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Research Article

Power Market Interconnection in the Caribbean Region

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Abstract

The interconnectivity of energy markets is a tangible reality that generates economies of scale, reduced reserves, more efficient operation of electrical systems, more optimal use of natural resources in each country or region, as well as the strengthening of relations between the countries participating in this new regional electricity market. Furthermore, the renewable energy potential in the Caribbean and South America, based on solar, wind, hydroelectric, biomass, geothermal, and tidal energy, among others, ensures a stable and reliable supply of energy to the region. Nevertheless, the greater the amount of renewable energy available, the greater the need for rotating energy from non-renewable energy sources to ensure the stability, security, and integrity of the electrical system, which increases its operational costs. Motivated by these premises, we develop a research project that allowed us to demonstrate the technical, economic, and financial feasibility of interconnected electricity markets in the countries of the Caribbean region. The Caribbean region, characterized by its diverse cultures and economies, faces unique challenges in energy supply due to its geographical fragmentation. This paper explores the potential for power market interconnection among Caribbean nations to enhance energy security, economic efficiency, and environmental sustainability. By evaluating technical, economic, and political aspects, this study aims to provide a comprehensive overview of how interconnected power markets could transform the region's energy landscape.

Keywords

Interconnection, Electricity Markets, Submarine Cables, Power Converters, Market Regulation, Renewable Energy Sources

1. Introduction

The Caribbean region consists of numerous island nations, each with its own energy infrastructure, policies, and resources. The reliance on imported fossil fuels has left these islands vulnerable to disruption and price volatility. However, the region is abundant in renewable energy resources, including solar, wind, and geothermal, which remain underutilized. This paper will discuss the concept of power market interconnection as a viable solution to these challenges.

2. Objectives of the Project

The general objective of this research was to determine the technical, economic, and financial feasibility of promoting a regional electricity market in the Caribbean region by inter-

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connecting the electricity markets of Florida, the United States of America, the Antilles, and South America through submarine cables, through the Bolivarian Republic of Venezuela, to allow for greater expansion of the Caribbean region's renewable energy potential [4, 5].

To achieve this general objective, the following specific objectives must be developed:

To study and analyze the electricity markets, from a technical perspective, of the countries of the Greater Antilles, namely, Cuba, Jamaica, Haiti, the Dominican Republic, and Puerto Rico; the countries of the Lesser Antilles, namely, Antigua and Barbuda, Barbados, Dominica, Grenada, Saint Kitts and Nevis, Saint Vincent and the Grenadines, Saint Lucia, and Trinidad and Tobago; and of South America, specifically Venezuela, and to evaluate the electricity production potential in each of the countries in the region. To characterize the electricity markets, from a regulatory perspective, of the countries of the Greater Antilles, Lesser Antilles, and South America, specifically Venezuela and Colombia.

Using the PowerFactory program from the German firm DigSilent, to conduct simulations of the market behavior in the region under study, the load flows between countries, and the responses of the electrical systems of each country and as a whole to electrical faults, such as short circuits, generation losses, load losses, and interconnection openings, among others.

Based on the previous studies, to proceed with the complete design and selection of power cables for interconnection between the different electricity markets, as well as the design and selection of fiber optic cables for voice and data transmission between telecommunications companies in the region under study. For the purposes of this research project, we will refer to this interconnection system as the "Electrical Interconnection System of the Caribbean Countries (SIEPCAR)."

Conduct pre-feasibility and economic feasibility studies to determine the financial viability of investing in the power and telecommunications interconnection of the countries in the region under study.

Define the guidelines for structuring the Caribbean Regional Electricity Market (CREM) as the regulatory body for electricity sold under this regional interconnection scheme.

Provide a reliable database and disseminate the research results to enable replication of our research project in other regions of the Americas and around the world.

3. Current Energy Landscape in the Caribbean

3.1. Energy Dependency

Most Caribbean countries depend heavily on imported oil and gas, leading to high energy costs and vulnerability to external market fluctuations [6].

3.2. Renewable Energy Potential

Abundant renewable resources offer an opportunity to diversify energy sources but require significant investment and infrastructure development [4].

3.3. Benefits of Power Market Interconnection [7]

3.3.1. Enhanced Energy Security

Interconnection can reduce dependency on external fuel sources by optimizing the distribution of locally generated renewable energy across borders.

3.3.2. Economic Efficiency

Shared infrastructure and cooperative energy markets can reduce operational costs and improve the affordability of electricity for consumers.

3.3.3. Environmental Sustainability

By promoting the use of renewable energy, interconnection can significantly lower the carbon footprint of the region, aligning with global climate goals.

3.4. Technical and Economic Considerations [8]

3.4.1. Infrastructure Development

The establishment of a regional grid requires substantial investment in transmission networks, smart grid technologies, and energy storage solutions.

3.4.2. Regulatory and Policy Challenges

Harmonizing the regulatory frameworks of diverse nations is critical to facilitate cross-border energy trade and investment.

3.4.3. Financial Models and Investment

Exploration of funding mechanisms, such as public-private partnerships and international financial support, is essential to mitigate the high initial costs.

3.5. Case Studies and Comparative Analysis [9]

3.5.1. Successful Models

Examination of existing interconnected power markets, such as in Europe and Central America, to derive applicable lessons for the Caribbean.

3.5.2. Pilot Projects

Analysis of ongoing pilot projects within the region aimed at establishing mini grids and regional cooperation frameworks. One very interesting case that has been studied in recent years is the power interconnection between Dominican Republic and Puerto Rico, through a HVDC 230 kV, 2-pole, submarine cable.

3.6. Challenges and Obstacles

3.6.1. Geopolitical Barriers

Political tensions and a lack of regional governance structures can hinder progress towards interconnection.

3.6.2. Technical Limitations

Geographical hurdles and technological gaps present significant challenges that require tailored engineering solutions.

3.7. Recommendations and Strategic Roadmap

3.7.1. Policy Recommendations

Formulation of strategic policy guidelines to promote regional cooperation and investment in interconnection infrastructure.

3.7.2. Implementation Roadmap

A phased approach to developing the infrastructure and regulatory environment necessary for successful market interconnection.

4. HVDC / HVAC Submarine Cables

The state of the art focuses on the use of cross-linked polyethylene (XLPE) cables, both for high voltage alternating current (HVAC) and high voltage direct current (HVDC), and mineral insulated (MI) cables, exclusive for direct current (HVDC) technology [10, 11].

5. Energy Converters [11]

Converter stations are technological structures for transforming alternating current into direct current and vice versa. They are part of the high-voltage direct current (HVDC) transmission system.

We selected the Voltage Source Converter because of the following properties:

1) They allow control of both active and reactive power;
2) Black start capability;
3) Greater flexibility and smaller usable area; and
4) They do not change polarity when the power flow is reversed.

6. Bathymetry in the Caribbean [12]

As a starting point, the next figure shows the concept and a possible layout for the energy interconnection analyzed in the research project.

Source: Google Image / Representation of the Author

Figure 1. Schematic representation of the interconnection of the Caribbean electricity markets.

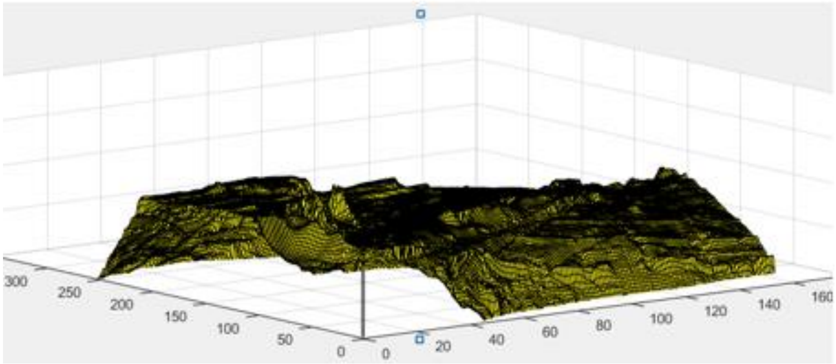
The methodology of this study was based on the use of the database provided by the General Bathymetry Chart of the Oceans (GEBCO), together with the Matrix Laboratory (MATLAB) software package.

Thus, the data provided on the GEBCO platform, https://download.gebco.net/, will be used to obtain and perform the following tasks:

1) Use digital images, with colors that describe the bathymetry, to approximate the layout to a more specific area.
2) Obtain the NC and ACS files that will be processed using the MATLAB [2] software to obtain a more specific layout, where a smaller unevenness is prioritized. NC and ACS files allow a resolution of 15 arc seconds (about 450 meters).

Regarding the MATLAB software package, it will be used to obtain a more precise trajectory of the energy network layout. To do this, the files of each zone with NC or ACS extension will be accessed, in search of the optimal layout in accordance with the established criteria.

The next figure shows the visualization of the NC and ACS files, obtained for an area of the present study. The Zone shown covers an area of 250 x 160 cells, that is, 112.5 km x 72 km between Cuba and Haiti.



Source: GEBCO

Figure 2. *MATLAB representation of an NC file.*

Following the procedure described, we determined the profile and bathymetry of the seafloor in the Caribbean.

7. Environmental Aspects [13, 14]

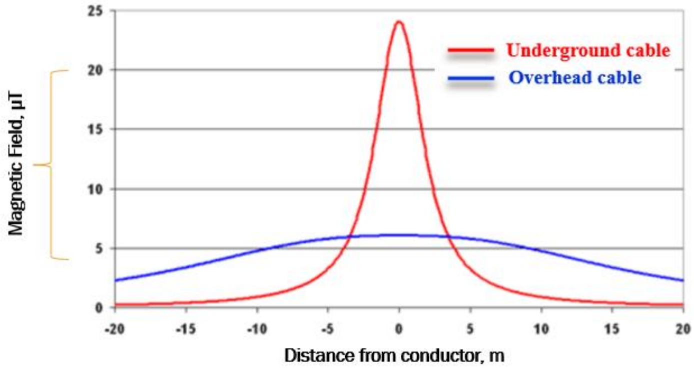
Table 1 shows the environmental impacts of the utilization of subsea HVDC/HVAC cables and the corresponding mitigation measures:

Table 1. *Mitigation of environmental impacts of submarine cables.*

Environmental Impacts	Mitigation Measures
Habitat Destruction	Avoid critical marine areas
Disruption of the behavior of marine species	Use of horizontal plowing and drilling techniques
Potential spill pollutant	Submarine cable monitoring to prevent spills
Effects of the magnetic field induced by high transmission voltage	Burials from a depth of 5 meters cancel the effect of the magnetic field

Source: Kemp, S., & Milne, S. (2019). *Mitigation of environmental impacts of submarine cables*. Journal of Marine Systems, 209, 103297. https://doi.org/10.1016/j.marpolbul.2016.06.022 [14]

The effect of the magnetic field and distance from conductor are represented in Figure 3:



Source: https://www.emfs.info/Source+of+EMFs/Underground/ [13]

Figure 3. Distance-related effect of the magnetic field on overhead and submarine cables.

The maximum value of the magnetic field inducted in a subsea HVDC/HVAC cable is approximately 25 µT, which is equivalent to 0.25 Gauss. If we compare this value with the Earth's magnetic field, which is 0.50 Gauss, no damage could be expected from this arrangement.

8. Use of DigSilent Power Factory® Software

First, we identify and locate, through the Google Earth® platform, the important electricity centers closer to the coasts of each of the countries and territories studied.

Likewise, we select for those generation centers remote from coasts, a connection point that will serve to install the corresponding converting station, either this AC/DC or DC/AC, depending on the type of interconnection with underwater cable that we have selected.

We use, as an information basis to determine the use of HVDC or HVAC technology, the figure "Submarine selection criteria for power transmission", Prysmian Cables and Systems (http: // https://www.prysmiangroup.com/en).

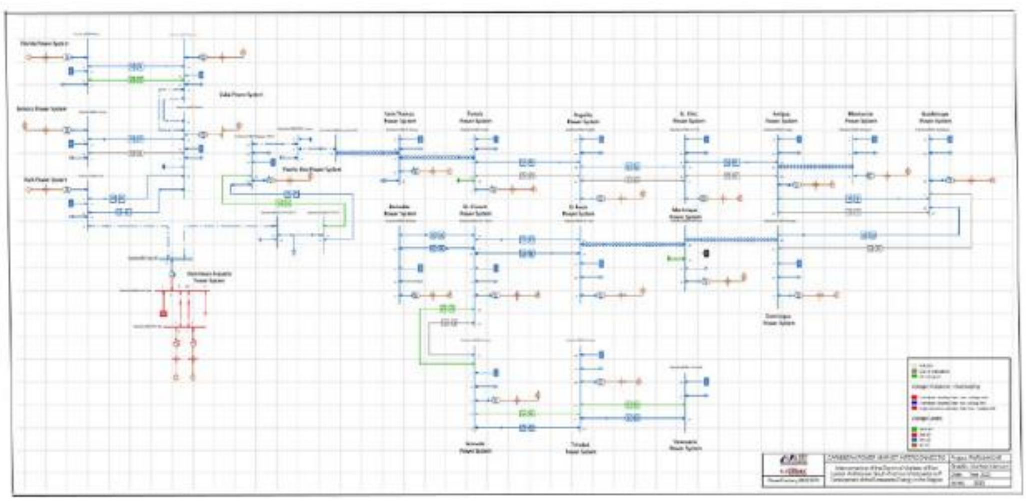
In all DC or AC interconnection links we select the 230 kV voltage to reduce electrical losses due to Joule effect.

We select the voltage source converter (VSC-Voltage Source Converter) of 500 MVA, 230 KVAC / 230 KVDC, 3-Pass, 60 Hz In cases where the interconnection is done with HVDC and HVAC cable, respectively.

In cases where it has been required, we include substations and power transformers to reduce tension from the level of exit of the converter to the transmission level of the country or territory considered.

Finally, we continued our research by building the interconnections between the electrical markets of the region, through the DigSilent Power Factory® program, verifying the technical viability of the proposed interconnection, through the load flows, according to the variable generation costs and the availability of the different markets.

To determine the technical feasibility of the project we use the PowerFactory software of the German company DigSilent, with the following results:



Source: The Author

Figure 4. General interconnection diagram made with DigSilent PowerFactory software.

9. Considerations Regarding UHVDC Subsea Cables Vs. HVDC Subsea Cables [15-17]

High-level comparison: HVDC vs UHVDC subsea cables (investment and cost-effectiveness)

Voltage class and capacity:

HVDC: typically, ±150 kV to ±500 kV, suitable for moderate long-distance links (tens to a few hundred km) and power ratings up to ~2–3 GW per bipole.

UHVDC: typically, ≥±500 kV (e.g., ±600 kV, ±800 kV, ±1,100 kV), used for very long distances and very high capacities (multiple GW per bipole).

Capital Investment (CAPEX):

Cable & converter cost per MW: HVDC has lower unit costs for short-to-medium distances because equipment and insulation requirements are less demanding.

UHVDC has higher equipment, insulation and manufacturing costs (higher-spec converters, thicker/substantial cable insulation, more stringent testing). However, its cost per MW-km falls faster with distance because higher voltage allows transmitting more power over same cable, reducing number of circuits and O&M per MW.

Break-even distance: UHVDC becomes more capital-efficient beyond a certain long distance/high-capacity threshold (depends on project — typically several hundred km subsea or very large power demand).

Transmission losses & operating cost (OPEX):

Higher-voltage UHVDC has lower losses per MW-km (lower current for same power), so lower energy losses and lower thermal stress — improving lifetime efficiency.

Over long distances, reduced losses and fewer parallel circuits lower OPEX and cost-of-delivered-energy for UHVDC compared with multiple HVDC links.

Project Scale and Economies:

For small to medium links (lower capacity or shorter subsea spans), HVDC is more cost-effective (lower upfront CAPEX, simpler logistics).

For very long subsea links or when very high capacity is needed (e.g., multi-GW interconnects, bulk renewable export), UHVDC yields better cost-effectiveness per delivered MWh despite higher initial investment.

Technical and logistical considerations affecting cost

Manufacturing capacity and supply chain: UHV equipment and very high-voltage cables are specialized and may increase lead times and premium pricing.

Converter complexity: UHVDC often uses advanced converter technology (VSC or high-power LSC variants) with higher converter-station costs.

Installation risks: heavier/ thicker UHV cables increase installation complexity and vessel requirements, potentially raising installation CAPEX.

Reliability and redundancy: UHVDC can reduce need for multiple circuits, lowering system complexity but raising single-point-of-failure risk that may require additional contingency cost.

Example heuristics (indicative):

If distance < ~100–200 km or power < ~1–2 GW: HVDC is typically cheaper and simpler.

If distance >>200–500 km and/or power > ~2–3 GW: UHVDC tends to be more cost-effective per delivered MWh.

Conclusion (concise):

HVDC: lower upfront cost and simpler for short/medium subsea links; more cost-effective for smaller capacities.

UHVDC: higher CAPEX but lower losses and better economies at very long distances and very high capacities, becoming more cost-effective per MW-km and per delivered MWh for large-scale/transmission-intensive projects.

10. Conclusions

1. Every country/territory studied has government institutions for energy, electricity and telecommunications, and legislation for both sectors; each owns at least one electricity producer.
2. Total installed electrical capacity across the study area is 100,359 MW; projected new renewable capacity is 3,929 MW.
3. Identified geothermal potential totals ~840 MW (Dominica 300, Guadeloupe 70, St. Kitts & Nevis 50–300, St. Lucia 170, St. Vincent & Grenadines upper value included).
4. Renewable expansion projections are island-based; interconnection would likely enable higher expansion.
5. Generation centers near coasts were located via Google Earth; inland plants were assigned converter-station connection points for AC/DC links.
6. HVDC vs HVAC selection follows Prysmian's "Transmission Cable System Selection Criteria"; 230 kV was chosen for links to limit Joule losses.
7. VSC converters specified: 500 MVA, 230 kVDC/230 kVAC, 3-phase, 60 Hz; transformers included where needed to match local transmission voltages.
8. PowerFactory (DIgSILENT) was used to model and verify technical feasibility of proposed interconnections.
9. The report covers HVAC and HVDC subsea cable technology, materials, selection criteria, and necessary seabed/geotechnical/environmental studies for installation; cable laying vessels and robots were described.
10. Electrical cable parameters (resistance, capacitance, impedance, inductance) were documented for voltage-drop/regulation calculations.
11. Submarine fiber-optic cables' economic and social importance and minimal environmental impact (per ICPC/UNEP-WCMC 2009 study) were noted.
12. The Interconnection System of the Countries of Central America (ISCCA), the Regional Electrical Interconnection Commission (REIC) and the Regional Operator

Entity (ROE) model were used as reference to propose a Caribbean Electricity Market Treaty (CEMT) and regional bodies, such as the Caribbean Regional Electricity Market (CREM), the Caribbean Network Operator (CNO), the Caribbean Electrical Interconnection Commission (CEIC), and the Company Owner of the Caribbean Network (COCN) to govern market, operation and regulation.

13. Financial analysis (internal return) considered two scenarios: current demand with interconnection (IRR/payback ~2.2 years) and projected 2028 demand with interconnection (IRR/payback ~2.5 years), both deemed financially feasible.
14. The study did not include potential telecom toll revenues from fiber capacity due to lack of data.
15. Recommendation: pursue a regional treaty and institutional framework and further detailed economic studies as continuation.

11. Recommendations

1) Engage directly with each country/territory's energy authorities to present the project and obtain up-to-date market data.
2) Conduct on-site surveys in every jurisdiction to collect current electricity and telecommunications information.
3) Deepen assessment of existing and potential renewable generation and update regional renewable expansion projections.
4) Update the DIgSILENT PowerFactory model with new data and run load-flow, short-circuit and stability studies under multiple scenarios.
5) Using model results, perform a revised equipment sizing and volumetric analysis (HVDC/HVAC cables, converters, transformers, lines, compensators, filters, etc.) to refine CAPEX estimates.
6) Use the software to determine economic dispatch strategies that minimize variable generation and dispatch costs for the interconnected system.
7) Consult telecommunications operators/regulators to evaluate technologies and revenue potential from embedding fiber in the submarine cable (toll/data traffic).
8) Commission detailed pre-feasibility and financial-feasibility studies with economics/business experts to structure the project for regional, US and South American investors.
9) Adopt ISCCA/REIC/NOC as a reference model and create regional institutions: REM (market), ROE (system operator), CEIC (regulatory commission) and EPRC (grid owner), with defined roles as outlined in the study.
10) Recommend further research: (1) comprehensive economic/financial analyses for medium- and long-term viability; (2) study of revenue and impacts from adding fiber-optic capacity to the submarine cable.

Final Invocation

To conclude, paraphrasing the late US President John Fitzgerald Kennedy's famous 1962 speech, which launched the space race, and adapting it to our current reality:

"The countries of the Caribbean region must strive to achieve a regional electricity market by the end of the 2030s, not because it is easy, but because it is difficult."

We trust that, like that 1962 speech, this quote will be a call to action and a symbol of the spirit of challenge and progress of this era and of the region's political and technological leaders.

Abbreviations

AC/DC	Alternating Current/Direct Current
ACS	Accoustic Communication System
CAEMFT	Central American Electricity Market Framework Treaty (SIEPAC in Spanish)
CANO	Central America Network Operator
CAPEX	Capital Expenses
CAREM	Central America Regional Electricity Market (MERC, in Spanish)
CEIC	Caribbean Electrical Interconnection Commission (CIEC in Spanish)
CNO	Caribbean Network Operator (ORC in Spanish)
COCN	Company Owner of the Caribbean Network (CPRC in Spanish)
CREM	Caribbean Regional Electricity Market (MERCAR in Spanish)
EISCC	Electrical Interconnection System of the Caribbean Countries (SIEPCAR in Spanish)
GEBCO	General Bathymetry Chart of the Oceans (GEBCO)
GW	Giga Watts
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICPC	International Cable Protection Committee
IRR	Internal Rate of Return
ISCCA	Interconnection System of the Countries of Central America (SIEPAC in Spanish)
KVAC	Kilo Volt Alternating Current
KVDC	Kilo Volt Direct Current
LSC	Line Switch Converter
MATLAB	Matrix Laboratory
MI	Mineral Insulated
MVA	Mega Volt Amperes
MWh	Mega Watt Hour
NC	Numerical Control
NOC	Network Operating Company (EOR in Spanish)
O&M	Operation and Maintenance
OPEX	Operating Expenses
REIC	Regional Electrical Interconnection Commission (CRIE in Spanish)

REM	Regional Electricity Market (MERC in Spanish)
ROE	Regional Operator Entity (EOR in Spanish)
UHVDC	Ultra High Voltage Direct Current
UNEP	United Nations Environment Programme
VSC	Voltage Source Converter
WCMC	World Conservation Monitoring Center
XLPE	Extruded Polyethylene Cable
µT	Micro-Tesla

Conflicts of Interest

The authors declare no conflicts of interest.

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