a much more ambitious time frame of 2025. The Jacobson et al. (2018) study did not claim that their scenarios were optimal, just that they were achievable.

7. Discussion: Is Cape Verde's 100% renewable electricity goal realistic?

Cape Verde has considerable renewable energy resources. However, it faces three challenges for meeting its NDC target. First, it must obtain financing for bankable projects. Second, it must build sufficient storage capacity, whether pumped hydro, batteries, or other technologies, to ensure grid reliability. Third, it must do this by 2025, an ambitious timeline.

Cape Verde is very close to achieving its unconditional goal of 30% renewable-based electricity by 2020. Renewable energy provides up to 25% of electricity production now. That level has stalled with the lack of additional renewable energy investments. Cape Verde is not on track to achieve the conditional goal of 100% renewable energy penetration by 2025. It has not attained the interim goal of 35% renewable energy penetration by 2016-2018.

Although the islands of Cape Verde are small, they offer a broad and diversified mix of renewable energy sources to contribute to Cape Verde's goals. Some of these resources could support bankable projects. Previous estimates (Gesto Energy, 2011; Heck et al., 2013) suggest that Cape Verde will need about 670 GWh by 2020. Simultaneously expanding the amount of electricity production, reducing the price (recently €0.25-0.30/kWh), and decarbonizing it is a formidable task. The path ahead will be challenging but Cape Verde could make great strides toward this goal. Table 4 lists the resources assessed in this document. The estimated levelized costs are those reported in the original source, but costs have fallen, sometimes dramatically, in the intervening years. Lazard (2018) published the latest levelized costs for renewable energy sources. Wind power now ranges from US$0.03-0.06/kWh, utility scale solar is US$0.04-0.05/kWh, rooftop commercial and industrial solar is US$0.08-0.17/kWh, rooftop residential is US$0.16-0.27/kWh, and geothermal is US$0.07-0.11/kWh. The LCOE estimate for utility scale solar PV plus battery storage is US$0.11-0.14/kWh. Costs may be higher in Cape Verde.

Table 4: Renewable energy sources for Cape Verde.

Source	Energy type	Resource size	Estimated levelized cost (original source)	Location
Heck et al. (2013)	Diesel and fuel oil (reference case)	117 MW	€0.19-0.30/kWh	Cape Verde
Gesto (2011)	Wind	241 MW	€0.05/kWh	Cape Verde
Gesto (2011)	Solar PV	315 MW	€0.25/kWh	Cape Verde
Gesto (2011)	Geothermal	22 MW	€0.18/kWh	Cape Verde
Heck et al. (2013)	Wind + solar + storage	543 MW (wind + solar)	€0.10-0.19/kWh	Cape Verde
Segurado et al. (2015)	Wind + desalination, pumped hydro	17 MW (wind)	€0.15/kWh	São Vicente, Cape Verde
Reavis and Zuckerman (2014)	Wave desalination	unknown	US$0.21/kWh	generic
von Jouanne & K.A. Brekken (2017)	OTEC	unknown	US$0.10-0.18/kWh	generic

These studies suggest that Cape Verde could meet more than half of its electricity needs in a cost-effective manner using wind, solar, and some forms of storage (battery or pumped hydro). Achieving the 100% renewable goal will likely require some level of adoption of emerging energy technologies, especially those that are less variable than wind and solar such as geothermal or OTEC.

Financing for bankable projects is now one of Cape Verde's main barriers to achieving its renewable electricity goals (Cruz, 2018). Cape Verde is working with the international community, both public and private sectors, to obtain financing for renewable energy projects. Cape Verde will likely require about US$1 billion to build the infrastructure needed to achieve the 100% renewable energy penetration goal (Republic of Cape Verde, 2016). The Cape Verdean government has established a strategy for mobilizing funds for sustainable energy (Cruz 2018). It is also working with the International Renewable Energy Agency's Lighthouses Initiative which helps facilitate financing.

The ambitious 2025 target is consistent with the 'eco-island' and development aid strategies described by Grydehøj and Kelman (2017) and Dornan and Shah (2016), respectively. In Cape Verde's case, the existing diesel-based energy infrastructure is both expensive and polluting. Although framed as a greenhouse gas reduction component of the NDC, Cape Verde's transition to clean, renewable electricity will, by most estimates, reduce electricity costs and lower conventional air pollutants. If so, it may boost local economic development and improve health outcomes. Cape Verde's choice of an ambitious target may be, in Grydehøj and Kelman (2017) words, 'conspicuous sustainability', but it may nonetheless provide tangible benefits that help it avoid the eco-island trap.

Cape Verde is one of 57 countries with a 100% renewable energy target. Several of these are archipelago SIDS, such as Comoros, Fiji, Kiribati, Maldives, Marshall Islands, Palau, Samoa, Solomon Islands, Tuvalu, and Vanuatu (REN21, 2018). Although not a SIDS, the US state of Hawai'i has also adopted a 100% renewable energy goal to be reached in 2045 (Solomon & Wellstead, 2018). Cape Verde's target date of 2025 is significantly more ambitious than most of its island peers.

Seventeen countries now generate more than 90% of their electricity from renewable sources and three run entirely on renewable energy (Albania, Iceland, and Paraguay). Hydropower is the leading source of energy in these countries (providing 100% of Albania's and Paraguay's electricity). Uruguay, Costa Rica, and Ethiopia also obtain more than 90% of their electricity from renewable sources with large contributions from wind power (REN21, 2018). Hydropower is dispatchable and can be managed to meet daily changes in electricity demand. This illustrates a practical challenge for Cape Verde: it lacks dispatchable hydropower.

Xcel Energy, one of the largest electric utilities in the United States, committed to delivering 80% carbon-free electricity by 2030 and being 100% carbon-free by 2050. 'Carbon-free' is not the same as 100% renewable, given that it includes nuclear power and carbon capture and storage, but it does suggest that ambitious targets are, in some cases, economically and technically feasible. In its press release, Xcel Energy (2018) noted that "its 2030 goal can be achieved affordably with renewable energy and other technologies currently available. However, achieving the long-term vision of zero-carbon electricity requires technologies that are not cost effective or commercially available today."

Hawai'i has laid out a strategy for achieving its 100% renewable target that might be appropriate for Cape Verde. Like Cape Verde, each Hawaiian island is an independent electricity grid. The state government has identified a target date for each island to achieve the 100% target. The schedule is based on population density, undeveloped land, and rooftop access for solar PV. Moloka'i, the second least populated of the main islands, is set to achieve it first in 2020. By that year, the Big Island of Hawai'i is expected to reach 80% renewable penetration, Maui 63%, and Lana'i 59%. Each of these islands is expected to reach the target five years early, in 2040. Oahu, home to 69% of the state's population, lags behind the other islands in current renewable penetration and will be challenged to meet the 2045 target (Solomon & Wellstead, 2018). Cape Verde could follow Hawai'i's path and identify a schedule for each island, from the easiest to the most challenging.

The resource assessments, modeling studies, and experiences in other countries suggest that Cape Verde could, with sufficient and appropriate investments, achieve a high level of renewable energy penetration by 2025. Reaching 100% renewables by 2025 is technically possible but unlikely to be achieved given the time required for site assessments, regulatory compliance, financing, and other aspects of project development. That does not, however, mean that Cape Verde should abandon its goal. Incremental progress in replacing expensive, polluting diesel generators with clean, renewable energy will bring economic, environmental, and health benefits.

8. Conclusions

Cape Verde has been successful in integrating wind and solar into its energy system. Renewable energy sources have displaced expensive and polluting diesel generators and renewables now account for about 25% of Cape Verde's electricity supply. However, the intermittent nature of wind and solar resources poses challenges for meeting its goal of obtaining 100% of its electricity from renewable sources. This report built on the previous 'roadmap' studies (Gesto Energy, 2011; Heck et al., 2013) and introduced a range of commercially available and emerging options for renewable energy. This report does not, however, prescribe a certain mix of energy sources.

Cape Verde has sufficient wind and solar resources to meet its goal but they can only be exploited if the energy can be stored or used when available. Combining intermittent wind and solar energy with dispatchable power, such as wave or OTEC, and battery storage or both desalination and pumped storage can avoid curtailment and allow greater renewable energy penetration. This will require an investment on the order of US$1 billion. An emerging alternative in energy storage is a vehicle-to-grid system. Electric vehicles are now available and are expected to make up a significant share of global vehicles over the next decade. By connecting parked vehicles to the electricity grid, the vehicle batteries can serve as distributed energy storage.

The alternative to additional grid electricity is to add more distributed generation in the form of standalone SHS or renewable-based microgrids. These could be the most cost-effective means for both providing electricity access in rural areas and adding additional renewable capacity without straining the electricity grid.

As an archipelago, Cape Verde faces both social and technical challenges to reaching its goal. Cape Verde, like many SIDS with similarly ambitious renewable energy goals, risks falling into an 'eco-island trap'. The ambitious goal may attract international financing, but Cape Verde is not on track and may ultimately fall short of achieving its goal. Adopting an island-by-island strategy, similar to Hawai'i, may improve its chances of success.

By building an energy system based on clean fuels and renewable sources, Cape Verde continues to make progress on the Sustainable Development Goals, particularly Goal 7: Ensure access to affordable, reliable, sustainable and modern energy for all. Cape Verde is also establishing itself as a leader in sustainable energy and serves as a model for other island nations facing similar energy challenges.

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