LUND UNIVERSITY
School of Economics and Management

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Almost Perfect: Challenges and Opportunities for Reaching Net Zero in Electricity Generation in Costa Rica

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Abstract:

Generally regarded as a sustainable country, Costa Rica faces the future challenge of maintaining their renewable energy performance amidst climate change impacts and the need to integrate intermittent renewables. This thesis explores the opportunities and barriers for Costa Rica to achieve 100% renewable electricity while maintaining energy security, despite its developing nation status. Through policy document analysis and key stakeholder interviews, the document characterises the country's energy system within a green windows of opportunity framework, identifying institutional, market, and technological windows, and assessing the current system's ability to react to opportunities and challenges. It was found that although it needs to make improvements to sectoral systems and modernise regulation, Costa Rica still holds significant potential for deploying emerging clean energy technologies. The research provides insights for developing countries navigating sustainable energy transitions under climate change and resource constraints, highlighting the importance of systematic strategies that balance sustainability, affordability, and energy security.

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1 Introduction

As the world approaches the first quarter of the 21st century, climate change has increasingly become one of the major tasks that societies and countries have had to tackle. The reaching of an agreement in the 2015 Conference of the Parties (COP) in Paris set in motion several specific commitments for several nations, in line to achieving a “more sustainable future”, one that protects more species, and overall, compromised less humanity’s ability to survive in earth’s environment. However, years after the objectives were drafted, only 9 countries have made commitments that are more or less in line with what is needed, and none have managed to align completely (Climate Action Tracker, 2024).

Costa Rica is one of the 9 countries whose sustainability commitments have been categorised as “almost sufficient” to reach the agreements of the Paris Conference. The country possesses great natural resources, it is home to about 6% of the world’s biodiversity (Embassy of Costa Rica, 2024), and its energy generation usually ranges from 90% to 99% renewable, mostly coming from water power, making it one of the cleanest electricity systems on the planet. Energy is one of the most important sectors that influence climate change, accounting for about 73% of greenhouse gas emissions (Ritchie, 2020), while also impacting other sectors like transport and industry, and thus, being able to generate electricity with almost all renewable sources is a great advantage for reducing emissions. Another important factor that the country has been highlighted for is the promise to remove the 12% fossil fuel electricity generation capacity it possesses by 2030, achieving a 100% renewable energy system (MINAE, 2019).

However, the Intergovernmental Panel on Climate Change (IPCC), the UN’s body for all climate science that affects the decisions made at COP, has issued warnings in its sixth assessment report about a high chance of erratic water availability in the Central America region (IPCC, 2022), where Costa Rica is located. Combined with the country’s water power accounting for 68% of electricity infrastructure (Jiménez et al., 2023), this future scenario threatens the ability to produce clean electricity. To diversify generation away from water, ICE, the company in charge of electricity, decided to greatly increase investments in solar and wind power, which could severely increase intermittency. Intermittency in energy is the result of energy production being affected by environmental, seasonal and daily cycles, such as lack of sun for solar energy generation (EnergyX, 2024). This changes in energy generation reduce the reliability of the sources, and can threaten energy security, while also raising the dependence on highly available, rapid response energy sources, which currently are thermal facilities operating with diesel and fuel oil.

Depending on paths that the country chooses to follow, the future resilience threat can be seen as either a set of opportunities for developments towards net-zero and clean energy security, or a challenge to keep one of the most highly electricity renewable countries from becoming less sustainable.

1.1 Research Problem

The possibility of Costa Rica not being able to reach net zero electricity generation, or a conceivable decrease in clean energy generation is particularly relevant to be analysed when considering the country's position within the world's global sustainability commitments. Studying the particular challenges and opportunities that the country has to face this possible scenario could give insight to other nations that will confront similar situations, either in the short or medium term.

Additionally, the current energy scenario in Costa Rica presents a unique case of study due to the combination of the very positive electricity performance in the country (over 90% renewable energy generation) with a rising challenge of the impact of climate change in the system, all in the context of an emerging economy that can't afford costly solutions unless absolutely necessary.

1.2 Research Gap

Previous studies have addressed the issue of energy security in intermittent energy systems, and while some of them have highlighted the resilience threat derived from climate change (Heuberger & Mac Dowell, 2018; Vanegas-Cantarero, 2020), most research has been of a theoretical nature, with technology testing at a smaller scale as possible alternatives to the reliability that fossil fuels give to electricity generation (Akinyele & Rayudu, 2014; Beaudin et al., 2010). However, most of the studies that focus on the paths to net zero, and do not rely in fossil fuel usage for achieving or maintaining energy security, have focused in developed economies, marginalising developing countries to a *catch-up* approach, in which these nations are expected to pick up technology improvements from countries that have the resources to research and test new technologies (Lema et al., 2021)

Costa Rica is a country that, in contrast to most countries commonly mentioned in research, already generates most of its electricity from renewable sources, while also depending on fossil fuels for energy security, and, with the imminent introduction of high-scale solar and wind, the stability of the system might face new challenges. The country also possesses a mostly government owned market, with the state controlling most of generation and planning, which could be impacting the level of competitiveness, public-private partnerships and incorporation of incentives that are highlighted as positive for sustainable futures by recent research (Varawala et al., 2021; Tzankova, 2020).

1.3 Aim and Scope

The scenario presented by the IPCC (2022) of climate threat to water availability, leading to increased risks to energy generation in Costa Rica, combined with the country's introduction of intermittency that could lead to higher dependency on fossil fuels, presents a compelling case for studying the potential effect of sudden rise of variable renewables. This added to the fact that the country in question is commonly regarded as sustainable, while also having the known budget constraints of a developing economy, outlines an interesting study case of possible paths that the country could decide to follow in the near future. An assessment of the ability of the country to recognise opportunities, react to potential challenges, and adapt emerging technologies given its advancements in clean energy generation can provide learnings not only to the local context, but to other countries that might face similar issues in the future. Therefore, the current research tries to answer the following research questions:

> *How can Costa Rica, as a developing nation, navigate intermittency and availability in electricity generation without fossil fuels?*
>
> *What is the potential for emerging technologies to be applied in the Costa Rican context?*

The answering of the research questions provides insight into the key characteristics to accurately maintain energy security without fossil fuels in a developing economy, while also answering which potential role Costa Rica can have in the forefront of technological research that aims to address this challenge.

The study of this case should complement existing research about the final decarbonisation step within energy transformation with a specific focus on budget-constrained economies, while also providing learnings of a possible path to maintain clean electricity generation in a climate threatened environment. Therefore, the results of this research could be of use for other developing nations struggling to implement clean energy generation technology, as well as highly renewable countries that need to diversify their energy matrix without compromising energy security to maintain their environmental performance.

1.4 Outline of the Thesis

After the introduction of the research topic and its relevance to the current debate, context about Costa Rica, their energy market, and sustainability performance is given, to enhance the understanding of the situation it is in. The theoretical approach and previous publications are then detailed, followed by the available data sources, data gathering methods and analysis.

Consequentially to the introduction of both theoretical frameworks and methods, the empirical results are presented, in accordance with the previously mentioned process. To the presentation of results follows a discussion that aims to connect the obtained data with the previous theories and publications, to finalise with conclusions about the research.

During the sections of this thesis, the position of Costa Rica as a sustainable nation, their policy decisions identifying and facing the future threats, and overall ability to seize windows of opportunity will be argued. The document presents recommendations for addressing an improved path to navigate intermittency and energy security in the local context, with potential extrapolation to other case studies.

2 Context

To fully understand the dimensions of the current electricity challenge that Costa Rica is facing, it is relevant to mention a few key aspects of the country's context, particularly related to how the energy market is regulated, the current distribution of electricity generation, and the global sustainable positioning of the nation.

Figure 1: Map of Costa Rica and its provinces (Geology.com, 2019)

Costa Rica is a country located in Central America, between Panama and Nicaragua. The country is divided into 7 administrative provinces (Alajuela, Cartago, Guanacaste, Heredia, Limon, Puntarenas, and San José) and has access to both the Pacific and Atlantic Oceans, which has led to the establishment of several free trade zones with manufacturing facilities from international companies (CINDE, 2017). With a population of about 5,2 million (Worldometer, 2024), and a GDP of 69,24 million USD as of 2022 (World Bank, 2023), the country has the 11th highest GDP per capita of the Latin America and Caribbean region, at around 16.000 USD/person (International Monetary Fund, 2024).

The combination of political stability, social contract and stable growth that the country has experienced has resulted in one of the lowest poverty rates in Latin America and the Caribbean, where the proportion of the population living below the World Bank's upper middle-income line decreased from 15,6% to 13,7% between 2010 and 2019 (World Bank, 2024), ranking better than the 26% average of the region (Hasell et al., 2024).

The country is known for the natural resources and species it possesses, containing about 6% of all world's biodiversity, in an area of only 51.100 km2. This characteristic has been enhanced by the fact that around 25% of the country is protected land areas for nature conservation, making Costa Rica an example of environmental protection (Embassy of Costa Rica, 2024).

2.1 Costa Rica's Energy Market

To understand how the Costa Rican energy market is assembled, it is important to briefly explain some key aspects of every electricity generation market. Electricity markets are usually divided into three main tasks as explained by Penn State University (2010):

- **Electricity generation**, which consists of using a resource such as water, solar radiation, wind, oil, or coal to power a generator that produces electric current.
- **Electricity Transmission**, which is the responsibility of taking electricity from the generation facilities, and using high voltage power lines, bring the generated power to substations that are closer to the areas of consumption, like cities or industrial sites.
- **Electricity Distribution**, that takes the electricity from the substations, and carries it to every customer, either residential or industrial. The company that manages this is usually also in charge of measuring the amount of electricity consumed, and collection of the consequential payment.

The three areas of an electricity system function cooperatively, however, since the administration and boundaries of each area are usually well defined, this allows for different companies to participate in different parts of the system, thus creating what it is called an energy market.

Energy Markets usually require a coordinator agency, which oversees matching the demand for energy from the customers side, with the supply of energy from the producer's side. This coordinator has the capabilities to mandate which generation facilities need to connect to the grid, and which need to disconnect, to always match the consumption.

Regulated vs Deregulated Energy Markets

Prior to the 1990s, most investor-owned electric utilities were regulated and vertically integrated, which means the utilities owned electricity generators and power lines, and operated as vertically integrated monopolies with oversight from public utility commissions (Cleary & Palmer, 2020).

As systems started to modernise, the method of a deregulated market started to become more popular among different countries and states, because it allowed for more competition and lower costs of electricity (Cleary & Palmer, 2020). In a deregulated market, or open market, there are several companies that decide to generate, transmit and/or distribute electricity, with different degrees of participation. Companies use bidding prices per unit of electricity (KWh) to trade energy between themselves (i.e. a generation company selling energy to a transmission company) or to the end user, and the system ensures that the lowest prices are picked to match energy demand, ensuring efficient costs, and promoting cheaper generation methods (Cleary & Palmer, 2020). There are several versions of deregulated markets, such as pure energy markets (i.e. bidding without regulation), capacity markets (i.e. bidding tied to generation costs), or mixed (i.e. regulation of some of the elements), depending on the area's capabilities, interests, and policies.

The Costa Rican Configuration

The Costa Rican energy generation market is configured as a completely regulated market, meaning that there is one sole buyer and distributor of electricity, the "Instituto Costarricense de Electricidad" or ICE.

Created in 1949, ICE is a government-owned entity entrusted with the mission of taking advantage of the country's energy resources with the objective of strengthening the economy and promoting the welfare of the Costa Rican people (Poder Legislativo de Costa Rica, 1949). ICE is currently under the direct supervision of the Ministry of Environment and Energy (MINAE).

Up until 1990, ICE was the only electricity generator, transmitter and distributor in the country, which changed with the introduction of Law N°7.200, that allowed for cooperatives and private companies to also participate in the generation of energy, and cooperatives to additionally participate in the distribution, maintaining transmission in the hands of ICE. Law N°7.200 also limited the sale of electricity from other actors only to ICE, and the amount of electricity that could be produced by non-public companies to 30% of the total available energy, and in projects no bigger than 20 MW, for a concession period of 20 years (Presidency of Costa Rica, 1990). Currently the interaction between these actors is regulated by the Public Services Regulatory Authority (ARESEP), which decides all the fees that the companies have to charge each other when purchasing energy.

The projects that other companies built were approved under two regimes: the most popular is the "Build Operate and Transfer" (BOT), which states that after the concession ends, the facilities need to be transferred to ICE, and the second one was the "Build Operate and Own" (BOO), which allowed private companies to keep their investment after the concession was over.

Another important characteristic of the Costa Rican energy market is that the coordinator agency, called DOCSE in the country, is managed within ICE group, possibly introducing a bias when assigning generation resources to satisfy demand. This has been seen when in 2021 DOCSE decided to not renew the generation contract for some private companies in favour of ICE's own generation, forcing them to shut down their operations, since they are only allowed to sell energy to ICE (Sánchez, 2021).

The predominant figure of ICE as the sole player in the Costa Rican energy market has allowed the country a great planning ability, since all coordination of stakeholders is internal, while managing to easily maintain the country's priorities for sustainable development, economic growth, and preservation of nature. ICE also has strong influence in the setting of fees, electricity rates and generation costs.

Due to this configuration, the responsibility of introducing new technologies in energy generation also falls within ICE, and therefore the company has an obligation of issuing a technical document every two years explaining all their electricity expansion plans, which includes a forecast of the demand, possible projects, cost calculation, and a chosen path. This document is one of the main inputs for the current thesis work.

2.2 Current Electricity Capacity and Consumption

Energy Capacity

The current scenario for electricity generation in Costa Rica has a capacity of 3,4 GW, which is higher compared to Nicaragua at 1,6 GW (GEM, 2022), slightly lower than their southern neighbour of Panama at 4,1 GW (GEM, 2022), but considerably lower than the average of EU countries, at 38 GW (Statista, 2023). The country's network is divided into six types of technologies, the biggest one being Hydropower, which comprises 68% of the current built capacity. Originally the country depended solely on water for their electricity generation, which started to change with the introduction of thermal, wind power and geothermal. Solar power has not considerably penetrated the market yet, making 0,2% of available capacity (DOCSE, 2023).

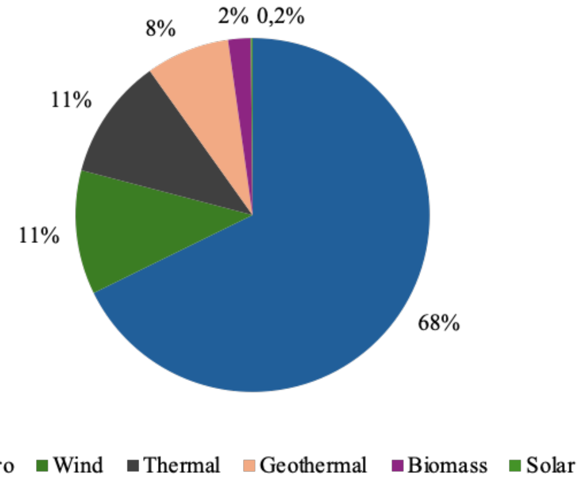

Figure 2: Energy Generation Method Build Capacity (DOCSE, 2023)

Hydropower in the country is also divided into run-of-river power, which uses already existing rivers and strong currents to generate electricity, and dams, which are reservoirs of water that allow the system to control when to produce energy by opening gates and letting water through turbines. The most important facility of the country is the Arenal reservoir, an 85 km^2 lake which holds most of Costa Rica's water reserves, and it is consumed during the period of no rain, or dry season, and refilled during the rainy season, each comprising about half of the year.

Costa Rica also has the capability to purchase and sell energy to an integrated Central American system (MER), or regional market, which consists of the connected energy network of Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama (Comisión Regional de Interconexión Eléctrica, 2023).

Although other companies are allowed to generate electricity within the Costa Rican energy system, due to the aforementioned restrictions, most of the capacity belongs directly to ICE, which controls 67% of the total 3,4 GW of available power, followed by 14% that belongs to community organised entities and other companies that are publicly owned. 10% of the energy capacity is attributed to other projects, which were built using the BOT method, and therefore will be transferred to ICE after they finish the leasing period, leaving 8% of energy generation capacity to private companies (DOCSE, 2023).

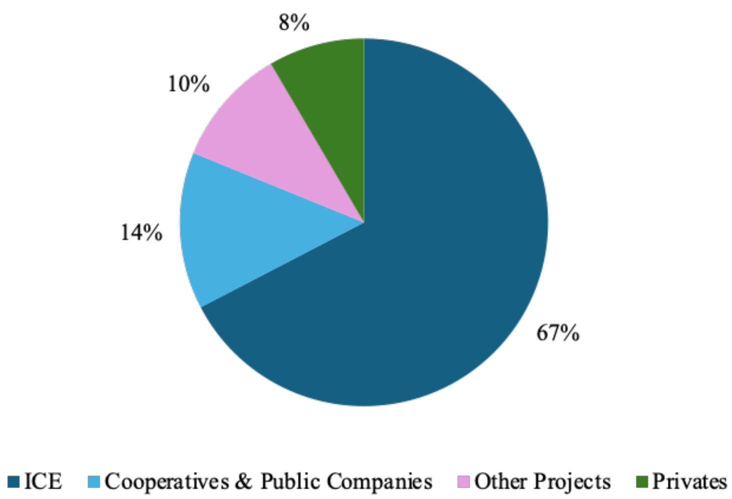

Figure 3: Participation of Companies in Energy Generation (DOCSE, 2023)

It is important to note that although Law 7.200 allowed for other companies to produce energy, it limited the building and operation of fossil fuels to ICE only, forbidding other actors to expand thermal capacity. ICE therefore holds all the country's "unclean" energy, and since DOCSE is a part of the company, they also make the decision of when to turn on or off said capacity. These attributions to the public company seem to be a unique case in the region, which has mostly transitioned to open privatised markets.

Energy Generation

When it comes to the use of the generation capacity, Costa Rica has historically prioritised the use of renewable energies over fossil fuels. The prioritisation of which energy to produce and consume falls to DOCSE, which makes the decision based on the price of every technology and company that is producing the energy. Usually, the price structure is as follows (DOCSE, 2024):

1. **Geothermal** and **Biomass** are usually the cheapest to produce, and therefore the firsts to be connected when available.
2. **Wind** and **Solar** when available have a zero cost of production, however due to the intermittency is not prioritised more.
3. **Hydropower**, which is the main source of energy and the most constant, due to the combination of the country's stored hydropower and the run-of-river (no reservoir).
4. **Regional market (MER)**, which varies depending on the informed prices from other countries.
5. **Thermal capacity**, due to the prices of crude oil is usually the most expensive method of power generation in the country, sometimes surpassed by the regional market.

This order changes sometimes due to variations in the prices of supplies (i.e. oil), but also depending on the company's efficiency when producing said power. According to ARESEP (Jiménez, 2021), the companies with the lowest prices are the private ones ($0,1 USD/kWh), followed by other public companies and cooperatives ($0,16 USD/kWh), and finally ICE ($0,25 USD/kWh). The combination of technologies and prices ultimately sets the priorities for entering the Costa Rican energy market.

However, since the availability of energy is sometimes dependable on weather conditions, such as rain for hydropower, and wind and sun for wind and solar power respectively, DOCSE also has to consider the sources of energy that can actually connect when needed, sometimes needing to connect to more expensive facilities to meet energy demand.

Considering all factors, the energy generation in Costa Rica has been on average 72% hydro, 13% geothermal, 11% wind, 3% thermal, and 1% biomass. From these technologies, only the thermal capacity depends on fossil fuels, meaning an average energy generation 97% sustainable, with some years relying more than others on the thermal generation, which is used mostly as backup.

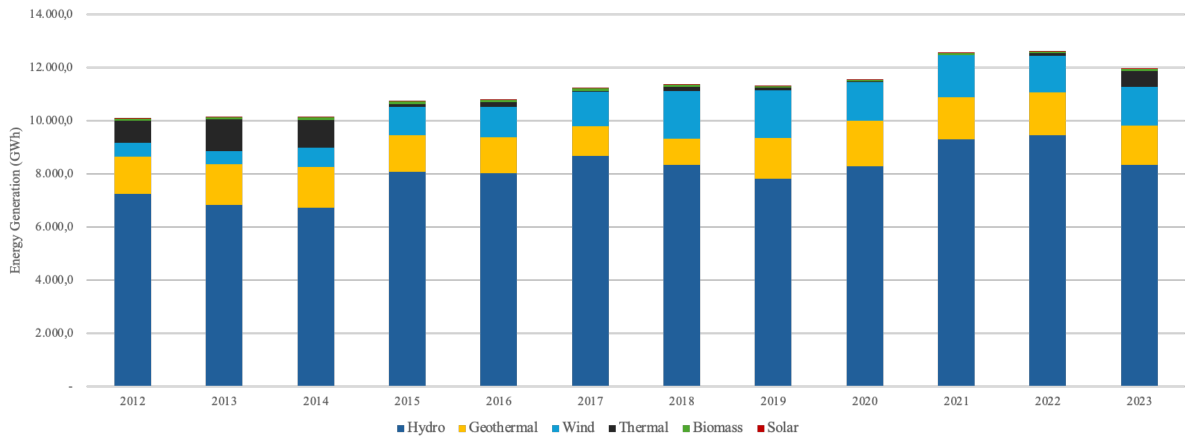

Figure 4: Energy Generation by type of technology (DOCSE 2023; DOCSE 2024)

It is possible to see that in some years the country has relied severely on fossil fuels, given the built capacity. This occurs due to the weather conditions produced by the climate phenomenon known as "El Niño", which reduces the amount of rains that the country gets, therefore greatly hindering the capacity for hydropower (Blanco, 2023).

Prices of Energy

Given the Costa Rican regulated market and high renewability of energy generation, it becomes relevant to analyse the average prices of energy, especially when compared to neighbouring countries and other countries with sustainable energy networks.

Country	**Average Price (USD/kWh)**	**Last Year Update**
Norway	$ 0,100	2023
Mexico	$ 0,110	2023
Sweden	$ 0,111	2024
Costa Rica	**$ 0,142**	**2019**
Panama	$ 0,143	2019
Brazil	$ 0,160	2023
United States	$ 0,170	2023
Guatemala	$ 0,179	2019
Honduras	$ 0,206	2019
El Salvador	$ 0,207	2019
France	$ 0,260	2023
Nicaragua	$ 0,330	2019
Germany	$ 0,400	2023

Table 1: Average Household Energy Prices (Pulso, 2022; Statista, 2024; Jämtkraft, 2024)

Compared to its neighbours, and members of the MER systems, Costa Rica possesses the cheapest price of electricity, and it's even cheaper than most of EU countries, with the exception of Norway and Sweden. The country is also cheaper than most of the identified Latin American countries, backing the assumption that higher renewables translate to lower electricity prices (Pulso, 2022). However, lower prices are also affected by other factors like operation efficiency, regulation, and the shape of demand curves, and therefore it is not possible to completely attribute the low price of Costa Rican energy to the renewability of the system.

The impact of a regulated market system also does not seem to affect the country's electricity prices, which according to theory should be higher (Cleary & Palmer, 2020), however this could be due to many other reasons that will not be assessed in this document.

2.3 Current Sustainability of Electricity Generation

After assessing the scenario for energy of Costa Rica, and presenting information about how the market is regulated, the electricity capacity, generation, and costs, it becomes relevant to shift the focus into the sustainability context of energy generation.

CO2 Emissions from Energy Generation

Most of the rise in CO2 emissions from energy generation in the Costa Rican system comes from the days when the thermal capacity is being used as backup, because of the fossil fuel's heavy CO2 intensity. For 2022, ICE estimates an overall emissions factor of 664 tCO2e/GWh for their use of fossil fuels, compared to 108 tCO2e/GWh for geothermal, and only 37,9 tCO2e/GWh for hydropower, the main source of electricity (ICE, 2023). These emissions factors consider all activities related to the production of energy in the facilities, following the method proposed by IPCC in 2003, and therefore energy sources such as water and geothermal also present some level of emissions.

Due to the country's almost successful avoidance of the use of fossil fuels (99,27% renewable in 2022), the high emission factor of the energy generation method is outweighed by the much higher generated electricity coming from hydropower, wind and geothermal, lowering the average emissions factor to 47,2 tCO2e/GWh in 2022. However, this factor greatly increases in the years where *El Niño* lowers the amount of rains, signalling a heavy dependency of the energy grid's emissions to rain forecasting.

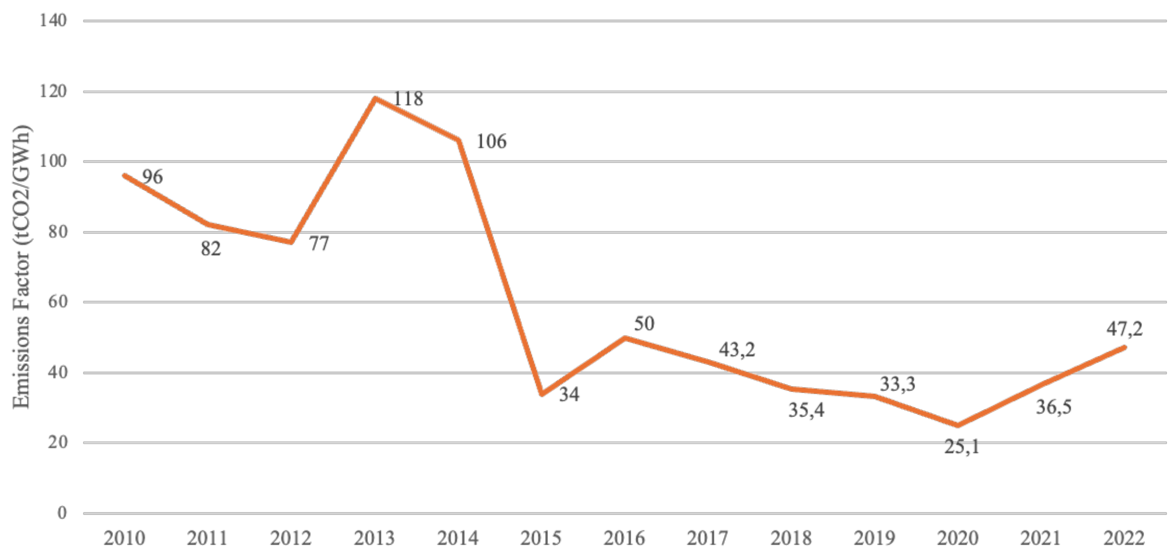

Figure 5: Electricity Generation Emissions Factor by Year (ICE, 2023)

To add perspective regarding Costa Rica's emissions factor, it is compared to neighbouring countries and referential economies, where it performs better than most of the nations, with the exception of Norway, who has a very similar composition of energy generation, France, who relies severely on Nuclear Power, and Sweden, who managed to have a lower emissions factor with only a 70% renewable system (Nowtricity, 2024).

Compared to the other countries in the MER, Costa Rica greatly outperforms all the other nations, followed only by Panama, with an emissions factor of 153 tCO_2/GWh, and since Costa Rica's purchases of energy in the MER system contain energy generated from all the countries that conform it, it is safe to assume that the country's indirect emissions are higher than the direct ones. See table 2 for more information.

Country	**Emissions Factor (tCO_2/GWh)**	**Last Year Update**
Sweden	19	2023
Norway	26	2022
France	85	2023
Costa Rica	**47**	**2022**
Brazil	102	2022
Panama	153	2021
El Salvador	194	2022
Guatemala	305	2021
Nicaragua	354	2021
United States	368	2022
Honduras	374	2021
Germany	385	2022
Mexico	424	2022

Table 2: Average CO_2 Intensity for Electricity Generation (Our World in Data, 2023)

Fossil Fuel Usage

Another important indicator of the sustainability performance of the Costa Rican electricity market is the amount of fuel that is being used to power the thermal capacity of the grid, which encompasses most of the CO_2 intensity.

Currently the use of fossil fuels in electricity generation is limited to five facilities owned by ICE: Garabito (194,7 MW), Guápiles (13,6 MW), Moín II (65,3 MW), Moín III (70 MW) and Orotina (9,5 MW). Of these, Moín II and III use diesel fuel for their operation, and the others use a heavier derivative of oil called bunker fuel, which is also used in maritime vessels and other heavy equipment (Jiménez et al., 2023).

Each facility operates at different efficiency, depending on several factors such as the type of generators, age of the technology, usage capacity, operation, maintenance, among other, generating an output of energy based on the amount of litres that are fed into the facility. Currently, Garabito is the main source of thermal generation, due to it being the biggest and newest, having started operation in 2011 (Jiménez et al., 2023). As of 2022, Garabito produced 85,8 GWh of energy, 93% of all thermal energy production during that year.

Considering that the country keeps their thermal capacity only as a safety measure (Jiménez et al., 2023), and that most of the energy generation is fossil fuel free, it is to be expected that the amount of litres that are used every year would remain constant or decline, with the exception of the years affected by *El Niño* (2012, 2013, 2014, 2023). This is mostly confirmed by the reported data from the sustainability department within ICE, which has shown a severe increase of the amount of litres used for the purpose of electricity generation, with growth of up to 1000% in years which did present either severe lack of rain or strong growth in the total energy generation, raising concerns about the sensitivity of fuel consumption to changing weather conditions. It is important to note that the information reported in the sustainability report does not show the same numbers, which was admitted to be a calculation mistake by ICE upon consultation.

Year	Diesel Consumption (Litres)	Bunker Consumption (Litres)	Total Fuel Consumption (Litres)	Yearly Growth (%)
2019	22.995.064	1.913.707	24.908.771	
2020	572.603	6.625.463	7.198.066	-73%
2021	447.290	1.270.562	1.717.852	-74%
2022	4.451.052	15.900.951	20.352.003	1085%
2023	64.238.841	89.173.389	153.412.230	654%

Table 3: Fossil Fuel Consumption for Electricity Generation in Costa Rica (ICE, 2023)

3 Theory

The following chapter describes the theoretical framework used to structure the data gathering, analysis and discussion, followed by a focused review of the previous publications and discussion regarding the main subjects that affect the research.

3.1 Theoretical Framework

In order to rightly answer the research questions in an organised and clear manner, a theoretical framework is needed. Theoretical frameworks provide the "lens" from which the research is viewed through, and therefore help define which method to use, dimensions to consider, and the way of analysing and presenting the results.

For the current study, the chosen theoretical framework is called the "Green window of opportunity framework", which was developed in 2021 by Lema et al., with the purpose of assessing latecomer catch up in green industries. The framework is based on how China managed to go from a latecomer to becoming leader in some green technologies, and the lessons learned from that case.

The Green window of opportunity framework provides an updated structure that has been proven useful when analysing system changes that are heavily influenced by technology, specifically the energy system, and it focuses on the understanding of developing economies. It is therefore considered a fitting approach to the previously described scenario, and although Costa Rica can't be considered a latecomer when it comes to renewable energy generation, it is important to distinguish advancements in electricity sustainability, where Costa Rica is at the forefront, with the introduction of sustainable technologies, public policies, sectoral processes, and economic growth, where the country might be considered a latecomer.

The Green window of opportunity framework was successfully applied by Lema & Rabellotti in 2023 as a background study for UN's UNCTAD Technology and Innovation Report, where the academics used the particular framework to find green opportunities in the global south, expanding more on the subject. The framework was applied again by one of its authors to assess green windows of opportunity in the electric vehicle sector in Brazil, India, and South Africa (Lema et al., 2024), however, given the recent publication date of the methodology, it has not yet been applied extensively, and therefore this research aims to attain a certain degree of novelty by using a proven, but not widely spread theoretical framework.

The framework consists of four connected sections, which are:

a) Green Transformations

Defined as a transformation that involves profound shifts in technology and investment decisions, towards greener technologies and modes of production and guidance (Lema & Rabellotti, 2023), green transformations are an international megatrend that involves a green economy greatly driven by technologies that directly address social value and climate-related goods, constantly creating new markets.

Green transformations are characterised by being greatly influenced by policy interventions, but also by global agendas, rules, mechanisms and, especially, those related to climate change (Lema & Rabellotti, 2023).

In this section of the framework the research will distinguish which global trends are affecting the country, either directly, or by becoming relevant to consider given the upcoming changes in climate and energy. Green transformations are divided in this research into New policy priorities, Technological changes and New markets.

b) Green Windows of Opportunity

These windows are defined as favourable, time-bound conditions for development, arising from changes in public institutions and policy interventions, markets and technologies associated with the green transformation (Lema & Rabellotti, 2023, p. 9), and are usually institutional, meaning that they have been brought due to government actions, but can also come from external causes such as changes in market requirements or new technology improvements.

Green windows of opportunity are influenced by demand conditions, such as acceptable price ranges, and technological changes, like a more efficient resource use that can create the conditions for the adoption of a particular technology. However, it is more often the case that the windows rely on direct government demand creation, which ensures the creation of a competitive market between non-green and green solutions.

This item within the framework is one of the most important for the particular scenario, given that most of the system is state-owned, and private participation is limited by the state. Some policies that might create green windows of opportunity are the fact that only ICE can hold and operate fossil fuels, which is ensuring that no private competitors can introduce non-green technologies at a more competitive price. Additional policies will be analysed as part of the research.

For the purpose of this research, green windows of opportunity have been divided into institutional, technological and market windows.

c) Sectoral Systems

Sectoral systems refer to the institutions within a certain region that are expected to react to a certain green window, such as public institutions that would recognise the opportunity, firms that have the capabilities to implement it, universities that will develop the knowledge required to adapt the opportunity further in a local market, with potential to contribute to the international advancement (Lema & Rabellotti, 2023).

Sectoral systems are divided into preconditions, meaning the existing capabilities within the system, and responses, which is the result of the meeting between the system and the green window of opportunity. A system that doesn't possess the preconditions to receive a green window could potentially fail to identify it (Lema & Rabellotti, 2023).

The type of response to an opportunity can differ depending on how the sector is structured, but it is mentioned in the framework that most of the times firms that have bigger investment and organisational capabilities emerge as national champions of certain technologies (Lema & Rabellotti, 2023), and that the development of strong collaboration within sectoral innovation systems (i.e. construction, or energy generation) contribute to an overall better response during the more demanding stages of implementation (Lema & Rabellotti, 2023).

Sectoral systems can also be influenced and/or motivated by public policy that can ensure collaboration, or directly participate in the creation of publicly available knowledge, preventing gatekeepers that would narrow the implementation scale of a certain technology.

The analysis of the sectoral systems is one of the main subjects of interest of the current research, given the objective of assessing how the country is reacting, or planning to react, to the challenges that are emerging in energy generation.

d) Catch Up Trajectories

The catch-up trajectories can be understood as the paths which a country follows to reach some level of leadership within the identified green window of opportunity. It was initially proposed as a measure of leadership in the global market, however Lema et al. (2021) distinguished between a market catch-up and a technological one, limiting the first one to the attaining of local and global market shares, and the second one to the strengthening of technological capabilities relative to the competitors, by either achieving new-to-the-world or new-to-the-country technology.

Although the division of trajectories allows for a deeper understanding of the effects of a reaction to a green window of opportunities, developing technological capabilities and attaining market shares can also be mutually supporting (Lema & Rabellotti, 2023, p. 14), since, for example, their interaction may allow access to larger and more sophisticated markets that provide critical knowledge enabling technology improvements (Schmitz, 2007).

This element within the theoretical framework will be applied to the current research by forecasting the potential impact of the country's current path of response to the challenges presented by the complete decarbonisation of the electricity grid, however most of the focus of the research will be on identifying the current conditions, capabilities, and position of the country.

Figure 6 aims to illustrate how the framework is structured. The figure is based on (Lema et al., 2021), but includes the addition of a stage category (Macro trend, Country scenario and Outcome Scenario) to specify the country's involvement with each of the sections of the framework.

As mentioned before, the current research focuses more on the "Country Scenario" part of the green window of opportunity framework, which will allow a deep understanding of the Costa Rican conditions, plans and potential, however potential future research might shift the focus into other sections.

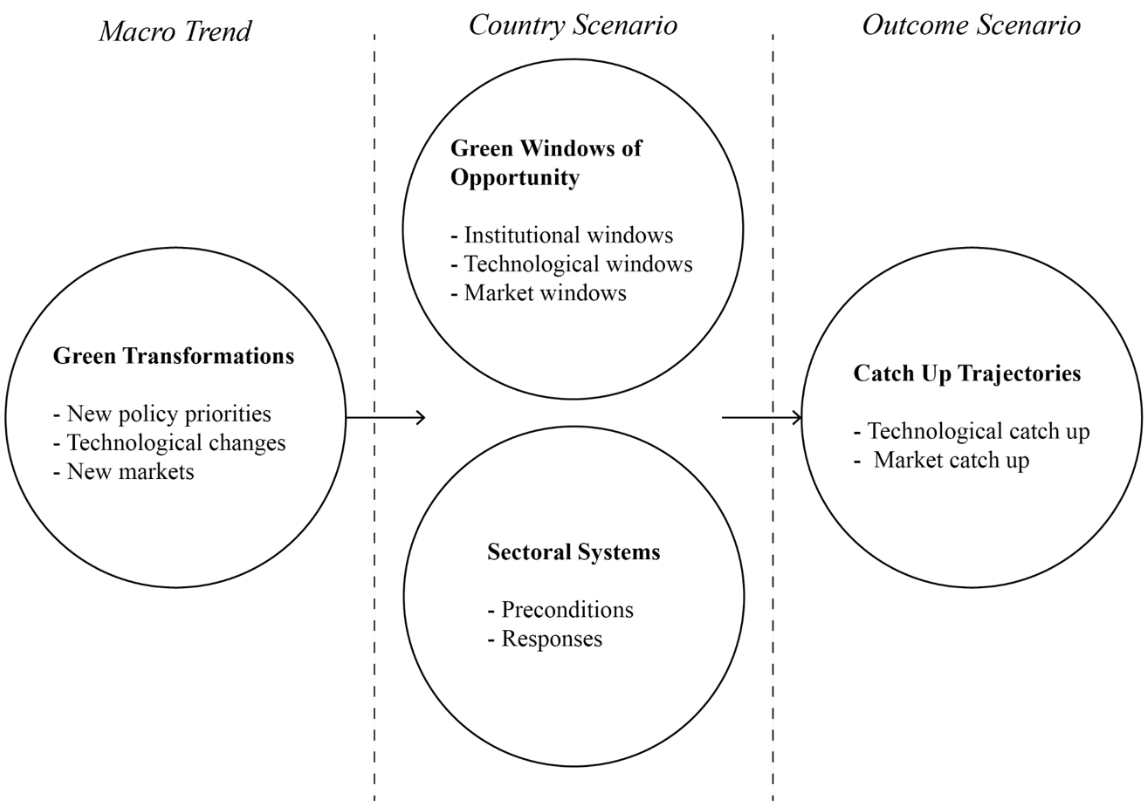

Figure 6: Green Window of Opportunity Framework (Lema et al., 2021)

3.2 Previous Research

The challenge of increased intermittency that the country is facing, combined with the emergence of new clean technologies, is a subject that has been studied before, although in other contexts. The chosen theoretical framework already outlines important discussions in the sections it covers, particularly energy transitions as one of the important green transformations affecting the case study, intermittency challenges, which are hypothesised to be creating green windows of opportunity for the country, new clean technological paths, that represent technological windows, and sustainable energy market structures, which encompass the study of sectoral systems aiming to interpret and react to windows of opportunity. Previous research helps inform about the state of knowledge in the subject, while providing crucial information for the identification of challenges and opportunities to navigate intermittency and energy security without relying on fossil fuels.

This section of the research aims to illustrate key topics of the discussion surrounding the case study, providing context that is referred to during the discussion section of the document.

Systems of Innovation

Before delving into the specific elements of study that are of interest to the current case, previous research into the latest discussion regarding Innovation Systems is necessary to deepen the understanding of Green Windows of Opportunity framework. In a systems view of innovation, innovation is an iterative, nonlinear, and evolutionary process of learning. Attention to different aspects of innovation requires collaboration and close relationships among different actors, thus making systems of innovation a better approach to complex challenges (Dahesh et al., 2020).

Innovation Systems have been discussed as methods for connecting decision inputs with innovation goals at least since 1989, as presented by Brown & Karagozoglu (1989), and have been integrating critiques both from theory and empirical experience since, giving space for newer frameworks that consider multiple factors, and branching to different perspectives, from private companies to public policy. Latest discussion focuses on environmental studies, particularly in developed countries such as the UK, the Netherlands, the United States, Germany, and Sweden (Dahesh et al., 2020, p.6), other major topics of application are Sustainability Transitions, Energy Transitions, Socio-technical Transitions, and Eco Innovation. Innovation systems have also apparently moved from the study of firm applications, such as Brown & Karagozoglu (1989) to national or regional systems, with a mission-oriented view, and highly influenced by public policy (Hekkert et al., 2020; Ghazinoory et al., 2020).

The focus on bigger systems, added to the application of the theory to different cases, has also called for the inclusion of a social innovation perspective and flexibilization of the system, as proposed by (Wittmayer et al., 2020), with specific focus on energy systems. Wittmayer et al. (2020) also called for a multi-actor approach to the application of innovation systems to energy, highlighting the several different actors and stakeholders, both economic and social that would be affected by the introduction of innovations.

Considerable amount of publications seem to mention that innovation systems are widely used for studying technological solutions, which is also the focus of the chosen framework for this research. The validity of the technological focus in innovation systems has also been proved effective, having been challenged in 2009 by Hekkert & Negro, who found that the functions of innovation systems framework was a valid framework for understanding sustainable technological change.

The framework presented by Lema & Rabellotti in 2023 builds upon aforementioned research by including the influence of both external and internal actors in the system, separating the types of stimuli to the framework between policy driven, market driven, and technology driven, and considering responses to the stimuli from the sectoral systems present in a determined context. The application of innovations systems in the energy context builds upon the several innovation systems that have been proven effective when applied to this specific environment, as mentioned by (Dahesh et al., 2020), however, the use of the green windows of innovation framework includes the perspective of a country that has catch-up capabilities, and is backed up by UNCTAD's latest technology and innovation report.

Energy transition in developing countries

Due to the upcoming change in the energy system, previous research focusing on energy transition, especially in developing countries is a relevant topic for consultation of relevant publications.

It is important to note that Costa Rica is not a country that can be considered to have experienced a classic energy transition from fossil fuels to cleaner energies, since most of the energy matrix has always been renewable. However, the country is now experimenting with solar and increased wind power, while also looking at other technologies, which could potentially change the energy behaviour. It is therefore of interest to understand what previous research has identified regarding transitions.

In 2020, Vanegas-Cantarero stated that approximately one third of developing countries were striving for 100% renewable energy systems in the medium term (2020, p. 6), which includes Costa Rica, who promised to be 100% renewable by 2030. In her publication, titled "*Of renewable energy, energy democracy, and sustainable development: A roadmap to accelerate the energy transition in developing countries*", Vanegas-Cantarero highlighted the challenges for countries similar to Costa Rica, particularly lack of access to reliable electricity in poor areas, size-constrained and unreliable power networks, poor energy planning, market reforms that have led to financial issues, and strong reliance and subsidies on fossil fuels. This last challenge was also highlighted by Espinoza et al. (2022) on their analysis of the Ecuadorian energy market, reinforcing the call for policies against a fossil fuel economy.

Of the highlighted factors, Costa Rica has managed to mostly isolate itself from fossil fuels, due to the low thermal energy generation, reaches most of the population with electricity, and has issued several energy planning documents. However, the country does have a small network with old transmission infrastructure (Jiménez et al., 2023), which could impact efficiency in energy generation, and create technical and non-technical losses. The country could also be susceptible to poor market reforms, due to the particular structure of the market.

After presenting the challenges that developing countries might face, Vanegas-Cantarero (2020) focuses on developing a theory of energy transition described as a socio-technical process that requires radical changes in three main dimensions: technology, society, and policies. In the technological dimension, the author suggests the adoption of smart energy systems that enable synergies between different technologies. In the societal dimension, the author emphasises the importance of energy citizenship, community energy projects, and public participation in decision-making processes. The policy dimension focuses on the need for democratic restructuring of institutions, accountability, and transparency to support the energy transition.

Finally, the author proposes an energy transition indicator that considers factors such as energy security, environmental sustainability, democracy and citizenship, and justice. A similar framework was used by Saldivia Olave & Vargas-Payera (2020) to discuss the environmental impact of geothermal projects for the cases of Chile, Costa Rica, Colombia, and Mexico, further highlighting the importance of public participation processes for local communities in all developing nations.

Newer documents about energy transition in developing economies are focusing more on the financial aspect of technology implementation. Anthony Afful-Dadzie (2021) questioned the feasibility of achieving a 100% renewable energy transition by 2050, aiming to refute a complex model presented by Bogdanov et al. in the same year (2021), which predicted a successful transition for the specific case of Kazakhstan. In his article, Afful-Dadzie pointed out that most developing economies must consider harder constraints to raise the needed finances to acquire their energy generation capacity, which is something developed nations don't struggle with, as they usually use the Levelized Cost of Electricity (LCOE), an economic measure used to compare the lifetime costs of electricity generation, and can access long term financial credits (Afful-Dadzie, 2021).

However, Ram et al. (2022), argued against Afful-Dadzie, pointing out that his oversimplification of complex models might lead to wrong conclusions, and although the challenges around obtaining affordable financing in developing countries exist, global capital is abundant if the right policies enable bankable projects. Ram et al. (2022) stressed the importance of climate finance activities from developed economies as critical for the growth of renewables in the global south, but also connected to what Vanegas-Cantarero (2020) proposed, by emphasising that developing countries must take proactive measures to attract investments by reducing risks, streamlining processes, and enabling competitive project tenders.

Energy Security and Intermittency Challenges

Additionally, to the discussion of how developing economies might achieve a 100% renewable economy, it becomes relevant for the case of Costa Rica to explore recent publications regarding energy security and intermittency, which are mentioned by Vanegas-Cantarero (2020) to be challenges to the systems that incorporate high shares of variable renewables.

Energy security is defined as the electricity system's capability to ensure uninterrupted availability of electricity by withstanding and recovering from disturbances and contingencies (IEA, 2021). There can be many disturbances and contingencies that can affect the electricity system, such as strong weather, unidentified peaks in demand, direct intervention of generation, transmission, and distribution networks, among others, however one of the challenges that can affect energy security comes from the generation provided by variable sources, such as solar or wind. This type of energy, which is not continuously available due to external factors that cannot be controlled, produced by sources that vary in their conditions on a fairly short time scale (University of Calgary, 2024) is called intermittent energy, and it needs to be complemented with high availability sources, to maintain energy security. Fossil fuels on the other hand are highly available sources that can be easily stored and transported, either in pipes, sea, or land transport, and used upon request, without any influence from climate, weather, or time of the day.

The publication by Vanegas-Cantarero already presents a possible solution to the intermittency threat to energy security, which is the use of Smart Energy Systems (SES) that are capable of integrating high shares of intermittent renewable energy into energy systems. However, these systems rely on the inter-linkages between renewable electricity and the remaining energy sectors, such as transport, industry, or heating, which are still highly carbon intensive in the case of Costa Rica, compared to electricity.

Liebensteiner & Wrienz published an article in 2020 named "Do Intermittent Renewables Threaten the Electricity Supply Security?", stating that given the technical infeasibility of large-scale electricity storage, big subsidies for variable renewables can threaten energy security. The authors also mention that this subject is severely under-researched, and conclude that it impacts energy markets when used to replace peak-load traditional capacity such as gas.

This type of analysis was complemented by researchers such as Heard et al. (2017), who argued that 100% intermittent renewable models did not hold when compared to empirical evidence, and that energy safety could not be ensured, or Heuberger & Mac Dowell (2018), who with models reached the conclusion that without considering fundamental future advancements in power system electronics, 100% intermittent renewable scenarios should be approached with caution.

However, the assumption that intermittent renewables threaten energy security is not a consensus among scholars researching the subject, with several publications aimed at explaining how systems can safely integrate a major share of renewables. Already in 2011, Hart et al. pointed out that by using advanced grid integration models it was possible for a high penetration of intermittent renewables without compromising system reliability. This mathematical modelling solution to the intermittency issue has other enthusiasts, that have proposed mixed integer nonlinear programming AC TEP models (Xie & Xu, 2022), and fuzzy theory probabilistic methods (Fei & Zhu, 2021), among other complex models that do not involve specific hardware.

Other authors have chosen a more physical technology path, with most of the older work focusing on short-term electrochemical (batteries) and mechanical (compressed air, flywheel) storage technologies (Akinyele & Rayudu, 2014; Beaudin et al., 2010; Chen et al., 2009; Díaz-González et al., 2012; Mahlia et al., 2014), and newer research suggesting alternative technologies like the use of energy storage either grid-scale like pumped hydro, or synthetic natural gas Ganzer et al. (2022).

The fact that research has not yet agreed if the possibility of energy security with high intermittency renewables is achievable suggests an interesting set of opportunities for studies in the Costa Rican context, who is high in renewables and will expand intermittent technologies. Current academic discussion also hints that there's no clear path of 100% detachment from fossil fuel electricity generation that the country can follow yet.

Sustainable Energy Technologies

Given that most of the solutions to ensuring energy safety in high intermittency systems seem to be of a technological nature, the state of the art of some sustainable energy technologies is of interest for reviewing as part of this research.

As it was mentioned before, most of the technologies that are mentioned as possible solutions for reducing the intermittency caused mostly by wind and solar are different types of chemical batteries, like lithium-ion, which has promoted applied research that increased their efficiency considerably, allowing for new applications (Dumé, 2023).

An alternative to chemical batteries has been under research that involves the production of clean fuels, using the "Power-to-x" process. Power-to-x means converting clean electricity into green hydrogen, which is then converted into a fossil fuel free fuel like e-diesel, e-methanol, e-ammonia, or others, that can be used directly in fossil fuel systems (Technical University of Denmark, 2023), with some companies already offering retrofit systems to thermal energy facilities (MAN, 2021). This energy storage method has been highlighted as a possible solution not only to eliminate emissions in electricity generation, but in the whole energy market (Kouchaki-Penchah et al., 2024). However, Power-to-x is heavily reliant on green hydrogen production, which has still challenges when it comes to competitive pricing (IEA, 2023).

A third type of technology which has been discussed, particularly for areas with strong solar radiation, is the use of Concentrated Solar Power, which captures solar radiation in a highly capable material like clay, glass, or molten salts, which are later used to create water vapour that is run through a turbine that generates electricity (Friesen, 2021, p.10). This technology is being used now mostly in the USA, Spain, Morocco, India, and China, and has experienced significant cost reductions, however, the big initial investment and dependency on a radiation-intense location has hindered its diffusion into other countries.

Other technological improvements have been highlighted, however they haven't been included in this review due to lower popularity or development within academic research.

Energy frameworks and public-private regulatory structures

As it is mentioned by Lukito Effendi et al. (2023), countries' renewable energy governance and market structure significantly influence sustainable development, with regulatory constraints and investment availability being key challenges. There are several different types of energy market structures, derived from different political stances, outcome preferences, path dependencies or other factors. Since every country possesses a slightly different energy market, it becomes relevant to understand the influence of how energy frameworks are structured on the developments of sustainable energy technology.

Latest publications have highlighted the importance of incentive-based markets. Varawala et al. (2021) proposed a system that incorporated the externalities of climate change and power mitigation into the incentives, coping with incomplete information of the system operator regarding generation costs.

Other publications focus on the public-private relationship in energy markets. Smirnova et al. (2021) stated that key drivers of influence on the renewable energy market were expanding access to financing for renewable energy sources and ensuring public-private support for renewable energy projects, among others. Jolink & Niesten (2021) also highlighted the importance of collaborative financing of clean energy projects between private and government actors, while Shahbaz et al. (2020) tied the discussion back to the importance of incentives, by showing a mathematically positive relationship between unregulated public-private collaborations and CO_2 emissions. Tzankova (2020) also found that private, market-driven governance initiatives targeted at reforming the choices and practices of the electricity sector are advancing energy transitions indirectly, by producing positive spill over effects on public policy and regulatory action towards electricity decarbonization.

Empirical studies on this matter have suggested that markets that promote competition are performing better in sustainability terms. García-Álvarez & Soares (2018) studied the EU-28 and concluded that the most successful countries within the region had a combination of stringent energy taxes, strong support for eco-innovation, research in development and deployment of renewable energy, reduced energy dependence, and continuous investment in energy efficiency measures.

Considering the percentage of renewable energy generation in the country, the study of the Costa Rican energy market configuration provides additional input into the discussion of which system characteristics are more successful at incentivising the carbon neutral electricity future.

In summary, previous research seems to highlight the importance of a systemic approach to the underlined issue that Costa Rica is facing, while the study of energy transitions highlights the importance of modernising infrastructure and implementing adequate financial structures. Energy security and intermittency research showed an ongoing debate about the applicability of 100% renewable systems, highlighting the lack of empirical information and tested solutions that are cost effective enough to be widely implemented, however, research does seem to agree that the issue needs to be studied further to reduce uncertainty.

Many sustainable energy technologies have been presented as potential solutions to decarbonising energy, chemical batteries being the most widely discussed, but with an emergence of the power-to-X technologies, although the latter still requires further research to be widely accepted, highlighting a potential gap to be studied with empirical applications. As a suggested approach to empirical applications of newer technologies, public-private collaboration research mentions the importance of setting the right incentives to achieve the desired outcomes, ensuring competition, access to financing and public support for projects. This can be tied back to the theoretical framework's Sectoral Systems section, as it also mentions the importance of having the right preconditions and responses to seize windows of opportunity.

The highlighted gaps in the aforementioned research strengthen the relevance of the research questions, presenting an ongoing debate about the path for reaching energy security with a decarbonised electricity system, especially in a developing economy. The answering of the second research question, related to the potential for emerging technologies to be applied, also relates to the debate about the lack of empirical testing in 100% renewable energy systems.

4 Data & Methods

This chapter details the relevant sources of information that help answer the research questions, explains how the sources are approached to ensure an efficient and effective gathering of data, and the analysis methods that are applied to the gathered information to produce the results of the research. Finally, potential biases and ethical considerations are detailed.

4.1 Data Sources

In order to answer the research question presented in this document, about opportunities of how Costa Rica as a developing nation can navigate intermittency and availability in electricity generation without fossil fuels, within the selected theoretical framework, it is important that the sources of information point at answering the specific gaps in knowledge.

Since the research discusses the issue of phasing out fossil fuels in a country that has already managed to produce electricity using over 90% renewable sources, the emphasis of the data is on identifying paths and readiness, rather than analysing outcomes that may not be present at the time of writing. Given the current scenario, most of the data collection is focused on identifying and understanding the green windows of opportunity, particularly institutional windows, and the preconditions and responses of sectoral systems.

To fully understand the current scenario and opportunities for fossil fuel free energy generation in Costa Rica, a mix of sources is used to gather the required information, with a focus on material that provides the opportunity to delve deeper into specific areas as desired, and allows for people's perceptions and opinions to be taken into account.

Due to the complexity of the ecosystem, and its many involved institutions, actors and roles, the aim of the gathering of data will be to characterise the system from different perspectives, which will have emphasis in particular areas. Data sourced from a regulations point of view might have more to say about the setting of prices, whereas an engineering point of view could focus more on the feasibility of certain strategies, even when referring to the same subject.

The specificity and biases of certain data sources is sought upon in the purpose of this study, because it complements each other to help inform of a broader, larger scenario, such as the Costa Rican electricity ecosystem. Due to this scenario, the data gathering methods and analysis need to allow different points of view and disagreements within sources to be maintained, instead of discarded or blended in seek of consensus.

A detail of the main data sources follows:

1. **Policy makers at ICE**

   The executives from different relevant areas of the publicly owned electricity company (ICE) are the main source of material regarding policies about collaboration with other actors, openness to new technologies, previous efforts, public research into fossil fuel free alternatives, and strategic planning of the energy market. Key areas within ICE are:

   a) Planning division: in charge of all new technological research, definition of future projects, testing of potential solutions and feasibility studies.
   b) Regulatory division: that oversees all fees, interaction with other actors, knows how prices are set and can influence future price structures.
   c) Sustainability division: that sets governance standards for sustainable practices, seeks financing of projects, and raises concerns for unsustainable or improvable practices.

   Researching these sources will help understand how the decision-making process shapes the chosen and discarded technologies, and the ultimate choice of not withdrawing fossil-fuel installed capacity, while also informing on the constraints and self-identified advantages of the electricity company towards the development of new projects.

2. **International agencies with local involvement**

   Agencies such as the Inter American Development Bank (IADB) or the German International Cooperation Agency (GIZ) have certain internationally defined priority topics that they will provide funding for, which usually involve sustainable measures and development practices. Aside from the interest in understanding the reasons why some projects are prioritised over others, and which projects are being currently sponsored, these agencies are also constantly performing market research and issuing recommendations to countries based on their experience.

   This data source will help gather an external outlook on the priorities of the electricity companies and the government, and understand how international parties are participating in the introduction of new technologies.

3. **Other companies in the electricity market**

   Other secondary involved actors can provide a different point of view of the electricity market, from the side of the companies that have to interact on a daily basis with ICE and the policy decisions made by them. Additionally, understanding the projects that these companies have and how they compare to the projects at ICE could provide an interesting contrast.

The data source will help inform about the competitiveness of the system, and the impact of the regulation of the interactions, while also providing an external outlook into the sustainability policies that these companies are also subject to.

4. External policy experts

Policy researchers and local academics also provide a less biased input to the electricity market scenario, when compared to policy makers. The input from academics that have studied the electricity market can incorporate a historical reasoning behind some policies, while also presenting a curated comparison with other countries, and improvement suggestions.

5. Sustainable technology experts

Executives from companies dedicated to the development and diffusion of certain technologies that could potentially replace the existing fossil fuel capacity provide an informative point of view about the existing environment and its capabilities to implement technological upgrades they are related to.

Understanding the innovators' outlook on the market will inform about which policies are perceived as incentives and which as barriers to the introduction of technology in energy generation.

6. Key issued documents

Some important documents gather the opinions, knowledge and priorities of public policy and legislators, and are therefore of great interest to the research. Example key documents are:

a) The Expansion Plan of Energy Generation (ICE)
b) National Decarbonisation Plan (Ministry of Environment)

The reviewing of documents such as these will provide background context for preparing conversations with policy makers, while also presenting the consensus of the public policy strategies. The contrast between the information written in the documents, and the input from policy makers also aims to provide a deeper understanding of the country's energy scenario.

4.2 The Methodological Approach

This section of the chapter presents the tools which are used to gather the data from the aforementioned sources, and the reasoning behind the selection of each tool as an input method for the analysis within the theoretical framework.

Due to the nature of the research questions, and the system approach that the chosen framework presents, an exploratory case study approach is used. The selection of a case study method is supported by the exploratory nature of the research question, the contemporaneous interest, and the interest in investigating the phenomenon in context, in accordance with the criteria detailed by Yin (2017). It is also supported by the low availability of data points, given the type of data sources (Panke, 2018, p.147).

4.2.1 Data Gathering

To ensure a correct gathering process of the main data sources, account for the differences in their nature, and compensate drawbacks inherent to the collection methods, two main data gathering tools are considered:

a. **Unstructured Interviews**

   The use of interviews is the main data gathering tool used in the research, due to the type sources being almost all people within institutions or experts. Given that the interest of the research is to understand not only the functioning of the Costa Rican environment, but also the efficiency, openness to technological changes, and other important factors, the opinions of the interviewees, in addition to their technical knowledge is also a valuable input.

   Interviews in general are better fitted for exploratory studies (Panke, 2018) such as this one, and among them, unstructured interviews are characterised by flexible questions (not standardised, where you ask different questions in each interview) in combination with open answers. The use of unstructured interviews allows to incorporate follow up questions within the areas of expertise of each interviewee while keeping a constant template that allows comparison of the answers during the analysis. The method also allows for a better gathering of opinions and impressions of the interviewee about a subject.

   The amount of interviews performed is divided among the available data sources, with more emphasis on the policy makers that are directly involved in the electricity environment in the country, and conversations with other experts that are not directly involved, as a complement to the main data from ICE. A total of 10 interviews are reached as follows:

Interview Source	Amount of Interviews
Policy Makers at ICE	5 Interviews
International agencies with local involvement	1 Interview
Other companies in the electricity market	1 Interview
External policy experts	1 Interview
Sustainable technology experts	2 Interviews

Table 4: Interview quantities for data collection

All interviews are anonymised and documented in text files for further analysis, detailed in the section below. Due to the unstructured nature of the interviews, the documentation is done by topic of discussion, and not by question, ensuring easier analysis later on.

b. Analysis of written documents

A secondary data gathering method is the review of official documents that have been published by the institutions in charge of structuring, regulating and influencing the electricity market. Using written documents as a data source allows for a more time-based data gathering, especially compared to interviews, where the focus is mostly on the present scenario, and answers about past events of future planning are usually not very accurate (Panke, 2018, p. 230). The analysis of documents is focused on understanding the country's plans for future developments, commitments with sustainability and growth, and technical considerations when forecasting energy demand and climate conditions, among others.

Institutions considered for this tool are ICE, MINAE, ARESEP among others, and the main two documents of interest are the Expansion Plan of Energy Generation (ICE) and the National Decarbonisation Plan (MINAE). Additional documents like sustainability reports might be consulted for relevant information or context, but are not analysed in depth.

4.2.2 Analysis Methods

After gathering and documenting the data from the relevant sources, the raw results are analysed, distinguishing between factual, countable, and specific data as well as data that are subject to interpretation, as recommended by Panke (2018). The analysis of interviews is coded according to the main covered topics, and repeating subjects that were discussed during the conversations, which are then clustered, curated and complemented by the findings of the document review.

The type of coding that is employed for the analysis of the data is of an inferential nature, because it allows for better drawing of conclusions about the Costa Rican system from limited sources of information (Aboagye, 2023). The result of this type of coding are direct themes that refer to major subjects of importance within the energy system, and that emerge during the coding process, as suggested by Saldana (2021, p.13), which are then grouped into categories, which allows for a more curated presentation of the results.

To increase the accuracy of the coding, themes are extracted from the transcripts in two different instances: the first being direct learnings from the transcripts, from which direct themes are extracted, and the second one being inferred themes that emerge from the reading, but are not directly related to a specific part of the interview. The direct and inferred themes are compared to ensure that no relevant subjects were left out, while also checking that no themes are overrepresented due to the order of reading. This exercise of recoding is recommended by academics to achieve a more attuned perspective of the results (Saldana, 2021, p.10)

The result from the coding and recoding process is summarised in a List of Insights. The insights list contains a few curated categories that are explained in depth, relating to the themes and codes that composed it. After the generation of the list, both that outcome and the previous themes and categories are analysed again, now within the Green Windows of Opportunity framework, to produce new insights that are specifically tied to the sections of the framework, and aim to answer Lema & Rabellotti's structure and highlighted subjects of importance.

4.2.3 Interpretation of the Results

There are two main results of the data gathering and analysis process: the list of insights and the completed green windows of opportunity framework.

The list of insights is a direct result of the coding of interviews, plus the statements, temporal information and relevant data gathered from the key document review. Each insight represents a cluster of categories, themes and key findings that help answer the research question (Panke, 2018), and it is shown as a summary statement, followed by a longer explanation of the relevance, characteristics, and possible direct references to the gathered data (quotes or key numbers).

The green windows of opportunity framework presents structured insights, answering which green transformations (new policies, technologies, and markets), Green windows of opportunity (institutional windows, technological and market windows) and sectoral systems (preconditions and responses) are present. Some potential catch up trajectories are mentioned, as foreseeable outcomes of current efforts.

The list of insights, along with the completed framework, allow to open the discussion of the most relevant findings that could impact the Costa Rican ability to react to future threats to their renewable energy generation, with a focus on the strengths (opportunities) and shortcomings (challenges) of the electricity environment. The discussion of the insights also allows for a presentation of possible solutions and recommendations that could help reach a sustainable outcome.

The Green Windows of Opportunity framework also allows comparison of the findings with the theory behind each section of the framework, in line with the analysis that Lema & Rabellotti published in 2023.

4.2.4 Potential Biases, Researcher Positionality and Generalisation

Due to the identified sources of information for the research being mostly human individuals, it is important to consider that some interviewee bias is inevitably introduced to the research. The use of contextual documents is expected to counter some of the bias by adding context and perspective to the answers, and the repetition of interviewee profiles should help distinguish factual information from personal opinions (Panke, 2018, p. 228). Nonetheless, quantitative studies always contain some level of bias.

Researcher positionality is also to be accounted for. Energy generation being a highly technical subject, researcher's academic background in engineering studies is expected to be of use to better understand the implications of technical limitations or capabilities, while being able to maintain conversations with technical actors and technology experts. On the other hand, researcher positionality could also introduce a bias towards high technology solutions.

The generalisation of this case study to other contexts is one key aspect of the research's relevance. While it might not be possible to directly correlate the scenario and responses of Costa Rica to other countries, it is believed that some of the learnings could be applied in either developing economies, or in low resilience, highly renewable systems.

4.2.5 Ethical Considerations

The data sources and methods described in this section of the research could potentially have an unintended impact on the interviewees, particularly due to the combination of the seeking of impressions and opinions about the local system with the fact that many subjects of interview are situated within the system itself.

To limit potential negative effects, the gathering of data follows a set of ethical rules, in compliance to the recommendations of Bryman (2008), that ensure total anonymisation of the information. Informed consent is asked before the beginning of every interview, no pictures or recordings of the interviewees are kept, and the data is grouped before being analysed, ensuring no outcome can be traced to a particular instance of interview.

Ethical considerations and uses of this study are also in line with the Good Research Practice manual provided by the Swedish Research Council (2017).

5 Empirical Analysis

This chapter of the document presents the results of the data gathering and analysis as it was described in the previous section. The list of insights is detailed, followed by the completed Green Windows of Opportunity Framework. Subsequently, a discussion of the results is presented.

5.1 Results

From the analysis of the gathered data, 5 main insights are produced. These insights represent several relevant subjects of discussion, which were summarised and prioritised to help inform the research questions, aiming also to maintain a concise number of conclusions for the analysis. With the information from the insights, the Green Windows of Opportunity framework was completed, thus relating the findings from the data gathering process and analysis to the theoretical framework for identifying opportunities that can help navigate intermittency and availability in electricity generation without fossil fuels.

5.1.1 Main Insights

Resilience Challenges

> *"The vice minister told me they are worried about becoming a less sustainable country in electricity, they voice this opinion publicly during our meetings"*
>
> - Industry Expert

The impact of climate change in weather in the Central Americas region has brought extended periods of droughts, followed by heavy storms, that are only expected to increase (IPCC, 2022). This scenario is recognised by policy makers to have a big impact on the Costa Rican electricity generation capacity, which is heavily dependent on the water resource, either in dry seasons, because of lack of water reserves, but also during heavy storms, because of the raising of sediments that complicate the usage of water for energy generation.

Aware of this, the Expansion Plan focuses on moving away from water dependency by heavily investing in solar power generation. The plan considers building 1.600 MW by 2040 of solar PV to increase resilience, and to incorporate 600 MW of battery storage in the same period, to reduce intermittency issues that come with the expansion of solar energy. However, it was mentioned by experts that the impact of weather in energy generation might be more severe than the forecasts are willing to admit, and that in combination with the rise in intermittency, the thermal energy capacity will probably end up being used more often than expected, even without pause.

This increasing expectation of relying constantly on fossil fuels in the future is met with divided opinions. Some argue that if reliance on this type of energy is to increase, clean fuels alternatives need to be considered before path dependency is reinforced, while others downplay the role of fossil fuels by pointing at the scenario of other nations that rely heavily on thermal energy. Although nobody denies the impact of fossil fuels in CO2 emissions, most of the concerns about increasing fossil fuel dependency are about price, and increased energy generation dependency in other countries, since Costa Rica doesn't produce oil.

Failure to increase resilience without relying in fossil fuels could threaten the success in renewable energy generation that the country is widely known for, however the issue seems to have been identified in time by some key players, who have pointed out that increasing the reliability of the Central Americas interconnected system (MER) could add resilience to the system. Currently the regional system is seen as an auxiliary resource, perceived by some as too unstable for long term contracts, due to political concerns and a strong focus of each country in their internal market. Increasing transparency, cleaning the energy matrix of neighbouring countries, incorporating long term planning, and installing system wide coordination are mentioned solutions to add reliability to the system, which can help reduce intermittency issues by increasing available energy, while also countering weather conditions by expanding the generation area.

Market Modernisation

> *"The Costa Rican market works for the consumer, not for the private investor"*
>
> \- Policy Expert

As it was mentioned during the context section of this document, Costa Rica currently uses a closed energy market, with ICE, the public electricity company, owning and operating most of the system. So far, this system has allowed the country to maintain relatively low prices of electricity through median cost setting, fend off private projects that would not benefit citizens directly, and kept fossil fuel built capacity to a minimum, without risk of increasing. It was also mentioned that due to the configuration of the system, long term planning was achieved, which ensured the high percentages of renewable energy generation.

This system has managed to serve the country's needs even when similar systems were failing in other countries in the past, and the main benefits of the closed market have become core values of Costa Rican policy makers, politicians, and citizens, and are heavily protected by regulation. ICE has a strong positive technical reputation, and it is recognised as a great company to operate the current electricity market by industry experts, private investors, and government regardless of political orientation, with private companies being used as auxiliary alternatives, and kept under tight regulation to ensure no additional profit goes to private individuals.

However, as the electricity market becomes more disruptive, with constant technological improvements, moving away from the traditional commodity structure, highly regulated public companies like ICE are found to have become slow in reaction, which could be hindering their ability to seize improvement opportunities. ICE is now being perceived as an institution that holds too much power within the market, with the ability to organise electricity coordination while being the main energy producer, dictate the country's next 20 years of energy projects, and having direct influence over regulations.

The regulatory framework on the other hand, which is considered responsible for maintaining the high percentage of renewables, forbidding oil surveying in the country, and ensuring that the price of electricity is as low as possible for citizens, is now being mentioned to become outdated. This critique is done mainly because it limits direct public investments in innovation projects, does not allow for special treatment of key projects, and forbids private institutions to participate in initiatives that involve public infrastructure.

Governments have already identified the necessity of adjusting regulation and the capabilities of ICE to allow the market to address the current and future challenges, especially to be able to allocate private actors within the system, but it is considered that regulatory agencies have been slow to introduce change, which could compromise the effectiveness of the response.

Although changes are being demanded in regulation, most of the actors within the system seem to prefer maintaining a closed market. While some mentioned that the institutions in the electricity market are not ready for an open environment, as it will force them to develop competition and commercial capabilities, the main concern seems to be that opening the market will allow private institutions to obtain profits from projects by raising energy prices, and limit the system capability for long term planning. When discussing the characteristics of an open market, most interviewees referred to traditional neoclassical structures that have allowed foreign companies to take all profit from energy generation projects out of the country, without concern for the environment, or to prioritise business to business contracts over delivering cost-effective electricity to mainstream population.

> *"Costa Rica is not ready for the demands and standards of an open electricity market"*
>
> - Industry Actor

Considering these factors, institutions working on market modernisation have to address the challenge of introducing flexibility that allows for innovation projects, bigger investments, and technological improvements to thrive, without compromising the core values that Costa Ricans are proud of. Either by opening the market or not, and adjusting the level of participation of private entities, market modernisation needs to find the balance between new business models and flexible regulation, and having a system that works for the people, and is capable of long term, sustainable planning.

Technology Surveying and Development

Lema & Rabellotti (2023) highlighted that one of the key elements for being able to seize a green window of opportunity is to have developed capabilities for technology surveying and research, and the ability to adapt, implement and maintain technologies that are brought to a country.

ICE's planning unit, the department within the company in charge of the Expansion Plan, mentions several technologies that are considered during the elaboration of the document, and their ultimate inclusion or exclusion of future projects in the country. Historically, this ability to survey technology has allowed the country to be a region's pioneer in the implementation of solar photovoltaic, wind, and other innovations in energy generation, and the planning ability of ICE is highly regarded partially because of the same reason.

However, as the energy ecosystem became more disrupted by technology, the required depth of analysis of new methods and innovation was also changed. The current role that technology surveying has in the expansion plan final document seems to be secondary in importance to the layout of new projects that are to be constructed, with a small section dedicated to explaining offshore wind, tide power, biofuels, and green hydrogen. The lack of transparency in technology surveying by ICE raises concerns about the depth of the analysis, however when consulted about their efforts for the elaboration of the document, interviewees mentioned that more work went into it, but that it is not prioritised to be divulged to the general public. During the interviews the policy makers mentioned several projects, both inside and outside the country, and approaches from technology companies based in Japan and Germany wanting to show advancements in certain techniques, mostly related to the applications of power-to-x.

> *"We have been approached by companies from Germany and Japan, offering us solutions for retrofitting clean energy into thermal capacity, but it was too expensive"*
>
> \- Policy Maker

In addition, from being aware of external projects, and being approached by external companies to offer new technology, policy makers also mentioned internal efforts for trying new energy generation methods, but admitted that political preferences did not allow for the use of public resources in disruptive technology investment, and that initiatives were limited to more traditional methods of generation.

One key aspect that was highlighted by some policy makers regarding the ability to survey technology was the use of a "cost first" evaluation, that does not consider price forecastings into the calculations, and decides to consider a technology as feasible solely on the current cost being lower than the average of the Costa Rican system. It is believed by industry experts that the incorporation of future prices of technology in this process could greatly increase the already acclaimed planning capacity of ICE, by rightfully scheduling the inclusion of innovations in their 20 year expansion strategy.

“We start from the assumption that the costs and benefits of the plan do not change in time during the analysis period [2022-2040]”

- Key Document

Complementary to technology surveying and planning, public officials have worked on a strategy to increase research and development capabilities for new energy technologies in the country. It is expected that the execution of the strategy will increase the ability to coordinate developments with several national and international entities, attract investors, lead key pilot projects, and install technical capabilities to adapt and maintain innovations, positioning the country as an energy technology hub in the region.

The successful establishment of this energy hub could answer to the requirements presented by Lema & Rabellotti (2023) to incorporate technologies, however, the lack of directives regarding capabilities for internal technology development in this strategy, and more presence of articulation and enabling capabilities also highlights the interest of policy makers in following a path of catch-up regarding energy, in contrast to becoming pioneers in the renewable energies of the future. The choosing of this path is mentioned to be a responsible and expected decision considering the developing economy in the country, but it is also said that it fails to leverage on the positive energy generation scenario in Costa Rica.

New Project Limitations

“There are fears that investors will come and produce a lot of hydrogen, but export all of it (...), attractive projects are the ones that serve the internal market”

- Industry Expert

Costa Rica is a land that has enough natural resources to satisfy the internal necessity of energy generation, and leave considerable unused potential for bigger exporting projects to take place within the country. The country also has a strategic position within the American continent, with access to both the Pacific and Atlantic sea, and closeness to the main hubs of consumption, like the United States, Canada, Mexico, and Brazil. Public institutions do not currently possess the capabilities and budget allowance to explore disruptive innovation projects, and their traditional cost-based evaluation of initiatives was mentioned to not integrate relevant externalities that could tip the scale in favour of new clean technologies.

The government and policy makers are aware of public institution’s limitations and have already set in motion a strategy that is expected to bring private companies that have investment capacity for technology development, while keeping market operation to ICE and other relevant governmental companies. This investment scenario, combined with the expected changes in regulation that are being discussed, should provide a highly positive environment for disruptive projects, some of them whose pilots are already ongoing.

However, the types of projects that the Costa Ricans are interested in allowing are not only conditioned by financial performance like profit, GDP growth or other, but also by political preference, and conditioned to current public infrastructure.

Infrastructure wise, public institutions are aware that to allow the successful allocation of future projects, modernisation of public assets is required. Current electricity transmission lines are known to struggle to transfer all generated electricity from the main generation location in the northwest of the country to the main sources of consumption in the centre, and therefore, new initiatives that are not considered in ICE's expansion plan could challenge even more the capacity.

> *"We were approached by a company wanting to do a carbon neutral fertiliser [...] had to reject it because the scale of the project was too big for the system"*
>
> - Policy Maker

Size of projects is also mentioned to be an issue for infrastructure and regulation, especially when compared to the size of the Costa Rican grid, which has about 3GW installed capacity. Some of the projects that interviewees mentioned being approached for, specially Green Hydrogen ones, could have bigger energy requirements than the whole system, and would therefore require heavy infrastructure investments. Policy makers already mentioned having to reject clean technology projects aimed at decarbonising agriculture and industry solely because the scale of energy requirements surpassed that of the country, or because the regulatory framework doesn't allow the company to serve them energy at the risk of compromising distribution to communities.

With this in mind, policy makers have incorporated to the strategy a prioritisation of "off grid" projects, that employ internal energy generation methods to serve the project's needs, and are hoping to introduce regulatory changes to allow private projects the construction of internal generation capacity within the framework of clean technology projects. Nevertheless, this scenario raises a scale barrier for incoming initiatives, forcing them to be compact enough to be served with internal capabilities, or big enough to justify building energy generation systems.

The scale constraint within the country is not only of a technical nature, but of a political nature as well. Several interviewees mentioned that the biggest concern of opening the energy system to private entities will be the development of big-scale projects that would only use the resources of the country in bigger markets, and not focus on the necessities of the internal market. While this concern is commendable, specially from a nature preservation perspective, it also increases the risk for private implementation of big scale investments, by limiting the available market to the internal one and hindering projects that could benefit Costa Rica, although perhaps indirectly. The challenge of setting a regulatory framework that can address current concerns while lowering project limitations is discussed in an upcoming section of this document.

Public-Private Capabilities

> *"If the country wants private companies to develop projects at their expected pace, they need to get involved in the financial aspect"*
>
> - Industry Expert

Although Costa Rica is not new to collaboration between public and private entities, it has a historical preference for solving country-wide problems through government owned institutions. Nevertheless, new public policy for the implementation of technology, R&D capabilities, and decarbonising energy, are heavily reliant in the hands of private actors, redefining the role of public entities as enablers of these transformations, rather than protagonists.

Aside from addressing the previously mentioned concerns about private investors taking profit from natural resources elsewhere, public policy needs to ensure that both actors are contributing their advantages to produce a fruitful collaboration.

> *"The energy expansion document has very high technical acceptance. Nobody questions what ICE says in this matter, regardless of political preferences"*
>
> - Policy Maker

Public institutions currently hold a highly regarded planning capacity and technical trust that is valued when introducing new technology, and is mentioned to rarely be questioned, even by political opposition. The trust in the planning capacity of ICE is also mentioned to be relevant when assessing a project's risk, and governmental backing of any initiative would enjoy lower financial interest as well. On the other hand, private institutions have shown to be more flexible in operation, enabling them to test new technology at a recommended rate, while also being able to take higher financial risks than infrastructure-oriented companies, but lack trust in the technical due diligence and hold fewer assets compared to public entities.

Even though industry experts have commended the presented strategy of public-private collaboration for technology, addressable improvements were also mentioned. The current government position of not being involved in the allocation of funds and negotiation of interest rates for projects is believed to be hindering the financial process, especially because of public institution's influence in the system, and their historical predominance in project ownership. Direct allocation of public funds to new technology projects, or governmental guarantees are said to be great impulses to the developments, and the overall public-private innovation capabilities.

5.1.2 Green Windows of Opportunity for Costa Rica

The presentation and detailing of the list of insights aims to give an overview of the findings gathered and clustered from the interviews and document review, but the use of the green windows of opportunity framework allows for a structured understanding of the produced insights. Since the insights are made to cover several inputs and findings into a cluster, these are not directly categorised into the framework, but split into smaller topics that better fit the structure of the theory. A completed version of the framework diagram is presented with the titles of the structured insights that characterise the Costa Rican context, followed by a brief explanation of each characteristic.

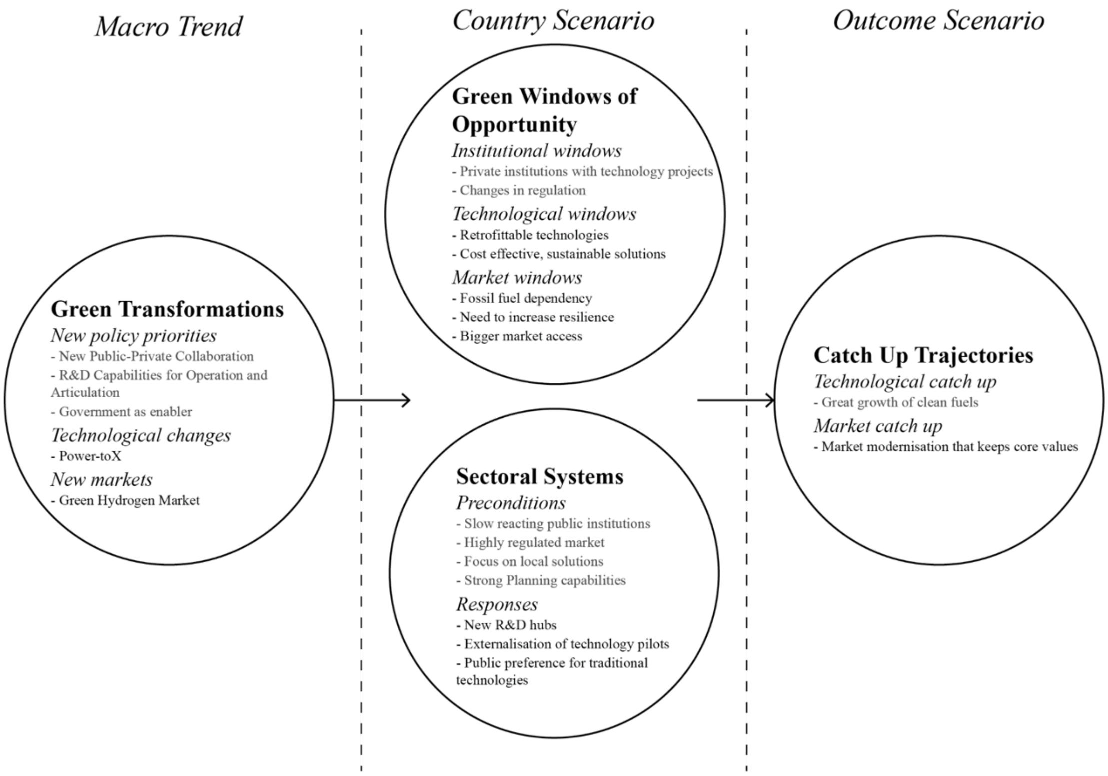

Figure 7: Completed Green Windows of Opportunity framework

A. Green Transformations

A.a. New Policy Priorities

A.a.i. *New Public-Private Collaboration*

Recent policy has been adopted that delegated disruptive technology implementations in the country to private companies, that collaborate with public entities, which are kept as market operators

A.a.ii. *R&D Capabilities for Operation and Articulation*

Policy is focusing efforts in developing new R&D hubs for the articulation and operation of new technology, not oriented to the development of new technologies

A.a.iii. *Government as enabler*

Policy has opted to act as an enabler of new technology improvements, focusing on rightfully structuring regulation, creating collaboration capabilities and operating support infrastructure

A.b. Technological Changes

A.b.i. *Power-to-X*
This new method for producing clean fuels seems to be the major disruptor of the Costa Rican system, because it allows to decarbonise energy and keep energy security while using natural resources through green hydrogen

A.c. New Markets

A.c.i. *Green Hydrogen Market*
The introduction of green hydrogen as a desired decarbonisation technique has created an international market that is expected to continue growing, and that offers Costa Rica new opportunities to gain predominance

B. Green Windows of Opportunity

B.a. Institutional Windows

B.a.i. *Private institutions with technology projects*
Due to the country's good environmental reputation, officials have been approached by companies wanting to develop projects in Costa Rica

B.a.ii. *Changes in regulation*
Although not yet implemented, the currently discussed changes in regulation are expected to allow more flexibility and participation of private institutions in the energy system

B.b. Technological Windows

B.b.i. *Retrofittable technologies*
New technological advances allow for implementing innovations without the need of heavily changing infrastructure, which will allow public companies to keep their assets while using cleaner alternatives that are locally produced

B.b.ii. *Cost effective, sustainable solutions*
With the disruption of the energy market in the early 2000s, more technologies are rapidly becoming cost effective alternatives that would be attractive to be tested

B.c. Market Windows

B.c.i. *Fossil fuel dependency*
The current position of Costa Rica as an importer of all fossil fuel used in the country sets a price and strategic incentive for the replacement of external sources of fuel with internal, affordable alternatives

B.c.ii. *Need to increase resilience*
The current sensitivity of the Costa Rican energy system calls for solutions that can detach the country from water dependence while maintaining low intermittency and high energy security. The incorporation of solar could increase this window

B.c.iii. *Bigger market access*

Either through the Central America Interconnected System, or maritime transport in both major oceans, Costa Rica has easy access to international markets that are demanding clean energy

C. Sectoral Systems

C.a. Preconditions

C.a.i. *Slow reacting public institutions*

Current institutions that are in charge of most infrastructure in the energy market have a composition that does not allow them to react to changes as fast as some private companies require. Their focus on operation allows them a commendable administration of the system, but reduces their participation in disruptive innovations and acknowledgement of some energy challenges

C.a.ii. *Highly regulated market*

Normative regulation has allowed for sustainable operation of the system, while keeping control in the responsibility of public entities. While regulation is key in ensuring future projects respect the country's values and priorities, it is also found to hinder the implementation of projects that are beneficial to the system and limit participation of otherwise willing actors

C.a.iii. *Focus on local solutions*

Either by regulation or direct preference, policy makers value projects aimed solely at solving problems in the local market over bigger initiatives that focus on international targets, while also addressing internal needs. Although this scenario is not believed to greatly harm seizing of windows of opportunity, it is mentioned to reduce the amount of available projects, due to the required smaller scale of solutions.

C.a.iv. *Strong planning capabilities*

The ability of public institutions of planning future projects, combined to their direct predominance in the market has allowed ICE to develop renowned planning capabilities. This structured work greatly allows for long term planning of development of innovations around it, but raises concerns about the lack of flexibility. The incorporation of disruptive innovations' price forecasting into the calculations is mentioned to potentially help address the introduction of new technologies in the strict planning of ICE.

C.b. Responses

C.b.i. *New R&D hubs*

The launch of the green hydrogen strategy has already started the development of an R&D hub that is in line with public policy. The hub is expected to congregate all actors interested in disruptive innovation projects, and articulate their execution

C.b.ii. *Externalisation of technology pilots*

As a direct result of public policy, most of technological pilots and currents innovations being tested in the country are sponsored by public institutions, but led and developed by private entities

C.b.iii. *Public preference for traditional technologies*
Industry experts have identified a public tendency to prefer widely known, proven technologies over new methods. Some actors within the system have expressed their choice of solving challenges through traditional methods instead of piloting new technology

D. Catch Up Trajectories

D.a. Technological Catch Up

D.a.i. *Great growth of clean fuels*
Although yet unmet, it is believed that Costa Rica has the potential to become leader in the production and use of clean fuels that are directly derived from the use of renewable natural resources within the country, however, the potential of the nation as an exporting power is contested

D.b. Market Catch Up

D.b.i. *Market modernisation that keeps core values*
Industry experts believe that reforms to regulation will be successful in allowing public-private collaboration, but that public dominance over infrastructure will be maintained. The end result is thought to be a more modernised market, that systemically incorporates innovation, but operates in a traditional way that allows for the protection of their core values

5.2 Discussion

Following the presentation of the results, the outcomes are discussed in relation to the relevant previous literature and the research questions.

Current Readiness for the upcoming challenges

Although the IPCC's reports have stressed that changes in water availability are coming for the Central America region (IPCC, 2022), not all actors within the Costa Rican system are visibly concerned. It was commented during the interviews that ICE's planning unit was performing future climate analysis, but that it severely underestimated the impact of climate change in the energy generation capacity. This scenario could lead to a shortcoming in the planned expansion of solar energy and battery storage, and it has been highlighted that it could increase fossil fuel dependency if not identified in time.

The expansion plan document, issued by ICE, enjoys almost undisputed technical trust, which has allowed constant expansion of traditional energy projects without major setbacks. However, the increased uncertainty of both climate and technology developments are perceived to be challenging the more traditional approach to planning from ICE, and therefore the company could benefit from slight external questioning of their issued documents, specifically from technology experts and climate change scientists.

Current ruling entities of the energy market, such as ICE, ARESEP (the regulation agency), and DOCSE (the energy coordination unit within ICE) seem to have taken a reactive stance to challenges, which has been shown in their approach to distributed energy generation, and is not allocating the necessary incentives as suggested by (Varawala et al., 2021). This reactive mindset could have impacted the new governmental strategy of introducing new energy technologies through private actors, since most of the focus of the new strategy was put into current challenges, like decarbonisation of transport and industry, with only potential spill overs reaching energy generation.

Dedicating efforts, either directly or through private entities, to the understanding of future challenges in energy generation could be highly beneficial for Costa Rica. On one hand, better understanding of the future climate scenario will allow for more efficient planning, and increased testing of intermittent energy can also give insight of the impact in energy security, which has been highlighted as hard to attain only with theory (Heard et al., 2017). On the other hand, a better identification of the future problem will allow for a more assertive evaluation of technology improvements (Lema & Rabellotti, 2023), which could help set the right incentives for private entities to tackle the issue (Varawala et al., 2021).

Costa Rica as a pioneer of future technologies

As it was mentioned during the results section, the current strategy in Costa Rica for tackling energy issues relies on private entities to bring and implement technology projects, limiting public institutions to the articulation and enabling of initiatives. Although this approach is mentioned to be in accordance with the country's economic capacities, it specifically limits innovation capabilities to being a receiver of developed technologies, instead of a lead actor in their development.

The chosen path of a catch-up nation greatly addresses the second research question: "*What is the potential for emerging technologies to be applied in the Costa Rican context"*. The current energy generation scenario of the country, combined with the capabilities of the public institutions present in the country could have suggested that Costa Rica had the opportunity of taking on a leading role in research and development of technology, however, the new R&D strategies specifically limit the institutions involvement in direct technology.

Although the R&D strategy has decided to position the country in a catch-up scenario, this does not mean that potential for emerging technologies is low, just slightly diminished. If the country manages to develop the right infrastructure, implementation, and maintenance capabilities, while ensuring the correct financial incentives, Costa Rica's natural resources and strategic geographical position could lead to a high potential for emerging technologies to be applied in the market, once the uncertainty of the first tests has been cleared by projects in other countries.

Financial planning of disruptive technology projects is one key aspect that has been highlighted by policy makers, industry, and technology experts. ICE's current evaluation of technologies when considering integrations into the expansion plan clearly states the use of a "current cost evaluation", which greatly favours traditional technologies by not considering the sometimes aggressive price reduction that disruptive technologies experience over time. The use of forecasted prices and overall more updated financial evaluations in the analysis of technologies for the expansion plan, like the ones presented as better by Afful-Dadzie (2021), could open up a space for a compelling business case that levels the field between traditional and non-traditional energy generation methods. The inclusion of these forecasts in the highly renowned expansion plan could signal investors of a lower financial risk and higher possibility of project implementation, greatly increasing opportunities for emerging technologies to be applied in the country.

Ability to seize Green Windows of Opportunity

Based on the information provided by the interviewees, it is possible to assume that most of Costa Rica's key actors within the energy system are aware of the challenges ahead, and see the future scenario as opportunities that the current leader companies have to tackle with a proactive stance. This belief is also shared among highly technical actors, although they are also cautious with introducing changes that could disrupt the current system. However, there is a tendency among some managers to downplay the possible impact of climate change and intermittency in the system, considering the issue of renewable energy generation a solved matter that will not change in the future, which could greatly threaten the ability to create appropriate responses in time.

The governmental strategy of public-private collaboration for the introduction of disruptive technologies greatly addresses most of the green windows of opportunity for navigating intermittency and availability without fossil fuels, especially considering that most of literature seems to agree that technology is the way to solve these type of challenges, either by increased efficiency in clean generation, like the ones mentioned by Dumé (2023), or new clean fuels that are becoming increasingly more affordable, and could revolutionise markets with retrofittable carbon neutral technology (Kouchaki-Penchah et al., 2024).

However, there seem to be two major possible setbacks to the successful capture of green windows of opportunity through the presented strategy. The first possible setback comes from the objectives of the public-private collaboration strategy, that aims to address the challenges of decarbonisation mostly in the transport and industry sectors, and considers technology solutions for energy generation as a potential spill over, or secondary effect of achieving the main goal. The collaboration strategy is mostly focusing on the applications of "power-to-x" technology, particularly the production of green hydrogen-based fuels, which is listed as one potential replacement to the current use of fossil fuels (MAN, 2021), and therefore the chance of a positive spill over from the development of this technology to the application in energy generation is possible, but still remains a secondary priority.

The second possible setback comes from the historical preference of the Costa Rican market for public institutions over private companies, and their bias towards the internal market. The country is relatively new to public-private collaborations in this market, and in contrast to many of their neighbours, is just beginning to develop the capabilities for making it work. Regulatory changes have already been proving hard to implement, especially considering the need of the regulation agent to balance both access to opportunities to the private companies with maintaining the core values that characterise the Costa Rican system, a market that works for the people and does not give away their natural resources to privates, which relates to what was highlighted by Shahbaz et al. (2020).

Regulatory changes also need to ensure that the scale of projects is balanced adequately between the responsible use of natural resources, and a size that allows for financial gains. The Costa Rican energy system is currently considered small for many green hydrogen projects, and therefore the capability of exporting the results of the production facilities needs to be considered by regulation, which will probably be met with resistance from the general audience.

Lastly, public involvement in project financing structures needs to be improved. As it was mentioned by Smirnova et al. (2021), and Jolink & Niesten (2021), public guarantee of access to financing is a key factor in project success. The current aim of the Costa Rican government is to not get involved in the financing of projects that are property of private entities, and while caution in this context is understandable, interviewees mentioned that some guarantees needed to be given, since public institutions currently hold most of the infrastructure and decision-making capabilities of the market these projects are expected to operate in. Granting higher public involvement in private project financing could greatly reduce the financial risk, gaining access to better conditions.

The development of public-private collaboration capabilities require not only an important change in regulation, but also a change of mindset of several of the involved actors of the system, and this process could take longer than available for reaching the windows of opportunity in time, however, the strategy is somehow in line with latest research aiming to navigate electricity generation without fossil fuels.

Contribution to the research

In summary, the study of the Costa Rican electricity scenario within a green windows of opportunity framework has given empirical backing to several of the identified issues mentioned in the current research.

The current readiness of the Costa Rican institutions seems to be at a similar standpoint to the academic discussion of 100% renewable energy systems. The lack of public involvement in direct empirical tests can be seen as a symptom of the lack of research into tangible evidence of solutions to the discussion of achieving completely renewable electricity systems while preserving energy security, however, future outcomes of the Costa Rican strategy could provide valuable answers.

The country has stated their preference for proven technology, choosing a catch-up path in line to the suggestions of Lema & Rabellotti (2023), however, it has also proven to be assessing new technology opportunities in a cost based strategy, which goes in line with the issues identified by Afful-Dadzie (2021) for developing economies, as it limits the implementation of projects with longer returns on investment.

Finally, the ability to seize the identified green windows of opportunity has been shown to be limited by factors of public-private collaborations that were previously mentioned by researchers, mostly the adaptation of regulation to ensure the establishment of the right incentives, and the government participation in financing structures to reduce financial risk.

6 Conclusions

This thesis has examined the challenges and opportunities for Costa Rica, as a developing nation, to navigate intermittency and availability in electricity generation without relying on fossil fuels. Through an understanding of the country's energy market, regulatory framework, and sustainability performance, as well as insights from key stakeholders gathered through interviews, and the review of key documents, this study has highlighted the complex factors shaping Costa Rica's path towards a clean energy future.

While Costa Rica has remained remarkably successful in generating over 90% of its electricity from renewable sources, the country faces significant challenges in maintaining this performance in the face of climate change and the need to diversify its energy matrix. The increasing vulnerability of hydropower to erratic water availability, combined with the potential for rising intermittency from the expansion of solar and wind power, could threaten energy security and lead to a greater reliance on fossil fuels if not properly addressed.

The identification of this scenario raised two main research questions, the first related to *how Costa Rica can navigate intermittency and availability in electricity generation without fossil fuels as a developing nation*, and the second one related to the *potential for emerging technologies to be applied in the Costa Rican context*. An analysis of the country scenario using the green windows of innovation framework allowed for the answer to these questions.

It was found that the aforementioned identified challenges present Costa Rica with green windows of opportunity that can be seized. Institutional windows, such as the ongoing discussions around regulatory changes to allow greater private sector participation; technological windows, like the emergence of retrofittable clean energy solutions; and market windows, such as the growing demand for green hydrogen are the biggest ones, but several smaller initiatives can be drawn from them. By leveraging these opportunities through well thought sectoral systems, Costa Rica can ensure right investment conditions, enhance innovation, and build the necessary capabilities to transition to a 100% renewable electricity system without compromising energy security. As for the potential for emerging technologies, the country has adopted a catch-up strategy, putting efforts into ensuring that R&D capabilities are developed for adapting and maintaining foreign technology.

Sectoral systems within the country revealed several barriers that must be overcome to fully capitalise on these opportunities. These include the slow reaction time of public institutions to enhance regulation, the limitations imposed by the highly regulated market structure, and the focus on local solutions that may constrain the scale and impact of clean energy projects. Addressing these barriers will require a concerted effort to modernise the electricity market, develop more flexible and adaptive regulatory frameworks, and establish the right collaboration structure among public and private actors.

The insights from this study have important implications not only for Costa Rica, but for other developing countries seeking to achieve sustainable development, without compromising energy security, natural resources, or incurring elevated costs. By documenting the Costa Rican experience, this thesis contributes to a growing body of knowledge on the challenges and opportunities involved in achieving a fossil fuel-free electricity system in a developing country context.

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Appendix A: Interview Questionnaire

Interview Questionnaire

Original Document (Spanish)

Consentimiento Informado

- Recibir permiso para realizar la entrevista
  - Esta entrevista será solo usada para esta tesis, y lo conversado no será reportado directamente en el documento
  - No se realizarán grabaciones ni fotografías
  - Los nombres de los entrevistados no serán mencionados
  - Es posible retirar el consentimiento de esta entrevista en cualquier momento, incluso una vez terminada la conversación
- ¿Acepta los términos?

Introducción

- Presentación del Entrevistador:
  - Estudiante de la Universidad de Lund
  - En Costa Rica debido a convenio con CINPE
  - Estudios previos en Ingeniería, interés en energías sustentables
- Presentación del tema de investigación:
  - Investigación sobre las oportunidades que tienen las tecnologías de energía sustentable en Costa Rica
    - Bajar variabilidad
    - Aumentar disponibilidad (velocidad)
  - Amenaza climática y presencia de combustibles fósiles

Contexto del Entrevistado

- Cuéntame de ti y del área en que te desempeñas
  - Cuánta gente hay en el área
  - Con qué áreas interactúa
- Qué proyectos están trabajando recientemente
  - Por qué los seleccionaron
  - Qué efecto esperan que tengan

Sobre la capacidad fósil

- En tu opinión, que se debería hacer sobre la capacidad instalada de búnker que tiene CR actualmente
- Cómo crees que conversan los planes de desarrollo del ICE con la estrategia de descarbonización del gobierno

Sobre algunas tecnologías e inversión

- Qué ventajas crees que tiene Costa Rica para implementar innovaciones de energía sostenible en la generación
- Qué tan abierto a la inversión privada o extranjera crees que está Costa Rica
    - Cómo crees que incentiva/desincentiva el sistema regulatorio de Costa Rica con respecto a la inversión
- Hablemos sobre algunas tecnologías en particular
    - Hidrógeno verde, y su capacidad de ser usado en celdas o como combustible
    - Biocombustibles
    - Baterías eléctricas
    - Energía Nuclear

Sobre el contexto de Costa Rica

- Que barreras ves que tiene Costa Rica en este momento para implementar algunas de las tecnologías que conversamos
    - De regulación
    - Políticas
    - Inversión
- Qué ventajas crees que tiene Costa Rica para implementar innovaciones de energía sostenible

Otros temas

- Con quién más debería hablar
- Algo que quieras agregar

Preguntas Específicas para ciertos actores

Sobre el Plan de Expansión

- Cuéntame sobre el documento de la Proyección de la Demanda Eléctrica.
    - Cuáles fueron los principales objetivos del documento
    - Cómo ves que se alinea con el plan de descarbonización del Gobierno?
    - Qué tan susceptible crees que es el plan con respecto a cambios tecnológicos y/o climáticos?

La regulación del ICE

- Cuáles son las regulaciones más importantes que normal al ICE en términos de nuevos desarrollos
- Qué regulaciones hay en temas de emisiones y sostenibilidad
- Que institución fiscaliza estas regulaciones, el MINAE?

El Reporte de Sostenibilidad

- ICE reportó el 2022 emisiones de 36,5 tCO_2/GWh, a pesar de tener 98,9% renovables. En qué se ubican las principales emisiones?
- Me llamó la atención el crecimiento en Litros de combustible fósil usado en generación, de 1900 litros de búnker en 2019 a 15 millones en 2022, a qué se debe esto?

Translated Document (English)

Informed consent

- Receive permission to conduct the interview
  - This interview will only be used for this thesis, and what was discussed will not be reported directly in the document.
  - No recordings or photographs will be taken
  - The names of those interviewed will not be mentioned
  - It is possible to withdraw consent from this interview at any time, even after the conversation has ended.
- Do you accept the terms?

Introduction

- Interviewer Presentation:
  - Lund University student
  - In Costa Rica due to agreement with CINPE
  - Previous studies in Engineering, interest in sustainable energies
- Presentation of the research topic:
  - Research on the opportunities that sustainable energy technologies have in Costa Rica
    - Lower intermittency
    - Increase availability (speed)
  - Climate threat and presence of fossil fuels

Context of the Interviewee

- Tell me about yourself and the area in which you work
  - How many people are there in the area
  - What areas does it interact with?
- What projects are you working on recently?
  - Why were they selected?
  - What effect do you expect them to have?

About fossil capacity

- In your opinion, what should be done about the installed fossil fuel capacity that CR currently has?
- How do you think ICE's development plans relate to the government's decarbonization strategy?

About some technologies and investment

- What advantages do you think Costa Rica has to implement sustainable energy innovations in generation?
- How open to private or foreign investment do you think Costa Rica is?
    - How do you think Costa Rica's regulatory system incentivizes/disincentivizes investment?
- Let's talk about some technologies in particular
    - Green hydrogen, and its ability to be used in cells or as fuel
    - Biofuels
    - Electric batteries
    - Nuclear energy

About the context of Costa Rica

- What barriers do you see that Costa Rica has at this moment to implement some of the technologies that we discussed?
    - Regulation
    - Policies
    - Investment
- What advantages do you think Costa Rica has to implement sustainable energy innovations?

Other themes

- Who else should I talk to?
- Something you want to add

Specific questions for certain actors

About the Expansion Plan

- Tell me about the Electricity Demand Projection document.
    - What were the main objectives of the document
    - How do you see it aligning with the Government's decarbonization plan?
    - How susceptible do you think the plan is with respect to technological and/or climate changes?

ICE regulation

- What are the most important regulations that come to ICE in terms of new developments?
- What regulations are there on emissions and sustainability issues?
- What institution supervises these regulations, the MINAE?

The Sustainability Report

- ICE reported emissions of 36.5 tCO_2/GWh in 2022, despite having 98.9% renewables. Where are the main emissions located?
- The growth in liters of fossil fuel used in generation caught my attention, from 1900 liters of bunker in 2019 to 15 million in 2022, what is the reason for this?