Resource assessment, technology development, public policies, and deploying large-scale projects of marine and ocean energy in Colombia

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I. INTRODUCTION

With resources like wind, solar, waves, tides, currents, and thermal and salinity gradients, the Colombian Caribbean and Pacific basins could play an essential role in decarbonizing the energy systems and diversifying the country's energy matrix in the medium term. The northern Caribbean region, encompassing Atlántico, Magdalena, and La Guajira, stands out with abundant resource potential, exceeding 1331 W/m^2 and 1700 W/m^2 in specific areas [1]. From the thermal gradients, 40 MW could be exploited near the coast of San Andres [2] and, 10 MW in Santa Marta [3], and 15,624 MW are theoretically available in the salinity gradients at some river mouths [4]. The average theoretical wave potential in the Caribbean is 5-6 kW/m and up to 4 kW/m in the northern Pacific [5]. Despite the high potential for ocean energy in Colombia, current efforts in this regard are limited to academic initiatives. The resource Ocean Renewable Energy sources distribution is sketched in Fig. 1.

This work compiles the most representative national studies and projects on ocean energy (marine renewable and offshore wind), including several resource assessments and technology development. Also, it discusses the national panorama in the context of Latin-American and Caribbean regions. Finally, it provides insights for joining the business sector, academic sector, government, and local communities towards promoting public policies and deploying large-scale projects.

II. RESOURCE ASSESSMENT

In one of our previous works [6], we gathered information about Colombia's ocean energy resources assessment. We showed that the country possesses a significant ocean energy potential that surpasses the current installed capacity of the National Interconnected System (SIN) [7]. Table 1 summarizes some of the significant findings in marine energy resource assessments in Colombia.

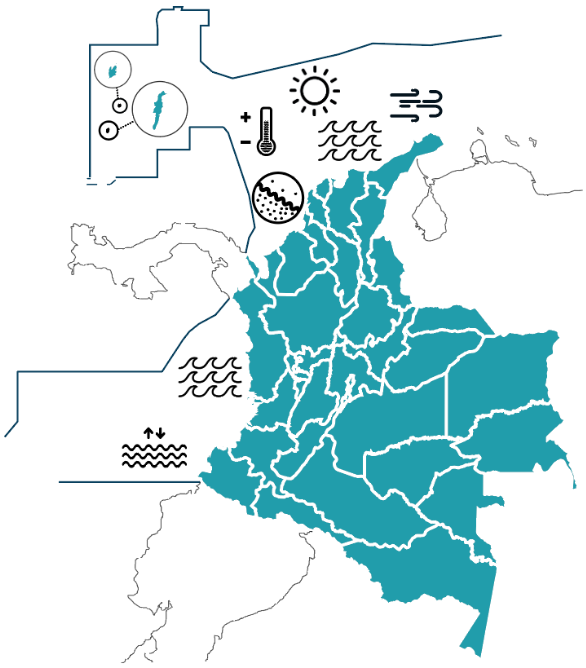

Fig. 1. Ocean Renewable Energy sources distribution in Colombia. The Colombian Caribbean has potential for thermal and saline gradients, waves, and offshore wind and solar, whereas the tides and waves are the most abundant in the Pacific basin. The blue line represents Colombia's territorial sea. Black lines show the borders of countries such as Panama, Ecuador, and Venezuela.

III. CHALLENGES FOR OCEAN AND MARINE RENEWABLES

Ocean renewable energies (ORE) have yet to see significant progress in their extraction [8] and present several economic, technical, social, and regulatory challenges due to their lack of maturity and development in the Colombian market.

TABLE I
MARINE RENEWABLE ENERGY POTENTIAL COLOMBIA. TAKEN FROM [6].

Resource	Potential	Units	Reference
OTEC – SAI[a] $\Delta T = 20°C$ Depth: 400-800m Dist: 7 km	9.5 – 40* (Tech)	MW	[2], [3], [5], [16]
OTEC - Santa Marta $\Delta T = 20°C$ Depth: 400-750m Distance: 16 km	10** avg. (Tech)	MW	[3], [5], [16]
Salinity gradient – Magdalena River	15,157(Theory) 780 (Tech)	MW	[4]
Salinity gradient - Canal Dique	154 (Theory)	MW	[4]
Salinity gradient – León River	187 (Theory)	MW	[4]
Salinity gradient – Atrato River	126 (Theory)	MW	[4]
Wave - Barranquilla	6	kW/m	[5]
Wave - Santa Marta	5	kW/m	[5]
Wave – north Pacific (Chocó -Nuquí)	Up to 4	kW/m	[5]
Wave – South Pacific Nuquí y San Juan	Up to 3	kW/m	[5]
Tides (San Juan - Buenaventura)	Up to 2.6	kW/m	[5], [13]

[a] SAI: San Andrés Island
* For hot water flows between 22 and 90 m^3/s. (Technical).
** For hot water flows 10 m^3/s. (Technical)

Hence, the challenges examined and analyzed in this report are crucial to addressing the gap between political, economic, and social constraints and available technologies. In this way, opportunities for implementing large-scale marine and ORE solutions can be unlocked.

Colombia has different laws (Ley 1715. 2014 and Ley 2099. 2021) that promote the study and implementation of these technologies. Still, the lack of experience in these issues applied directly to the Colombian territory hinders the development of innovative and functional projects that take advantage of these political and financial benefits. Despite those laws, Colombia is still in an early process of energy transition, and given that most ORE are in development and present a high levelized cost of energy compared to other renewables sources, studying the variability of income, investment, and operational costs, as well as the energy market is a significant challenge in the development of these technologies, for this it is possible to take as a starting point the experiences in other parts of the world but without leaving aside the characteristics and conditions of the territory.

Due to the special mountainous, geographic, oceanographic, and fluvial conditions, the country presents an excellent opportunity for developing this industry in isolated or non-interconnected regions and locations [9]. In most non-interconnected or potential areas where black, indigenous, or peasant communities are located, implementing pilot projects in these areas can be a great social challenge since their worldview must be respected, regulatory conditions must be determined, and the best alternatives must be found directly with the communities. ORE projects should be seen by communities as a way not only to bring electricity to the area but also to offer real benefits in terms of clean water, education, and economic development.

On the other hand, at the environmental level, the deployment of ORE projects will have to face, prevent, or minimize the adverse effects on the environment, even though some of these technologies involve few civil works, a challenge that is always present is to find the proper implementation zones avoiding protected areas and causing minimal or no negative impact [10].

From another perspective, the importance of the role in creating training and education programs to increase the learning of competencies and skills focused on developing and growing these technologies in the Colombian context is also emphasized, addressing the different aspects.

The OREs have great potential in Colombia, but undoubtedly, many challenges must be addressed to develop this industry. However, just as there are many challenges, there are great opportunities and benefits associated with the growth of these technologies, such that they would contribute to the diversity of the energy matrix, independence from other polluting sources, and constant sources of electricity for remote or non-interconnected zones.

IV. SALINITY GRADIENT ENERGY IS AN EXCELLENT OPPORTUNITY FOR COLOMBIA AND THE REGION

In previous research, we have shown the great potential of the Salinity Gradient Energy (SGE) in Colombia [4], especially in the estuary of the Magdalena River [11]. At this location, we have investigated the technical and financial feasibility and the possible environmental and social impact of implementing. Additionally, a lab-scale pilot in Colombia is already generating SGE using Reverse electrodialysis technology (RED) [12].

Given this context, we are working to implement the first pilot unit (150 Watts of installed capacity) of SGE in Latin America. The unit will use RED technology and work with natural waters. It will be constructed in a place of new urban development for the city of Barranquilla, bringing together tourism, sustainability, and the implementation of new technologies. We expect to have it operating by mid-2024.

The pilot unit includes four main components: (i) the water intake pipes and pumps, (i) the pre-treatment units for river and seawater, (ii) the saline gradient power generation device, and (iv) a monitoring and control system to register the water quality, pressures, water flows, and generated energy. This pilot will allow dealing – among others – with the challenges relating to plant construction, upscaling, and working with natural waters – a significant challenge for SGE worldwide.

V. TIDES, LESS EXPLORED BUT WITH POTENTIAL MARKET

Researchers from Universidad del Valle, in the Pacific Colombian coastal zones, identify the potential of tidal turbines for generating electricity, where 3D hydrodynamic models (calibrated and validated) with measured water level and marine currents data revealed that existing potential for implementing tidal turbines in Buenaventura Bay [13]. Preliminary results of the projects suggest the potential for producing energy from tidal turbines integrated with gates and dams, known as tidal barrages. Figure 1. shows the annual energy production of several turbines working in a chamber and regulated with gates, revealing the potential for producing this electricity.

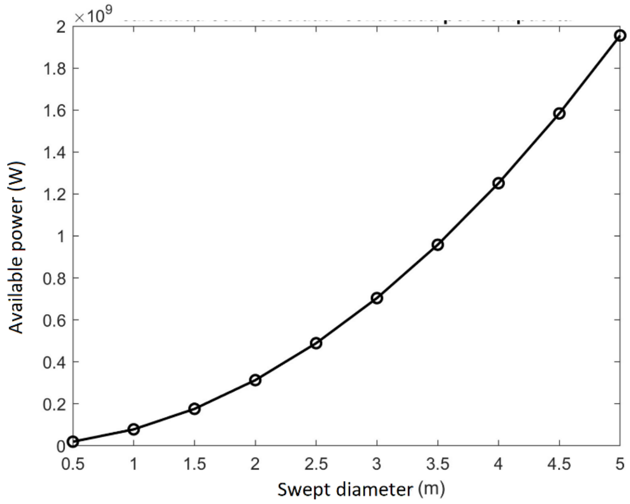

Fig. 2. Annual energy production for turbines with several swept diameters.

VI. WAVE ENERGY IN COLOMBIA AGAINST ALL THE PACIFIC OF SOUTH AMERICA

It is well known that wave conditions along extensive segments of the Pacific shore are generally regular and highly persistent over all seasons, usually have long periods, and arrive from a narrow range of directions. Even though these features lead to the specific dynamic behavior of beaches in the area, they are particularly favorable for wave energy production. They provide one of the world's most significant levels of the wave exploitability index [14]. The eastern coast of the Pacific Ocean is one of the most feasible regions for wave energy harvesting for grid energy production.

Eelsalu et al. [15] show the spatial and temporal variability in the wave power that approaches the western shore of entire Southern America, from the latitude of 7°N to 55°S along the Pacific coast from Panama to Chile (Fig. 3). While typical wave height, period, and approach direction vary considerably along this coast, they also mapped the most frequent energy-carrying wave conditions along the entire shore and attempt to quantify alongshore variations in the directional variability of the annual wave power. The analysis of this sort of spatiotemporal variability in the wave energy resource is based on wave time series over 63 years. This long-time interval also makes it possible to characterize the areas where the wave energy flux has been stable and to identify long-term changes in the wave energy flux.

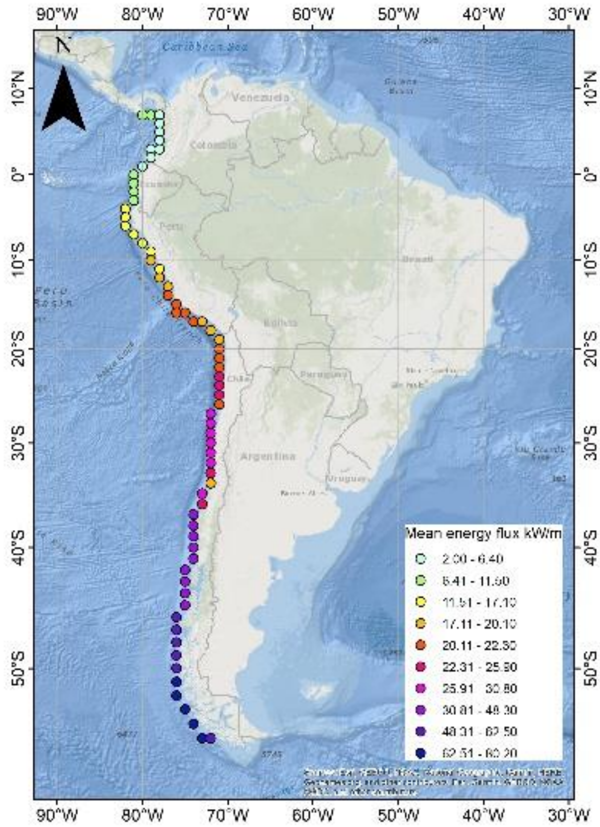

Fig. 3. Long-term mean wave energy flux in 1959–2021 for wind seas and swell. Taken from [15].

VII. WIND OFFSHORE, THE EMERGENT MARKET FOR COLOMBIA AND THE REGION

There is a global surge in offshore wind technology, evident from recent wind power capacity reports, market expansion expectations, and international research endeavors. Rueda-Bayona et al. [8] reported that despite Colombia's abundant resources, a coherent legal framework is absent to oversee the sustainable and safe exploitation of offshore wind energy. The development of offshore wind technology in the country could serve as a solution for meeting energy demands during low hydroelectric power generation periods, particularly in dry hydrological conditions and El Niño-Southern Oscillation events.

Examining Colombia's renewable energy administrative framework has revealed a dearth of information concerning the implementation of offshore wind technology. Furthermore, the scrutiny of various ORE studies underscores the necessity for augmenting the understanding of offshore wind energy. Local initiatives geared towards generating electricity from non-conventional renewable sources (others than hydro) have omitted offshore wind energy projects.

Consequently, the authors of [8] scrutinized wind speeds and computed wind power densities at varying altitude levels, revealing substantial magnitudes and positive trends. These findings justify the need to intensify research in Colombia's offshore wind energy. Notably, recent years have witnessed increased technical, economic, administrative, and legal (RESOLUCIÓN 40284 of 2022) information about renewable offshore wind energy in Colombia. This growing knowledge can inform decision-making by diverse stakeholders and underscore the feasibility of implementing offshore wind farms near the Colombian Caribbean coastline. With its exceptional resources, Colombia is well-positioned to embrace offshore wind energy technologies, thereby decreasing reliance on fossil fuels and serving as an alternative when other energy systems cannot ensure consistent supply.

VIII. Conclusions

Colombia has an enormous potential to generate electricity from offshore wind and marine resources, yet its harnessing is null. Marine resources play a minor role in national policy; the indifference might be related to the low maturity of most marine energy technologies worldwide. So far, public funds finance most of the research projects for basic science, but the outcomes mainly serve academic purposes. The lack of regulation makes it difficult to develop joint projects that are attractive to the interests of the public, private, and academic sectors. We want to encourage decision-makers to recognize the opportunities for marine energy in the country and join efforts towards its harnessing. The resource assessments encourage diving into the long-term run, investing in developing local technology, and strengthening inter-institutional and intersectoral cooperation. We finally want to remark on the country's privileged location and the nascent marine energy industry worldwide; Colombia still can become a successful case in this field.

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