Coca Codo Sinclair Hydropower Plant: A time bomb in the energy sector for Ecuador or a successful project?

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Abstract — **In Ecuador, the electricity sector has undergone significant transformation over the past 15 years, with a marked increase in renewable energy capacity, particularly hydropower, which grew from 1,707 MW in 2000 to 5,100 MW in 2022. This shift, driven by the need to diversify the energy grid and reduce fossil fuel dependence. Despite its importance, the Coca Codo Sinclair project with 1,500 MW has faced several technical, environmental, and social challenges, including erosion and structural issues, raising concerns about its long-term sustainability. This article aims to analyze these challenges, their causes, impacts, and potential solutions, providing insights for future hydropower developments in similar regions. Coca Codo Sinclair is an example of the ambition of a government that did not follow the recommendations of technical studies on the maximum capacity that could be generated by a plant that now has more problems than advantages, analyzing all the associated drawbacks that the largest hydropower plant in Ecuador, it is important to understand that technical criteria must prevail over political decisions. In order to keep the more than 3 billion dollars of investment going, urgent action is required on CCS remediation works, with a combination of investments in repairs and maintenance activities, improvements in management and governance of the project, therefore, currently the largest plant in Ecuador represents a time bomb that can collapse due to any of the various problems.**

Keywords: **Case study, Coca, disadvantages, energy grid, hydropower, Quijos, river.**

Resumen — **En Ecuador, el sector eléctrico ha experimentado una importante transformación en los últimos 15 años, con un marcado de la capacidad de energía renovable, en particular la hidroeléctrica, que pasó de 1.707 MW en 2000 a 5100 MW en 2022. Cambio, impulsado por diversificar la matriz energética y reducir la dependencia fósil. A pesar de su importancia, el proyecto Coca Codo Sinclair con 1500 MW ha enfrentado varios desafíos técnicos, ambientales y sociales, incluidos problemas de erosión y estructurales, lo que genera preocupaciones sobre su sostenibilidad a largo plazo. Este artículo tiene como objetivo analizar estos desafíos, causas, impactos y posibles soluciones, brindando perspectivas para futuros desarrollos hidroeléctricos en regiones similares. Coca Codo Sinclair es un ejemplo de la ambición de un gobierno que no siguió las recomendaciones de los estudios técnicos sobre la capacidad máxima que genera una planta que ahora tiene más problemas que ventajas, analizando todos los inconvenientes asociados que tiene la hidroeléctrica más grande de Ecuador, es importante entender que los criterios técnicos deben prevalecer sobre las decisiones políticas. Y, para mantener en marcha los más de 3 mil millones de dólares de inversión, se requiere actuar urgentemente en obras con una combinación de inversiones en actividades de reparación y mantenimiento, y mejoras en la gestión y gobernanza del proyecto, pues actualmente la planta más grande del Ecuador representa una bomba de tiempo que puede colapsar por cualquiera de los diversos problemas.**

Palabras Clave: **Estudio de caso, Coca, desventajas, red energética, hidroelectricidad, Quijos, río.**

I. INTRODUCTION

IN Ecuador, a South American country, its electricity sector has been changing for almost 15 years, increasing its capacity in areas of renewable generation, and thus its energy grid grew widely, specifically moving into hydropower development in the year 2000 with 1,707 MW, to 5,100 MW in 2022, means, in 22 years, Ecuador's installed hydroelectricity capacity grew by around 300 % [1], [2].

Ecuador has experienced notable growth in the renewable sector, driven by the need to diversify its energy grid, and reduce dependence on fossil fuels. This development has been an integral part of national energy policies, which seek to meet the growing demand for energy and mitigate the environmental impacts associated with traditional electricity generation [3].

Hydropower has been the keystone of the growth of renewable energy in Ecuador. Emblematic projects such as Coca Codo Sinclair, with a capacity of 1,500 megawatts, have been fundamental to increasing the country's installed capacity [4]. Other important hydroelectric projects include the start-up of: Sopladora, Minas San Francisco and Toachi Pilaton, which have contributed significantly to the generation capacity and the stability of the electricity supply with 487 MW, 270 MW, and 254 MW respectively [5], [6].

The Coca Codo Sinclair hydropower plant (CCSHP), located in the Amazon region of Ecuador (Fig. 1), is one of the largest and most ambitious infrastructure projects in the country. Inaugurated in 2016, this hydroelectric central is the largest in

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installed capacity in the country, which makes it a key piece for Ecuador's energy supply [7]. However, since its conception, the project has faced multiple technical, environmental and social challenges that spark widespread debate and concern both nationally and internationally [8], [9].

Fig. 1. Coca Codo Sinclair in Ecuador. Source: [10].

The planning and construction of Coca Codo Sinclair began with the objective of harnessing the hydroelectric potential of the Coca and Quijos rivers to meet the country's growing energy demand and reduce dependence on fossil fuels [11]. Mainly financed by mostly Chinese international loans, and built by the Chinese company Sinohydro, the project promised not only a stable energy supply, but also economic and development benefits for the Amazon region [12], [13].

Despite these promises, the central construction was marked by delays, cost overruns and controversies related to the quality of the materials used and poor project management practices [14]. The need to meet deadlines led to hurried decisions that subsequently resulted in significant structural problems, including cracks in critical infrastructure components [15].

One of the most critical issues facing Coca Codo Sinclair is erosion on the Coca and Quijos rivers, exacerbated by the construction of two dams and natural events such as the San Rafael waterfall slide in 2020 [16]. The alteration of the river channel and the modification of sediment flows have intensified erosive processes, putting both the plant's infrastructure and local communities and ecosystems at risk [17].

Erosion has caused the loss of agricultural land, affected biodiversity and forced the relocation of several communities. Additionally, it has generated significant additional costs for the repair and maintenance of the plant facilities, calling into question the long-term economic and environmental sustainability of the project [18]. The Coca Codo Sinclair hydropower plant has the capacity to supply approximately 30% of the electrical energy consumed in Ecuador, however, since its inauguration, it has faced operational and technical challenges, but remains a crucial component in the country's energy grid [19].

With this background, it observed that there is a technical gap that society is unaware of between the investment made in the Coca Codo Sinclair hydropower plant, and the current problems that must be discussed to generate sustainability for the project, which cost approximately 3.2 billion of american dollars to Ecuador, a figure that includes the cost of construction, equipment, inspection, administration and other aspects until the largest hydropower plant in the country is launched [20].

Thus, this article aims to analyze the problems associated with the Coca Codo Sinclair hydropower plant, exploring the causes, impacts and possible solutions. Through a comprehensive review of literature, and technical data to provide an inclusive understanding of the challenges faced by this project and lessons learned that can be applied to future hydropower developments in similar regions.

II. METHODOLOGY

This study employs a technical-scientific analysis to evaluate the Coca Codo Sinclair Hydropower Plant, focusing on its operational, environmental, and economic implications. Information for this analysis was sourced from official project documentation, including feasibility studies, technical designs, and performance reports published by government agencies, project contractors, and independent auditors. Additionally, data from scientific publications and engineering journals provided a foundation for cross-referencing project outcomes [21], [22].

Key regulations and standards relevant to hydropower and energy infrastructure were reviewed, including Ecuador's legal framework for energy generation, environmental impact assessments, and international hydropower guidelines from organizations such as the International Hydropower Association. These were compared with Coca Codo Sinclair's adherence to ensure compliance and evaluate sustainability.

Technical documents analyzed include structural integrity reports, turbine performance evaluations, and reservoir management strategies. Particular attention was given to assessing compliance with seismic safety codes, given the region's geologic instability. This involved a comparative analysis of global engineering practices in similar projects to identify any deficiencies [23].

Economic data, including construction costs, maintenance expenses, and revenue projections, were analyzed to assess the project's financial viability. Secondary data from government audits and independent financial assessments were incorporated to identify deviations from initial projections and their implications for national energy policy.

Lastly, public records were used to contextualize socio-environmental impacts, focusing on displacement, biodiversity, and downstream water use. This holistic approach ensured a robust understanding of the project's technical, economic, and social dimensions.

III. RESULTS

Through the development of a mega structure like Coca Codo Sinclair, several geomorphological faults, environmental problems, migration of communities, and energy stoppages to Ecuador have been triggered. First there was a 144 meters waterfall called San Rafael, which, due to the manipulation of the direction of the Coca River, now presents pronounced regressive erosion [24].

In Ecuador, in February 2020, a catastrophic reestablishment of the basin upstream and downstream of the hydropower plant began. This sudden failure in river control and regressive erosion continued with processes familiar to geomorphologists that are not previously observed at this scale during the historical era [25].

However, this event is just one more of the problems since 2016 after starting up the plant, problems that have been getting worse, the Coca Codo Sinclair central faced difficulties such as: The location of the plant in a geologically unstable area has caused a phenomenon of regressive erosion in the Coca River. Studies have found that the construction of the plant increased the erosion rate in the area by 42 %, increasing sediments [26], [27].

On the other hand, failures and microcracks have been detected in the plant's infrastructure, which has generated uncertainty about its safety and long-term stability and highlights the importance of a rigorous evaluation of this project. Therefore, the Coca Codo Sinclair hydropower plant has faced several problems since its construction and start-up, following the main problems detected:

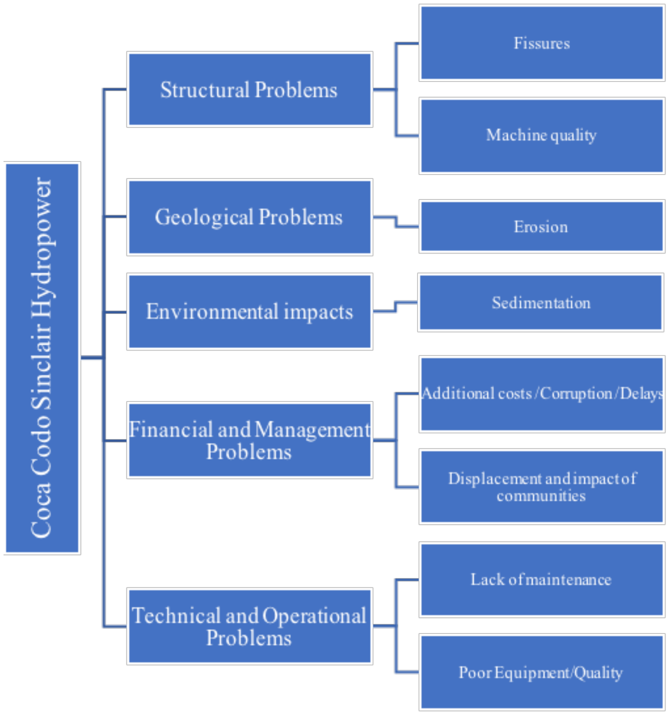

Fig. 2. Problems identified at the Coca Codo Sinclair hydropower plant in Ecuador.

With the references in Fig. 2, the development of each drawback was followed for a better understanding and future discussion in a technical manner:

A. Structural Problems

There are fissures and cracks in the water accumulation and distribution plants, prior to the turbines, as one of the most notable problems. These cracks have raised concerns about the structural integrity and safety of the plant [28].

Likewise, the government entities of Ecuador have still decided not to formally receive the work from the Chinese company Sinohydro due to the quality of construction with criticism about the effectiveness of the materials and labor used in the construction, which contributes to structural problems [29].

These two problems are serious, major and are under discussion in an International Arbitration because these findings are inside the power house, the heart of the hydropower plant, only this part that contains the distributors, water conduits, and turbines required 1.1 billion of dollars, and is the core of the entire plant [30], [31].

In the case of the International Arbitration trial between Ecuador and Sinohydro for the Coca Codo Sinclair hydropower plant, it is carried out under the auspices of the International Chamber of Commerce (ICC). According to the Ecuadorian information, the sponsorship of the lawsuit is in charge of the Attorney General's Office of the State of Ecuador, in coordination with the Electric Corporation of Ecuador. In this specific case, the seat of the arbitration is in Paris, France, it began in 2019, and the main grounds of this arbitration include the following key points:

- Construction Defects,
- Responsibility for Repairs, and
- Additional Costs and Overruns.

B. Geological Problems

The Coca Codo Sinclair plant was built in a geologically unstable area, rather than a more stable zone as is the usual practice for this type of large-scale hydropower projects. It caused a phenomenon of regressive erosion in the Coca River, hence breaking away at the banks of the river and threatens to affect key infrastructure such as the water collection of the plant itself [32].

Additionally, the location of the dam is in an area with seismic activity of the Reventador volcano that poses additional safety challenges. According to an analysis by the United States Army Corps of Engineers from 2023, it was mentioned that pre-construction studies would have used outdated data on water flow and geological risk, without taking into account the effects of climate change, reason for which these physical problems are currently accentuated [33]. The Fig. 3 is a comparative image of the geomorphological displacements in the area.

Fig. 3. Coca River erosion (Before 2020 – Now 2024). Source:[34]

Thus, the landslide near the plant is located in a geologically active area, which resulted in earth movements that affect the infrastructure and access roads. Finally, the induced seismicity due to the construction of the reservoir raises concerns about the possibility of loss of part of the region's infrastructure [35], [36].

C. Environmental impacts

Erosion in the Coca River basin is now evident, the construction of the dam significantly altered the river dynamics, causing erosion problems downstream, which affected, among other things, the San Rafael waterfall, which collapsed in 2020, and it currently no longer exists (Figure 4). It was a 140-meter waterfall and served as a place for tourist visits due to its extensive majesty [37], [38].

Fig. 4. San Rafael Waterfall near CCS (Before 2020 – Now 2024). Source:[34].

In February 2020, the basin upstream and downstream of the hydropower plant presented a sudden failure in river control and regressive erosion that continued with accelerated processes. During the first three years after faulting and rupture (2020-2023), the erosion front migrated almost 13 km upstream, at speeds controlled by the variable resistance of the underlying substrates and the sequence of flows [39].

Erosion of the main valleys and tributaries upstream of the lava dam generated a sediment pulse estimated at 500 MT in three years (one of the largest in modern times), which deposited sediment several meters thick along dozens of kilometers downstream of the dam near the site of the San Rafael waterfall [40], [41].

In contrast, the riverbed at the upstream end of the degraded reach began to open up and form a more channelized flow path, but the Coca River will likely require a decade or more to export most of the sediment. Additional supply from erosion and the presence of sediment storage tracts in the downstream river corridor will slow recovery time [39], [41].

Likewise, another problem is sedimentation, the accumulation of material in the reservoir affects the storage capacity and efficiency of the plant, and has caused several stoppages of Coca Codo Sinclair due to removing these sediments manually in the sand traps. In 2024 there will already be 16 stoppages, as indicated below [42], [43].

TABLE I
STOPPAGES AT COCA CODO SINCLAIR
DUE TO SEDIMENT CLEANING IN THE SAND TRAP

No.	Year	Stoppages	Observation
1	2019	3	-
2	2020	3	-
3	2021	1	-
4	2022	10	-
5	2023	9	-
6	2024	16	Until May 2024*

Source: [44]

Together, these two problems of erosion and sedimentation are serious since the erosion of the surrounding areas, both upstream and downstream of the plant, generates stoppages to release the waste that prevents both the accumulation of water and its discharge.

D. Financial and Social Management Problems

Additional costs in the hydropower plant's development arise from structural and maintenance issues, leading to unforeseen expenses that increase the financial burden on Ecuador, including foreign debt to China's Exim Bank [45].

Likewise, the management of the administration is very questionable, showing variations throughout the contracts, there have been complaints and suspicions of corruption in the awarding of contracts and in the project management, which has affected the transparency and efficiency of the central denoting overprice.

Associating, the Attorney General's Office of the State of Ecuador investigates an alleged network of bribes for approximately 76 million US dollars related to the construction of Coca Codo Sinclair between 2009 and 2018, in which former ex-president of Ecuador, public officials and the company Sinohydro are involved [46].

Finally, there is displacement and impact on communities, the construction of the power plant and its reservoirs (compensation and generation) has affected local communities, both in terms of displacement and in the impact on their traditional livelihoods such as fishing, tourism, hunting and agricultural activities [47].

E. Technical and Operational Problems

One of the main difficulties is the lack of Maintenance, the need for frequent repairs due to structural problems has affected the continuous and efficient operation of the plant, but above all, since there is no structured preventive maintenance plan, it takes its toll throughout of the operation of the hydropower plant.

Likewise, the operating capacity of the plant, although has an installed capacity of 1,500 MW, technical problems have limited its ability to operate at full power, and according to historical data, it appears that it was not adequately sized in capacity, operating at 70 % average energy generation as indicated in Table 2.

F. History of Coca Codo Sinclair

On the other hand, after defining these problems in various schemes, magnitudes, and that in the end determine the efficiency of the plant, it is important to understand where these difficulties came from, wherefore pertinent to mention the history of the Coca Codo Sinclair.

The Ecuadorian Institute of Electrification (INECEL in Spanish), created in 1961, studied the Coca Codo Sinclair Project between 1970 and 1992, with the support of international consulting companies, such as: Hidro Service from Brazil (1976-1980) and Electroconsult from Italy (1986 - 1992), of which concluded that the work would depend on an underground powerhouse built in two phases, 432 MW and 427 MW, totaling 859 MW, with flows of 63.5 m^3/s to generate 6,000 gigawatts/hour each year (GWh/year), with a plant factor of 0.8, in which the total cost of the project was 915 million dollars [48].

After 15 years of Italian, Brazilian and Ecuadorian studies, in 2007 there was talk again of the construction of the Coca Codo Sinclair Project, and in 2008, the company Coca Codo Sinclair EP was created. Where new design parameters were defined for the hydroelectric project, and the power was changed from 859 to 1,500 MW, with a design flow of 222 m^3/s and a plant factor of 0.65 to generate 8,800 GWh/year, with a project cost of 1.6 billion dollars [43].

In general figures from Table 3, it changes and decisions represent a 43 % increase in energy generation compared to the original project, and also an additional 75% investment, without considering all the complementary works, defining this increase as a political proposal, and unrealistic to the current generation data of Coca Codo Sinclair that are later observed with historical generation information [48].

Subsequently, on October 5, 2009, when there was still no firm financing, the Coca Codo Sinclair company and the Chinese company Sinohydro Corporation signed the contract for the construction of the 1,500 MW project, for a value of 1,979,700,000 USD; value that consists of two parts: 85 % Chinese financing, through debt, and 15 % contribution from the Ecuadorian government, that is, 1,682,745,000 USD and 296,955,000 USD, respectively [48].

Next, on May 31, 2011, a Coca Codo Sinclair Management and Supervision contract was signed between Coca Codo Sinclair EP and the company CFE – PYPSA, for a final value of 140,667,692 USD, due to complementary contracts, made for first year of activities, the details of which are not known in detail so far [49].

Also, to transfer the energy from Coca Codo, power lines were needed, for which high voltage transmission lines were installed to carry the electricity generated from the plant to the consumption centers, this included the construction of substations and towers. of transmission. Access Roads and Bridges were also developed to allow access to the construction site and to facilitate the transportation of materials and equipment. And finally, it was spent on Environmental Control measures which included the construction of wastewater management systems, reforestation programs and other actions to mitigate the environmental impact of the project.

Finally, in April 2016 the first four turbines were provisionally received and in November the other four. The new project entered into commercial operation on November 16,2016 and during the last 8 years, it has generated, on average, about 6,551 GWh/year, which means that the hydropower plant provides a value in energy similar to that predicted by INECEL in 1992, but with a smaller plant and cost as indicated in Table 2 in the energy delivered since 2016.

TABLE II
ENERGY DELIVERED FROM
THE COCA CODO SINCLAIR PLANT IN GWH

Years	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**Average**
Energy produced GWh	3,264	6,242	6,488	6,730	7,140	6,969	7,202	8,376	**6,551**
Percentage change %	-	91%	4%	4%	6%	-2%	3%	16%	-

Source: [50]

IV. DISCUSSION

Starting from the fact that to finance Coca Codo Sinclair as the largest work carried out in Ecuador, external credits were required, this project was carried out with Chinese loans and oil agreements were generated that allowed Ecuador to access a large part of the necessary external credit, which became the main source of income to change the electricity sector [45]. However, at the same time it is particular that after generating the credits, the project was built by China.

After understanding that by generating debt, a large-scale work was built, the negotiations became political, and with that, it is assumed that the pressures decided for the construction of China, however, the first finding that since studies, from investigators of China in others cases of energy constructions reveals that quality failures are caused by defaults by workers, inadequate checking procedures, incomplete construction site surveys, wrong design work, and fraud of construction companies that conclude in quality failures [51].

Relating, although rework is a common phenomenon in the Chinese construction industry and significantly affects projects success, an interview with 13 experienced construction professionals in China to prioritize these causes determines that the unclear project process management, poor quality of construction technology, and the poor construction materials are the principal causes [52].

From the compiled history, after generating new calculations from the engineering studies, increasing the capacity of the hydropower plant, the geomorphic adjustment of the Coca & Quijos rivers was not predicted, which now represents an unusual natural disaster that threatens life, property, important infrastructure and energy security, since it compromises nearby oil pipelines and the largest hydroelectric installation in Ecuador. However, this rare event creates valuable opportunities to learn how a major disturbance and recovery of an autogenous basin evolves, with important lessons for understanding the geomorphic transience and sedimentary record of volcanic landscapes [53], [54].

Nevertheless, after verifying the current problems of the hydropower plant, it is important to discuss how to prevent imminent damage to the works to seek to maintain it, which has a high cost and can establish a risk of paralysis at any time. Thus, based on the 2021-2022 analysis of the United States Army Corps of Engineers in coordination with the Corps of Civil Engineers of Ecuador, options have been generated, especially in nearby works to avoid erosion as the biggest problem that generates stoppages at the moment.

In July 2021, the United States Army Corps of Engineers visited the Coca Codo Sinclair area to inspect the progress of regressive erosion of the Coca River that, since February 2020, has threatened the hydroelectric plant. Among the improvement options there are several discussions, however, the three viable alternatives to mitigate the impacts related to the problems identified so far are considered and updated with investigative criteria:

1. Dredge the river upstream and downstream;
2. Develop sediment retention structures in mountains
3. (foundation walls);
4. Automate sediment tramps (sand filters).

Regarding these three options proposed and discussed, it is considered that they are valid for the current situation of the plant, in which the operational development management could be largely improved for proper operation. Additional to the design of the United States Army Corps of Engineers at the request of the Ecuadorian government, these improvements are the minimum necessary to guarantee the safety and efficiency of the plant, as well as to identify and mitigate any potential problems that could affect its operation, and the safety of nearby communities.

However, again the United States Army Corps of Engineers, during a visit in 2023, generated more recommendations, and as options for aggressive and major changes, in the same study, it was also proposed:

1. Raise the number of machines, which would imply rebuilding this part of the plant;
2. Divert the outlet downstream through a longer tunnel;
3. Change the water reception distributors.

Nonetheless, it is important to mention that what these other three proposed options would do is eliminate the guarantee that the Chinese construction company, Sinohydro, must still cover, because the Ecuadorian State has not yet received officially the plant, and it would also require an abysmal expense, therefore, the first recommendations are the necessary ones, until in international instances, the International Arbitration is resolved, which if it is fair should give Ecuador the reason to grant equipment changes in the powerhouse due to the low quality verified [55].

Though, after discussing these improvement options, it must open the discussion, about how it was abruptly decided to change the initial configuration, in which the original proposed design flow was 63.5 m^3/s, and when deciding to build step by step 222 m^3/s, that is, the amount of water needed to generate hydrogeneration increased by more than 220 %, changing the power from 859 MW to 1,500 MW in a bureaucratic manner, without technical criteria or updated data on the possible effects that a work would have. in capacity increased by 75 %, an unreal value to achieve, if one considers that Ecuador has seasonal periods in which the capacity drops even more than the effective designed one. Followed by a comparative table of the dimensioned values before and after construction with the comparison of percentage variation.

TABLE III
COCA CODO SINCLAIR COMPARISONS
(INITIAL AND FINAL PROJECTION)

No.	Parameter	Unit	Initial	Final	Percentage change
1	Design flow	m^3/s	63.5	222	**+250%**
2	Power	MW	859	1,500	**+75%**
3	Investment	Millions -USD	915	1,600	**+75%**
4	Energy	GWh/year	6,000	8,800	**+43%**
5	Plant factor	-	0.8	0.65	**-19%**

Source:[30], [43], [56].

Table 3 discusses the initial and final design criteria and parameters, but the plant factor shows a reduction as a negative percentage variation. However, it is important to understand that the plant factor means that the operating efficiency of the central, and when projecting an increase in power, flow, and investment, it is important to note that the teams were not analytical with the power factor that is ultimately related to the real approved energy that will enter the system [26].

With this background, this research serves as a case study that should be raised to energy policy decision makers, as well as those responsible for the construction of hydropower systems who must act in a committed manner because it is demonstrated that with a good idea that was irresponsibly modified, more problems were generated than solutions, and this shows that the research gap with energy simulations of real efficiency could avoid these current disadvantages, understanding that Coca Codo Sinclair is a plant with a considerable number of failures for a project of only 8 years of operation.

A. Improved Solution Evaluation for Coca Codo Sinclair Hydropower Plant

1. Economic Feasibility: To determine the economic viability of the three proposed solutions—dredging the river, developing sediment retention structures, and automating sediment traps—it's essential to conduct a cost-benefit analysis that assesses funding sources, expected return on investment, and long-term maintenance costs. This analysis should take into account both direct funding opportunities, such as government and international grants, and possible indirect financial im-

pacts, like the protection of surrounding agricultural land and infrastructure from erosion. Given Ecuador's limited budget, prioritizing cost-effective measures that promise a sustainable return of inversion will be crucial to ensure the plant's continued operation without excessive financial burden. However, having already executed the most expensive work in the history of the country, the expenses to maintain its operation are strictly necessary, and indispensable, like this proposal.

2. Technical Feasibility: Evaluating Ecuador's current technical capacity to implement and maintain these solutions is vital. This feasibility check should consider whether local industries and personnel can support complex operations such as automated sediment filtration and construction of large sediment retention walls, or if it will be necessary to introduce external technologies and specialized training programs. Collaborations with international engineering firms, like the U.S. Army Corps of Engineers, may provide insights into necessary adjustments for these solutions to be successful within Ecuador's technological landscape. However, it is believed that for this proposal, there is technical feasibility in Ecuador, therefore, as a recommendation, it could be linked to the academy to form an interdisciplinary group, teachers who know about hydrology, civil engineering, structures, etc. [57].

3. Social Feasibility: Each proposed solution has potential social implications, particularly for communities near Coca Codo Sinclair. Assessing social feasibility means analyzing how these solutions could affect local employment, economic opportunities, and quality of life, as well as identifying any possible social resistance. Local job creation, especially in construction and maintenance, could foster community support; however, it is worth mentioning that most of the impacts have already been deployed, because the work of developing hydropower has already been developed, and what is now proposed are supplementary works.

4. Environmental Feasibility: Long-term environmental impact is a critical factor in the feasibility assessment of the proposed interventions. Dredging, constructing sediment barriers, and adding automated sediment traps all impact the river ecosystem, potentially affecting local flora, fauna, and water quality. A thorough environmental impact assessment would be necessary to predict and mitigate any adverse effects on biodiversity and to ensure that solutions do not unintentionally create new environmental challenges. This evaluation would help Ecuador prevent further degradation of natural habitats while stabilizing the operational environment of the Coca Codo Sinclair plant [58].

5. Community Engagement: Building trust and gaining support from nearby communities are crucial steps in project success. Engaging local stakeholders in the planning process through informational meetings and discussions can help to identify community concerns early on. This engagement would support transparency and ensure that the needs and voices of the local population are integrated into the project's design and implementation, fostering a sense of shared purpose and reducing the likelihood of opposition [59].

6. Monitoring and Evaluation Mechanisms: Once the selected solutions are implemented, establishing a continuous monitoring and evaluation system is essential to assess their effectiveness over time. This system should include performance metrics, regular environmental impact assessments, and a feedback loop to allow for adjustments as needed. The development of a robust monitoring plan would ensure that Coca Codo Sinclair remains a viable and safe power source while protecting the surrounding environment and communities. This proactive approach could serve as a model for future hydropower projects in similar regions [60].

Summarizing, analyzing the long-term impact of the proposed solutions for the Coca Codo Sinclair Hydropower Plant (dredging, constructing sediment retention structures, and automating sediment traps) requires careful consideration of environmental, operational, and community implications. Dredging could reduce sediment buildup and mitigate regressive erosion, yet, if done repeatedly, it risks disrupting aquatic ecosystems and impacting water quality downstream. Building sediment retention structures on mountainous terrain could effectively limit erosion but may alter natural water flow and potentially affect nearby habitats. Automating sediment traps would streamline sediment control with less human intervention, improving efficiency and operational stability, yet this technology requires continuous monitoring and maintenance to ensure long-term functionality [61].

Balancing these interventions with ongoing environmental monitoring would be critical to ensure that the benefits of enhanced plant stability and erosion control are not offset by unintended ecological disturbances.

B. Implementations Costs

Estimating the exact cost of implementing solutions with the nowadays data, would be:

1. Dredging: Costs for dredging depend heavily on the volume and nature of sediment to be removed. For example, dredging a port can range from $15 to $20 million for large projects removing 400,000 to 600,000 cubic meters. Per cubic meter, costs may range from $6 to $8 USD depending on the equipment used. Applying this to Coca Codo Sinclair, 252,286 m^3 of sediment must be removed. This would fill 100 Olympic swimming pools [32], [44].

The volume of sediment to be removed corresponds to an analysis by the Río Coca Executive Commission of the Ecuadorian Electric Corporation in Eq. 1, therefore:

$$\text{Dredging: } 252{,}286 \text{ m}^3 \text{ x } 8 \text{ USD/m}^3 \qquad (1)$$
$$\text{Dredging: } 2{,}018{,}288 \text{ USD}$$

However, since dredging is directly related to other actions such as wall foundations and sand trap automation, an additional 20% of impact that could result from material must be proposed in Eq. 2, therefore, the final cost is considered to be:

$$\text{Total Dredging: } 2{,}018{,}288 \text{ USD x } 1.20 \qquad (2)$$
$$\text{Total Dredging: } 2{,}421{,}956 \text{ USD}$$

2. Sediment Retention Structures: Building sediment retention walls in mountainous regions is costly due to construction challenges and specialized engineering requirements. However, the construction phase involves reinforcing both sides of the

river for 15 km upstream of the intake structure and 10 km downstream after water has passed through the turbines. With an average wall height of 20 meters, the total reinforcement area is estimated at 1,000,000 m^2

The estimated cost per square meter is approximately $55 USD, given the need for specialized equipment for mountain foundation work in Eq. 3. Additionally, 15 % is added to the cost to account for extra civil works, such as soil leveling to prevent future erosion in Eq. 4. Thus, the calculation for the total cost is:

Sediment Retention = 1,000,000 m^2 x 55 USD (3)
Sediment Retention = 55,000,000 USD
Total Sediment Retention = 55,000,000 USD x 1.15 (4)
Total Sediment Retention = 63,250,000 USD

3. Automated Sediment Traps (AST): Automating sediment management requires both initial setup costs and ongoing maintenance. Automated traps are generally less labor-intensive and can reduce operational disruptions, but require technology investments, potentially including sensors and filtration systems, whose costs vary based on technical specifications, which are presented below as approximate costs:

a. Sediment Dredging System (SDS): The cost of a mini dredge for 8 gates of the desander is related to the size and capacity, this desander has 8 water discharge gates, and each part of the mini dredge per gate. Furthermore, it is important to mention that the Coca Codo Sinclair Project consists of a run-of-river development with a capture flow of 222 m^3/s [40].

The Coca Codo Sinclair sand trap is made up of eight chambers with grids to retain solid particles with a diameter greater than or equal to 0.25 millimeters which, at high speed, can cause damage to the turbines. According to inquiries, 17,000 dollars is needed for each grid in Eq. 5:

SDS = 8 gates x 17,000 USD (5)
SDS = 136,000 USD

b. Automatic Sediment Washing System (AWS): Implementing an autonomous sediment washing system requires calculating the amount of sediment removed monthly, and it is necessary to know the time it takes to remove the sediment [56]. Assuming that the removal time is a minimum of 60 minutes each day, the amount of sediment removed monthly is calculated as follows in equations 6 -7-8:

1. Removal time each day: 60 minutes.
2. Water flow: 222 m^3/s.
3. Volume of sediment removed per unit of time each day:
222 m^3/s x 60 minutes/day x 60 s/m = 799,200 m^3/day (6)
4. Amount of sediment removed daily (5%):
799,200 m^3/day x 0.05 = 39,960 m^3/day (7)
5. Amount of sediment removed monthly:
39,960 m^3/day x 30 days/month = 1,198,800 $m^3/month$ (8)

Under this average minimum automatic washing capacity, it is projected that due to the complexity of the system and the evacuation capacity, it would require

Total AWS = 1,500,000 USD

c. Monitoring and Control System, and Information and Analysis (MCS): To install monitoring systems that allow real-time supervision of the sediment level in the sand traps, sensors that detect any problem before a stoppage occurs, alarms and connection to the control system in the powerhouse. The cost of a monitoring system would reach USD 500,000 [18], [62].

In summary, the total cost of automating the Coca Codo Sinclair sediment desander would be as follows in Eq. 9:

Total AST = SDS + AWS + MCS (9)
Total AST = 136,000 + 1,500,000 + 500,000
Total AST = 2,136,000 USD

Each of these solutions would benefit from a tailored feasibility and cost analysis specific to Coca Codo Sinclair's conditions to ensure sustainable and cost-effective implementation, giving the total cost of Eq. 10:

A: Dredging = 2,421,956 USD
B: Sediment Retention Structures = 63,250,000 USD
C: Automation of sediment traps = 2,136,000 USD
Redesign Cost = A + B + C (10)
Redesign Cost = 67,807,956 USD

Finally, due to any inconvenience, such as an additional technical study, supplementary work, external structure to deposit the collected sediments, or other intervention, it is projected that 5% of the total will be projected due to any unforeseen event as show the Eq. 11.

Total Redesign Cost = 67,807,956 USD x 1.05 (11)
Total Redesign Cost = 71,198,354 USD

Once the necessary investment was defined, the estimated loss due to inactivity of the hydropower plant was projected, which contained loss of income, cleaning and maintenance costs, and administrative costs, it represents (Eq. 12):

Installed capacity Coca Codo Sinclair: 1,500 MW (12)

The average rate at the national level with the application of the Tariff Schedule approved at 2024 by the National Electricity Council Board of Directors is 9.20 cUSD/kWh, as shows the Eq. 13.

Average price of electricity: 92 USD/MWh
Maintenance duration average: 1 day (24 hours).
Loss of income = 1,500MW x 24hrs x 92 USD/MWh
Loss of income = 3,312,000 USD/day (13)

In addition, Coca Codo Sinclair sediment cleaning and maintenance costs is 70,000 USD to cover labor, materials and equipment. The administrative costs have an additional cost of 10,000 USD to cover planning, coordination and supervision (Eq. 14):

Total estimated cost = Loss of income + Cleaning and maintenance costs + Administrative costs
Total lost cost = 3,312,000 + 70,000 + 10,000
Total lost cost = 3,392,000 USD (14)

Thus, it is defined for each economic literal in recovery, for which, the following list of payments to the proposed investments of energy optimization is obtained in Eq. 15:

$$\text{Recovery time} = \frac{Total\ proposed\ project}{Total\ losses\ per\ stop} \tag{15}$$

$$\text{Recovery time} = \frac{71{,}198{,}354}{3{,}392{,}000}$$

Recovery time = 21 days

According to Electric Corporation of Ecuador data, the large volume of sediment (composed of silt - soil thicker than clay -, clay and sand) has caused the hydroelectric plant to be shut down 20 times until August 2024. In addition, on some occasions, these shutdowns have been for up to eight hours in a single day, which means that the projected recovery time of the proposal is amply justified due to the need to eliminate said shutdowns [30].

Finally, there is a hidden cost that is much more representative of the stoppages of the largest plant in Ecuador, so, as a second comparison, it has that every time there is a stoppage, Ecuador imports energy from Colombia to supply its demand, however, from journalism data, it is known that the kWh of the neighboring country is much more expensive when requiring this service as show Eq. 16:

Ecuador: Average price of electricity: 92 USD/MWh.
Colombia: Importation 21 cUSD/kWh, it represents 210 USD/MWh.
Import loss = Current average capacity CCS_{2024} x Duration x Import price MWh
Loss of income = 900 MW x 24 hours x 210 USD/MWh
Loss of income = 4,536,000 USD/day (16)

C. International Cooperation for Hydropower Projects

1. Creating an International Quality Supervision Framework: To ensure quality and accountability in large-scale hydropower projects like Coca Codo Sinclair, establishing a collaborative international supervision framework is essential. This framework would define standardized protocols and methodologies for quality checks, involve international experts in periodic project assessments, and incorporate real-time quality monitoring systems. Countries with advanced hydropower experience, such as Norway or Canada, could share best practices in quality control, thereby helping emerging economies like Ecuador implement high standards across construction phases. This cooperative framework would also facilitate timely identification and correction of quality deviations, ensuring the longevity and safety of the project [63], [64].

2. Clarifying Roles and Responsibilities for Quality Control: Effective international cooperation requires that all parties involved—local governments, foreign contractors, and international investors—have clearly defined roles in quality supervision. For Coca Codo Sinclair, this could mean that each stakeholder agrees to a transparent and shared accountability structure, where the quality obligations of engineering firms, environmental consultants, and local authorities are precisely delineated. This structure would facilitate the division of labor, streamline communication channels, and ensure consistent project standards. The experience of other international projects has shown that role clarification fosters accountability, reduces delays, and helps prevent misunderstandings that could compromise project quality and safety.

3. Developing a Sustainable Supervision and Maintenance Mechanism: Beyond construction, establishing international partnerships for the ongoing supervision and maintenance of hydropower projects can be crucial for their long-term success. This might include creating an international committee for regular inspections, utilizing advanced monitoring technology from partner countries, and sharing resources for the training of local engineers. For Coca Codo Sinclair, this ongoing international collaboration could support Ecuador in maintaining operational efficiency, managing environmental impacts, and addressing potential technical challenges proactively [65].

As a comparison, the Three Gorges Dam is a prime example of successful international cooperation in large-scale infrastructure, demonstrating effective strategies for optimizing collaboration across nations. This project benefited from partnerships with international engineering firms, financiers, and environmental experts, each bringing specific expertise to address various challenges. To ensure high construction standards, the project implemented a global supervision framework, involving frequent consultations and assessments by foreign specialists. Additionally, the participation of international environmental organizations encouraged stricter environmental standards, ensuring that project impacts on local ecosystems were minimized and that there was consistent oversight across all stages [66], [67].

The project also emphasized role clarity and transparent communication among all stakeholders, which fostered accountability and efficiency. By creating dedicated committees for quality control, environmental management, and financial supervision, each aspect of the project had specialized international support, reduced delays and increasing operational efficiency [68].

These committees, along with regular audits and transparent reporting, allowed the Three Gorges Dam project to maintain high standards of quality and environmental compliance while optimizing costs through pooled international resources. This approach illustrates the value of structured, specialized international roles and consistent oversight in achieving successful outcomes in complex hydropower projects, best practice that can implement in projects as Coca Codo Sinclair.

V. CONCLUSIONS

- Coca Codo Sinclair is an example of the ambition of a government that did not follow the recommendations of technical studies on the maximum capacity that could be generated by a plant that now has more problems than advantages, hence, when analyzing all the associated drawbacks that the hydropower plant has largest in Ecuador, it is important to understand that technical criteria must prevail over wrong political decisions.
- In order to keep the more than 3 billion dollars of investment going, urgent action is required on CCS remedia-

tion works, with a combination of investments in repairs and maintenance activities, improvements in management and governance of the project, and continued attention to environmental and social impacts.

- The problems of the Coca Codo Sinclair hydropower plant reflect challenges in large-scale infrastructure projects such as migration of populations, surrounding erosion and low quality of equipment that were notably not prevented in Ecuador, and are now risks, especially in this region with high geological activity and complex environmental conditions.
- After verifying the history of Coca Codo Sinclair, exploring the causes, impacts and possible solutions, there must be an exhaustive reflection that the technical data of capacities, infrastructure, reservoir, type of turbines, and other equipment must provide a comprehensive understanding of the challenges that each project will face in the future, therefore, currently the largest plant in Ecuador represents a time bomb that can collapse due to any of the various morphological, environmental, or operational problems.
- Future studies should consider simulation algorithms of the real efficiency of Coca Codo Sinclair, and define the generation capacity to standardize the maximum energy quantity and maintain a homogeneous power that does not require the accumulation of too much water in a place that has too many seismic and geological disadvantages.

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