SCHOOL OF
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The emergence of green hydrogen in Costa Rica

A case study examining the impediments and opportunities to decarbonize the energy and transport sector

Abstract

Tropicalizing a technology entail adapting it to a tropical climate. This paper analyzes how an innovative solution for decarbonization – the green hydrogen - is introduced to Costa Rica. This research examines a niche trying to enter a sector under construction, contributing to the growing literature about this emerging sector. This thesis deeply examines the green hydrogen niche, building an innovation biography to depict the barriers and enablers this niche faces. The energy and transport sectors are analyzed in detail to determine path dependencies. The research design is a case study, and data are gathered through semi-structured interviews conducted by the researcher in the field. Evidence suggests that Costa Rica's energy and transport sectors present difficulties for path-breaking innovations like green hydrogen, but it also presents some promising windows of opportunities.

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List of terms and acronyms

- ACH2: Asociación Costarricense por el Hidrógeno (Costa Rican Hydrogen Association)
- ACOPE: Asociación Costarricense de Productores de Energía (Costa Rican Association of Energy Producers)
- ARESEP: Autoridad Reguladora del Estado (State Regulatory Authority)
- ARIAE: La Asociación Iberoamericana de Entidades Reguladoras de la Energía (The Ibero-American Association of Energy Regulatory Entities)
- CINPE: Centro Internacional de Política Económica para el Desarrollo Sostenible(International Center of Economic Policy for sustainable development)
- GHG: Greenhouse Gas Emissions
- GH2: Green Hydrogen
- GIS: Global Innovation Systems
- GIZ: Deutsche Gesellschaft für Kechiche Zusammenarbeit
- ICE: Instituto Costarricense de Energía (Costa Rican Energy Institute)
- IDB: International Development Bank
- NDC: National Determined Contribution
- MLP: Multi-level perspective
- PV: solar photovoltaics
- RECOPE: Refinadora Costarricense de Petróleo (Costa Rican Oil refinery)
- TIS: Technological Innovation Systems
- SIEPAC: Sistema de Interconexión Eléctrica de los Países de América Central (Electrical Interconnection System of the Central American Countries)
- SNM: Strategic Niche Management framework

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1. Introduction

1.1. Background

"The Anthropocene provides an independent measure of the scale and tempo of human-caused change – biodiversity loss, changes to atmosphere and ocean chemistry, urbanization, globalization - and places them in the deep time context of Earth history." (Steffen et al., 2011, p.755).

Nowadays, we live in this geographic epoque, where human-dominated landscapes have affected nature at every scale. Rockström et al. (2009) describe *planetary boundaries* that allow humanity to evolve safely, but they require urgent climate action and firm commitments. These boundaries determine thresholds at multiple scales that would trigger abrupt environmental changes if ever surpassed. The authors emphasize the need to keep the CO2 concentration in the atmosphere below 350 parts per million (ppm) to tackle climate change and operate safely. In line with these assumptions, it is vital to foster urgent climate action to avoid surpassing the so-called "*tipping points,*"; but how? Where do we start? A valid starting point relies on the decarbonization of the economy.

Most countries' Greenhouse Gas Emissions (GHG) result from their heavy reliance on fossil fuels. Recent events like the Russian invasion of Ukraine have shown the economic drawbacks that this source entails for its price volatility. The Paris Agreement's central aim is to strengthen the global response to face climate change by committing to keep global temperature below 2 degrees Celsius. This multilateral agreement translates into Nationally Determined Contributions (NDC) per country, which allow for drafting roadmaps and decarbonization plans. The urgency led scholars to focus on finding innovative solutions to reach net-zero goals. Following the vital research agendas in the field, this paper chose Costa Rica as the context for its exemplary sustainable economic development.

Costa Rica is a small upper-middle-income country with firm environmental commitments and a remarkable green reputation. Hence, in line with its NDC, Costa Rica launched a holistic National Decarbonization Plan (2018) touching upon multiple sectors and entailing innovation efforts to reach carbon neutrality in 2050. With almost 100% of its energy coming from renewable sources, Costa Rica's most emitting sector is transport, so most innovative solutions are related to mobility and energy sectors. Biofuels, electric vehicles, carbon capture, and storage are all these initiatives that emerge to foster decarbonization, and Costa Rica is now exploring the opportunities of green hydrogen. Multiple projects have analyzed this technology from a practical standpoint. However, there is a clear gap in the literature in understanding how these new industries emerge and how- as niche innovations- they are enabled and constrained by existing systems. This thesis examines the emerging role of green hydrogen in the decarbonization of Costa Rica, with particular attention to the regime level. This thesis consists of four themed chapters: Literature Review, Data and Research Methods, Results and Discussion, and Concluding remarks.

1.2. Research Aim

This paper aims to trace the emergence of green hydrogen as an innovative niche for Costa Rica's decarbonization process by looking at this innovation biography. To this end, data is gathered in the field to gain a deeper understanding of the components of Costa Rica's green hydrogen niche to identify its key actors and how they interconnect. The researcher visited Costa Rica for an Innovative practice in collaboration with The International Center of Economic Policy for sustainable development (CINPE). This research centre belongs to Universidad Nacional de Costa Rica. The overarching research question that guided the research is:

How is the Costa Rican energy sector shaping the development of green hydrogen?

For a better understanding and to make more accessible the analysis, the three sub-research questions are suggested:

- *How can Green Hydrogen contribute to decarbonizing Costa Rica?*
- *What are the main barriers for green hydrogen to scale up?*
- *How can green hydrogen be managed to "unlock" the socio-technical system?*

1.3. Motivation and contribution

As indicated in the introduction, one of the most significant challenges humanity faces is climate change, which makes it essential that researchers work together to find potential solutions to face it. As decarbonization is one of the mechanisms to do this, exploring how innovative solutions like green hydrogen can contribute to decarbonization is of paramount importance. Green hydrogen is now in the spotlight as it is a critical component that could play a key role in decarbonization efforts. This paper may contribute to the small but growing body of literature in the field by adding perspectives from a specific context where technology is emerging. The research has focused on engineering and pure economy rather than innovation and sustainability transitions, so this paper includes a crucial perspective in the field. For instance, the theories that explain how innovations can develop in emerging sectors like clean tech are scarce. Thanks to this study, the researcher explores the theoretical standpoints that may have explanatory power for understanding how green hydrogen could decarbonize specific sectors and challenge the existing systems. In addition, as the draft of Costa Rica's green hydrogen roadmap is ongoing design, this research may add valuable insights for policymakers.

2. Literature Review

As discussed in the introduction, decarbonization requires profound transformations of various industries. Due to their importance as sources of CO2, the energy sector and the mobility sector are usually central pieces of national decarbonization strategies. Many theories explain how institutions, society, and market dynamics shape the way industries transform. Indeed, most analyses of sectoral transformations tend to focus on mature sectors and fail short explain how innovations can develop in emerging sectors. This section revisits the existing work in innovations for decarbonization (eco-innovations) and green hydrogen as an example.

2.1. Sustainability Transitions

Evolutionary economists tend to perceive innovation as crucial for economic growth, and hence eco-innovations as the key to sustainable development. Evolutionary economists tend to perceive innovation as crucial for economic growth, and hence eco-innovations as the key to sustainable development. Nevertheless, innovations can also be essential for sustainability transitions. The term eco-innovation refers to innovations aimed at greater environmental sustainability. Cecere, Corrocher, Gossart & Ozman (2014) remark that eco-innovations can potentially reshape technological trajectories in multiple industries. Meanwhile, sustainability transitions do not happen overnight, as innovations confront path dependency. To explain the mechanisms that foster these transitions, Geels (2002) proposed the "Multi-Level Perspective" (MLP) framework, where the author distinguished three key levels: (1) the socio-technical system, (2) niche innovations, and (3) the landscape.

This thesis uses these three analytical levels, mainly focusing on the niche and regime levels. Geels (2002) defines niche innovations as those with the potential to make radical changes in the existing dominant system. Meanwhile, the regime or socio-technical system; tends to be stabilized by lock-in mechanisms, which are discussed next in detail. Finally, the exogenous landscape is what Geels (2002) perceives as the determinant of changes; shocks can destabilize the system and let niche innovations break the regime. The author explains that transitions occur when these three levels are aligned. In a later publication, Geels et al. (2017) contextualized this framework in line with net-zero goals. He claimed that transitions could be accelerated by (1) increasing the momentum of niche innovations, (2) weakening the existing systems, and (3) strengthening exogenous pressures. As explained next, a few scholars have analysed each of these processes in the decarbonization context.

Regarding the niche, Jin and Mckelvey (2019) focused on promoting the niche of new energy vehicles in China, and Galvan (2021) analyzed the green hydrogen niche in Costa Rica. Using Ruggiero et al. (2018) framework: "Strategic Niche Management, " they analyzed this case." This theory tackles the gap between R&D and market introduction. The authors pointed out how to enhance niches' scaling-up by three interrelated processes: (1) expectations should be met, (2) social networks must expand, and (3) the learning processes need to enhance.

Regarding weakening the existing system first, it is crucial to describe the system itself clearly. Traditional evolutionary economists focused on different analysis scopes: national, regional, sectoral, and technological innovation systems. In the field of decarbonization, many scholars opted to focus on technological innovation systems (Hacking, Pearson & Eames (2019); Suurs, Hekkert, and Smits (2009); Bach et al., (2020)) and sectoral innovation systems (Koasidis et al. (2020) as a framework. Decarbonization seems to present interdependences across different parts of technological systems, but mainly in the transport and energy sectors. These frameworks allow depicting the features that define how innovation systems are compound but to identify how to weaken the existing system, it is crucial to determine what factors impede development. To this end, Cecere et al. (2014) refer to a set of categories that tend to cause lock-in and path dependence within sectors. The authors assure that eco-innovations face substantial barriers to escape from pollution-intensive technologies, which are consistently reinforced by the existing paradigm (Bento, 2010; Dijk et al.,2011).

The third process mentioned is related to exogenous landscape pressure, which most scholars recognize as a source of acceleration for decarbonization with events like climate change, electricity prices, or oil instability (Suurs, Hekkert & Smits, 2009). Nevertheless, for the matter of decarbonization, there are multiple sources of path dependency and inertia at a sectoral level (Bach et al., 2020)

Except for Schot and Geels (2008), the conditions that allow niches to destabilize regimes through windows of opportunities- niches can destabilize regimes, have not been widely discussed in the literature. Here we refer to when and how particular windows of opportunity might emerge. In this respect, a look into the literature on windows of opportunities concerning more significant socio-technical transitions and catching-up processes can bring some exciting dimensions to the discussion. The following section provides a deeper analysis of this notion.

2.2. Windows of opportunity

Perez and Soete (1988) coined the term "*Windows of opportunities,*" referring to the conditions that result from discontinuities in the existing system, which allow latecomers to enter an industry. The authors perceive that the gap between latecomers (niche actors) and incumbents (regime actors) narrows down with new techno-economic paradigms. Multiple scholars in the field claim that these *windows* differ across industry types (Binz, Gosens Yap, and Yu, 2020; Malerba and Nelson, 2011; Lee and Malerba, 2017), but literature also shows that sectoral particularities tend to be scarce. Remarkably, Lee and Malerba (2017) combine this notion with Sectoral innovation systems and distinguished technological, demand, and institutional dimensions that may emerge during the lifetime of industries within a sector. The authors perceived these discontinuities as a tool for firms and countries to become industry leaders, a dynamic process called "catch-up cycles." Under these assumptions, latecomers would manage to catch up depending on the type of windows opened and how the key players in the system respond to these changes. Most scholars have used this framework for mature sectors (i.e., Malerba and Nelson,2011), but these dimensions are present in emerging sectors. As a result, the mechanisms that technological innovations follow to catch up in emerging sectors remain under-specified.

Recent studies have attempted to analyze the industrial dynamics followed by emerging sectors, giving special attention to clean-tech and renewable energies, in line with this paper's focus. Binz and Truffer (2017), Binz, Gosens, and Yu (2020), and Gosens, Gilmanova, and Lilliestam (2021) stand out as the most updated researchers on clean-tech innovation dynamics. Binz and Truffer (2017) used their framework "Global Innovation Systems" (GIS) to evaluate innovation systems in four specific clean-tech sectors: solar photovoltaic, wind power, carbon capture storage (CCS), and electric car industries. The authors claim four determinants: legitimation, market formation, investment mobilization, and knowledge creation. In a later publication, Binz, Gosens Yap, and Yu (2020) made a deeper analysis of four clean-tech sectors and found that the speed and disruptiveness of early leadership differ due to the distinct innovation and valuation processes per industry. The authors attributed these features to the ability to exploit different windows of opportunities; for example, solar photovoltaics presented broader opportunities than wind power due to different innovation modes. In a similar vein, Schmidt and Huenteler (2016) analyze how life-cycle patterns differ between two specific energy sources: solar photovoltaics (PV) and wind power. In the first case, when PV emerged, it rapidly became a mass-produced good, whereas wind power followed a complex product cycle.

Overall, there is a lack of consensus about the catch-up cycles that sectors follow in their early stages, which is when they still constitute a *niche* in the market. Ruggiero, Martiskainen, and Onkila (2018) proposed the Strategic Niche Management framework (SNM) to identify scaling-up solutions for community energy systems. SNM theory emerged to explain why sustainable innovations struggle to enter the market. How can niches become path-breaking? This process is referred to as "scaling-up," and it occurs when the niche becomes global thanks to the interaction of local projects (Geels and Raven, 2006). Raven et al. (2016) pointed out that broad networks can be a solution for niche evolution when all the actors are committed and internally aligned.

This research builds on Gosens, Gilmanova, and Lilliestam's (2021) work, which analyzed how windows of opportunities differ between mature and emerging clean-tech sectors. The authors consider a sector to be formative (or in formation) if technological alternatives remain a significant competitor; institutions are yet to be formalized, and market entry is low. These studies allow a better understanding of how emerging sectors can take advantage of windows of opportunity to "catch up" the leading industries in a certain way. However, the studies referring to specific sectors remain scarce. This thesis focuses on green hydrogen, which seems to be a formative sector[1], so Gosens Gilmanova and Lilliestam (2021) were used as a theoretical framework. However, windows of opportunity are used differently in this case, following Yap and Truffer's (2019) idea of endogenizing them. The authors conceived this process as translating global opportunities and threats into internal drivers of technological trajectories. Hence, this paper aims to explain how Costa Rica can face regime path dependence in terms of decarbonization; by integrating the windows of opportunity that could open for the green hydrogen niche.

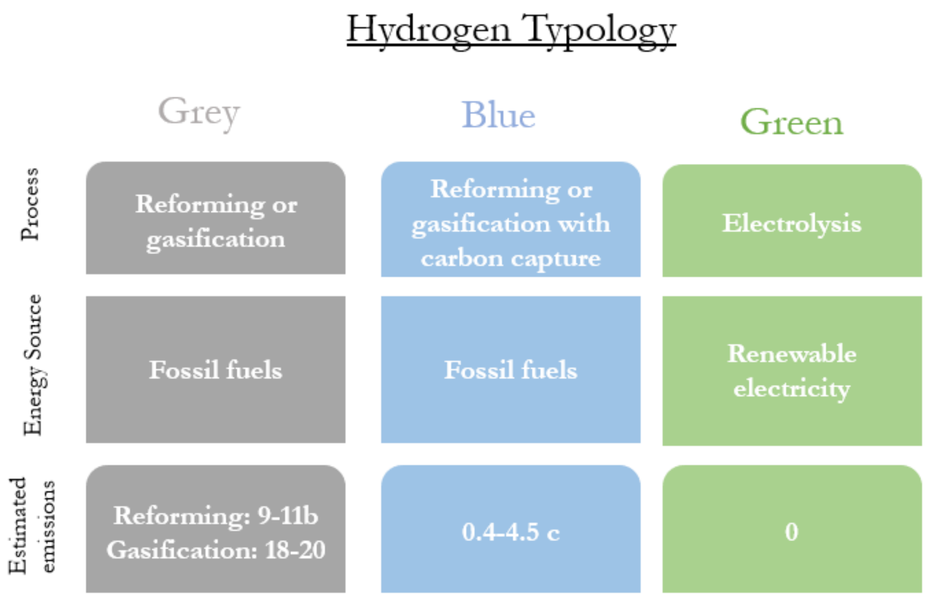
[1] The term "Formative sector" is interchanged with "emerging sector" along the text; both referring to a sector that is still under construction.

2.3. Green Hydrogen

2.3.1. Definition, usage, and challenges

One of the main innovations with the potential to decarbonize the economy is green hydrogen. Hydrogen is the most abundant element in the universe - found in standard compounds such as water or fossil fuels- and it is a proven energy carrier for energy transport and storage (IRENA, 2019). As a gas, hydrogen is transparent, so what makes it green? The mechanism used to produce hydrogen explains its classification as grey, blue, or green hydrogen (Nelson et al., 2020). *Figure 1* presents the differences between them, considering the estimated emissions that their production led to. Hydrogen is denoted as *green* or *clean* when the electrolysis (separation of water into hydrogen and oxygen atoms) to produce it is powered by renewable energy sources such as wind or solar power (IRENA,2022). As a result, green hydrogen (GH2) is carbon neutral, which explains why it has gained attention. Even if GH2 production is limited, there is an increasing interest worldwide to accelerate and scale up this energy source.

Figure 1: A selected colour-code typology of hydrogen production



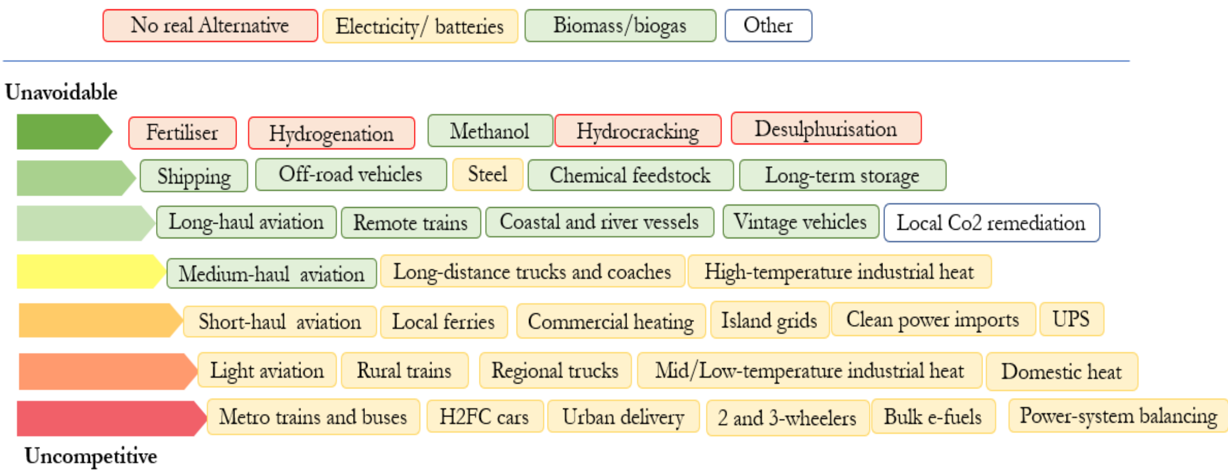
Source: Adapted from IRENA (2019)

Regarding the practical use of hydrogen, several sectors could improve thanks to this technology. IRENA (2019) determines all the potential uses of hydrogen, distinguishing it as a chemical feedstock (oil refining, ammonia synthesis, and methanol production), as a fuel (fuel cells for electric vehicles), and as a source of heat (when burnt). Nelson et al. (2020) emphasize that the benefits of green hydrogen overcome its costs. They conceive that apart from reducing GHG, it can create jobs, reduce waste, diversify fuels, repurpose infrastructure and prevent renewable curtailment. The latter refers to the renewable energy waste derived from market fluctuations, where GH2 could enable 100% utilization by storing the surplus.

To better understand how green hydrogen can be implemented, Liebreich (2021) proposed the "*Clean Hydrogen Ladder*", compiling multiple sources to build a tool to visualize how the use of green hydrogen could be prioritized in terms of feasibility. There is a lack of consensus about when GH2 is more efficient than other technologies, but what is clear is that it needs to find a way to enter the economy and become competitive. As shown in Figure 2, Liebreich (2021) located GH2 as the only alternative for chemicals and processes (i.e., fertilizers), long-term storage, and transport are outstanding. For the latter, green hydrogen is better for off-road, shipping, and aviation rather than private vehicles.

Meanwhile, Agora Energiewende (2021) perceived long-haul aviation, maritime shipping, and renewable energy backup as the leading sectors for GH2 to succeed.

Figure 2: The Clean Hydrogen Ladder



Source: Author's elaboration, based on Liebreich (2021)

This case study focuses on GH2 use for transportation, so Table 1 presents the different subcategories that can be used, including the demand perspectives, opportunities, and challenges for future deployment. Based on *IEA (2019),* this table suggests that the highest expectations are on heavy-duty vehicles and shipping. Cost appears to be the differentiating factor of using hydrogen compared to alternatives, followed by volume and efficiency issues. Nelson et al. (2020) explain that GH2 suits better transports requiring rapid fueling, long distances and large charges. Hence, the authors believed that trucks and buses could use GH2 to alleviate electric pressure; but they are hard to decarbonize, especially in marine shipping and aviation.

Table 1: Potential uses of hydrogen and derived products for transport applications.

	Current role	Demand perspectives	Future deployment	
			Opportunities	**Challenges**
Cars and vans (light-duty	11 200 vehicles in operation, mainly in California, Europe, and Japan	The global car stock is expected to continue to grow; hydrogen could capture a part of this market	**Hydrogen**: - Short refuelling time - Less weight added for energy stored - zero tailpipe emissions - Fuel cells could have a lower material footprint than lithium batteries - Overcome low utilization of refuelling stations Long-distance and heavy-duty are attractive	**Hydrogen**: -Initial low utilization of refuelling stations raises fuel costs -reductions in fuel cell and storage costs needed -efficiency losses **Power-to-liquid**: -Large electricity consumption + high production costs **Ammonia**: -limited to professional operators
Trucks and buses (heavy-duty vehicles)	Demonstration and niche markets: (25 000 forklifts, 500 buses, 400 trucks, 100 vans). Several thousand buses and trucks are expected in China* by the end of 2019	Strong growth segment: long-haul and heavy-duty applications are attractive for hydrogen		
Maritime	Limited to demonstration projects for small ships and onboard power supply in larger vessels	Maritime freight activity is set to grow by around 45% by 2030. 2020 air pollution targets and 2050 greenhouse gas targets could promote hydrogen-based fuels	**Hydrogen** and **ammonia** are candidates for both national action on domestic shipping decarbonization and the IMO GHGs Reduction Strategy, given limitations on the use of other fuels	**Hydrogen**: Higher storage cost **Hydrogen/ammonia**: cargo volume lost due to storage (lower density than current liquid fuels)
Rail	Two hydrogen trains in Germany	Rail is a mainstay of transport in many countries	**Hydrogen** trains can be most competitive in rail freight (regional lines with low network utilization and cross border freight)	**Rail** is the most electrified transport mode; hydrogen and battery electric trains with partial line electrification are both competitive substitutes
Aviation	Limited to small demonstration projects and feasibility studies	Fastest-growing passenger transport mode. Large storage volume and redesign would be needed for pure hydrogen, making power-to liquid and biofuels more attractive for this mode	**Power-to-liquid:** Limited changes to status quo in distribution, operations, and facilities; also maximizes biomass use by boosting yield **Hydrogen**: Together with batteries, they can supply on-board energy supply at ports and during taxiing	**Power-to-liquid**: Currently 4 to 6 times more expensive than kerosene, decreasing to 1.5–2 times in the long-term, potentially increasing prices and decreasing demand.

Source: Author's elaboration using content from IEA (2019)

The GH2 hype encompasses high expectations for multiple applications, but it also comes with challenges. Velazquez Abad and Dodds (2020) perceived standardization problems and emphasized the need to ensure hydrogen's "green" origin. Moreover, GH2 production entails safety issues due to its extreme flammability, making this molecule's store and transport problematic (Energy Transition Commission, 2021). Bottorff (2022) remarked that hydrogen use as a power source implies energy conversion losses, water losses, and nitrogen oxide emissions (a harmful pollutant). Hence, it appeals to be less efficient than direct electrification. All these challenges should be kept in mind for the deployment of green hydrogen projects, especially in the growing phases. Overall, GH2 is perceived as a technology with the potential to decarbonize what electrification does not reach. Robinious et al. (2017) emphasized that decarbonization requires a holistic transformation across sectors, so GH2 is a tool for sector coupling. It would allow the transport, heat, electric, and industrial sectors to benefit from renewable energy surplus.

Regarding GH2 prospects, it seems to be a core element of future economic structures (Brandon and Kurban, 2017) and the geopolitical landscape (IRENA,2022). From the economic perspective, green hydrogen presents potential synergies with alternative low-carbon technologies that would lead to cost-effective decarbonization (Brandon and Kurban, 2017). At the same time, locally producing alternative fuels would improve energy security and reduce reliance on oil price volatility, thereby reducing import costs (Jimenez et al., 2020). From a geopolitical point of view, energy sources have consistently increased countries' bargaining power while shaping international relations. Likewise, hydrogen aspires to enter international trade as a commodity, starting a significant energy carrier that would reshape value chains, creating opportunities for other countries and eventually changing the spatial distribution of industrial activities (IRENA, 2022).

2.3.2. Green hydrogen and energy transitions

While the previous section introduced the concept of green hydrogen, the current section aims to review existing literature about GH2's potential for sustainability transitions. Few studies have systematically investigated how lock-ins in specific sectors affect green hydrogen development. Oltra and Saint Jean (2009) and Bento (2010) associated the lack of market penetration of fuel cell cars with the perception of technology unreadiness and the lack of existing infrastructure. Noailly (2007) named the arguments given by car manufacturers to reject fuel cell engines as the "*chicken-and-egg problem*",; arguing that infrastructure should be cheap without considering that demand needs to increase equally for prices to decrease. Bento (2010) analyzed the critical arguments that block investment in hydrogen, enhance “carbon lock-in,” and delay innovation market introduction. The author adds that fuel cells and hydrogen face more difficulties as it is perceived to be disruptive.

GH2 may gain supporters by reducing costs, improving equipment’s efficiency (especially electrolyzers) and fully developing its value chain commercially (IEA, 2019). To this end, innovation efforts and strategic planning are essential. The first step regarding research efforts may be gathering lessons from previous transitions of innovative vehicles entering the socio-technical system. A starting point would be the literature analyzing electric vehicle diffusion mechanisms (Dijk, Kemp, and Valkering, 2011) or the different innovation frameworks that could apply (Jin and McKelvey, 2019). However, the literature linking innovation efforts and green hydrogen development remains scarce; previous studies concentrate on engineering and chemistry. For example, Chapman et al. (2019) analyzed GH2 potential for decarbonization under different temperature scenarios. Some social scientists analyzed green hydrogen using the “Technological Innovation Systems” (TIS) (Bach et al.,2020; Hacking, Pearson, & Eames, 2019; and Suurs, Hekkert, & Smits, 2009). These authors used it to analyze green shipping (Bach et al.;2020), hydrogen fuel cells evolution in the UK (Hacking et al.,2019) and the Netherlands (Suurs et al., 2009).

Moreover, the role of stakeholders’ expectations and Gh2 differing discourses caught scholars’ attention (Bakker & Budde,2012; Bellaby & Clark, 2014; and Budde, Alkemade & Weber, 2012). Stakeholders’ expectations can accelerate or slow down the GH2 niche development (Budde, Alkemade & Weber, 2012), so it is crucial to identify the factors that shape outlooks. Bellaby & Clark (2014) identified different concerns across age cohorts, and Bakker & Budde (2012) distinguished different stages of expectations across stakeholders. Even though its cost and safety issues are still a concern (Bellaby & Clark, 2014), there seems to be a technological *hype* regarding green hydrogen potential. Budde, Alkemade & Weber (2012) insisted that stakeholders’ perceptions about GH2 ability to reshape the energy system could lead them to engage in the technological trajectory. Bakker & Budde (2012) added that the technological hype triggers actors, funding, and favourable regulations.

Researchers have captured the different dynamics that may explain the success or failure of green hydrogen, and as Geels (2017) always insists: “there is no *one-size-fits-all* blueprint for accelerating low carbon transitions”. Several countries have entered the green hydrogen race worldwide, and each of them seems to present a different discourse. The front-runners are

China, the United States, India, Japan, the European Union, and the Republic of Korea (HINICIO, 2021). Chile seems to be the leading country in the Latin American context, with high ambitions to produce and export the cheapest green hydrogen by 2030 (IEA, 2019). There are multiple countries in Central and Latin America with similar conditions, so they might be able to learn from their neighbour. This paper is focused on Costa Rica to identify country-specific dynamics.

2.4. Green hydrogen transitions in Costa Rica

The body of literature concerning Costa Rica's energy sector concentrates on energy transitions (Notten, 2006; Vargas-Alfaro, 2015), the monopolistic structure of their system (Vargas and Otoya, 2003) and its rural electrification scheme (Richmond-Navarro et al., 2019).

The primary energy source for excellence in Costa Rica has always been hydropower, although the matrix has become more diverse through the years. For instance, in 1995, law 7200 was modified to entitle new actors to produce renewable energies like geothermal, solar, or wind power. This reform was supposed to lead to drastic changes, but the production of alternative sources did not gain much importance. Vargas (2002) conceived that clean energy sources compound a cluster, limiting development by an old-fashioned sectoral structure. Avendaño Leadem & Sánchez (2019) conceived that the system's lock-in was due to path dependencies, as even when alternative energy sources were more efficient, hydropower always remained a priority. Vargas (2002) suggested four ways to trigger alternative energies: (1) green energy procurement policies; (2) public-private knowledge transfer; (3) an independent regulatory office; and (4) solid informal networks. There is a relatively small body of literature to fight this sector's existing lock-ins.

A few studies have analyzed Costa Rica's mobility sector and decarbonization. John and Derkosh (2022) hold that transportation presents path dependencies, which is why the use of fossil fuels is also locked in the system and is difficult to substitute. Concerning how it can affect decarbonization. Likewise, Godinez-Zamora et al. (2020) and Vargas (2016) concluded that deep decarbonization requires intensive electrification of the transport sector using renewables. Additionally, introducing alternative fuels such as Diesel LPG Hybrid, natural gas, Diesel-natural gas hybrid, and electric is crucial, while Murillo (2007) suggested biofuels instead. While green hydrogen is an alternative option, scholars have not analyzed this technological innovation in the Costa Rican context except Galvan (2021). What deserves further investigation is the dynamics followed by each of these innovative solutions to define how to make them path-breaking. John and Derkosh (2022) claim that to foster low-mobility innovations in Costa Rica, knowledge-sharing networks shall be fortified through stronger industry-academia collaborations, which Pisu and Villalobos (2016) perceived as the main impediment to electric vehicles becoming path-breaking. Hence, this case study will contribute by gathering various perceptions of green hydrogen.

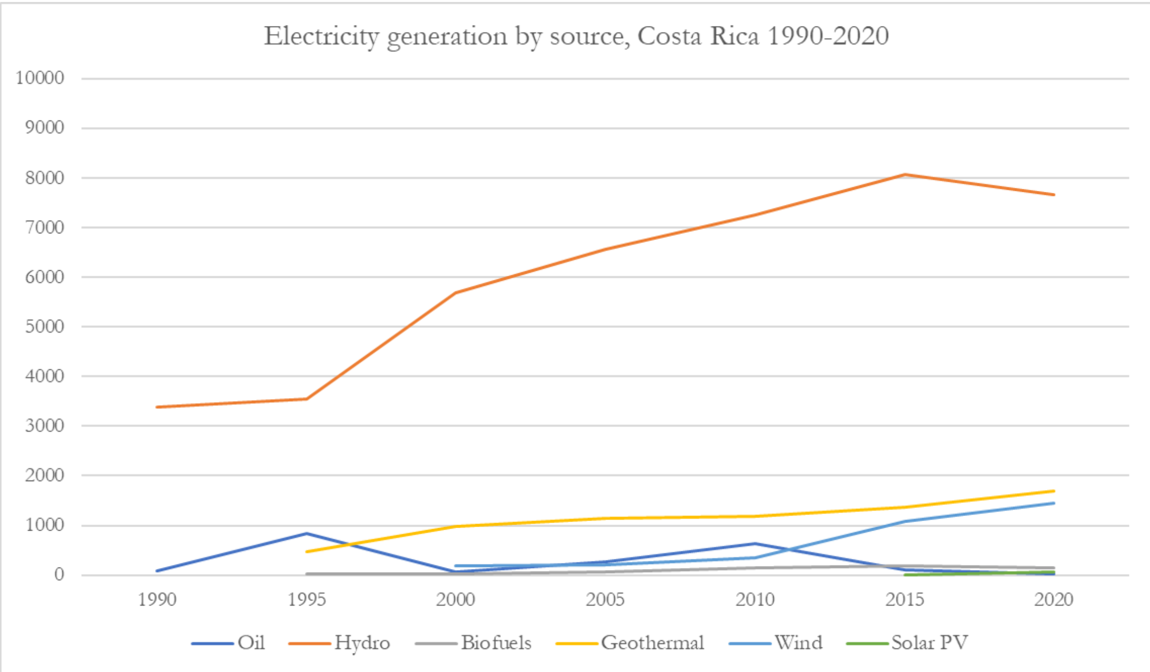
Costa Rica aims to use green hydrogen to decarbonize the transport sector. In 2011, the firm Ad Astra Rocket launched a pilot project to produce green hydrogen to power fuel cell vehicles (Ad Astra,2022), starting a *niche* that caught the attention of a few authors (Galvan,2020; Salazar, 2020). This study aims to contribute to this growing area of research by exploring the potential opportunities that this emerging niche could use to scale up this technology toward the net-zero national target and its potential applications to the decarbonization of the mobility sector in Costa Rica.

3. Context

3.1. The energy sector in Costa Rica

Costa Rica is a leading country in renewable energies; in 2021, its electricity was 99,92% sourced from renewable energy, presenting similar figures for the sixth year in a row (CENCE,2021). According to the International Energy Agency's (2020) latest figures and in line with Figure 3, Costa Rica produces electricity mainly from hydropower, followed by geothermal and a smaller percentage of wind and solar power. It seems that fossil fuels have lost relevance during the last few years, reaching values close to zero in the last year. Even if the energy matrix is almost wholly based on clean energy sources, it lacks diversification. The excessive dependence on hydropower could be problematic due to the rainfall fluctuations that result from climate change (Loría et al., 2017).

Figure 3: Total energy supply (TES) by source, Costa Rica 1990-2019

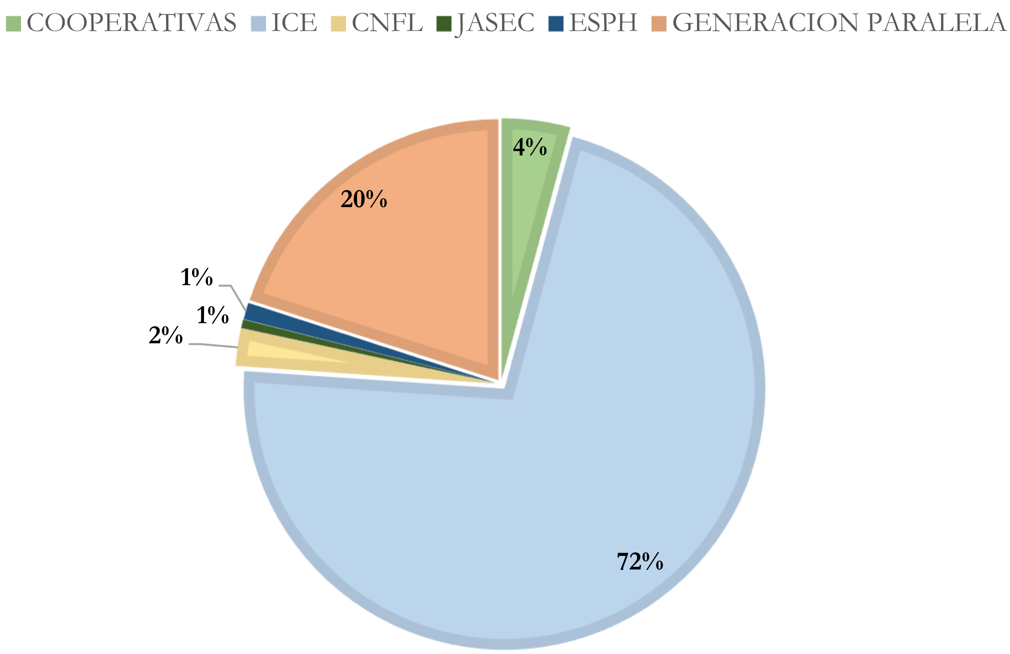


Source: Author's elaboration using International Energy Agency (2020) data

Analyzing the energy sector is particularly challenging as it involves multiple stakeholders on both the supply and the demand side. From the supply side, it is important to distinguish different stages: (1) Electricity generation, (2) transmission, and (3) distribution. Costa Rica's electric sector is centralized, there are two state-owned companies that domain the market:

the *"Instituto Costarricense de Electricidad" (ICE)* and *Compañía Nacional de Fuerza y Luz (CNFL*), a subsidiary of ICE under the so-called *ICE* Group (Loría et al., 2017). *ICE* is a vertically integrated monopoly, controlling the generation, transmission, and distribution grids through a non-competitive regime (IRENA, 2019). Figure 4 shows how the electricity production is distributed per company in Costa Rica, showing the latest data available, from the seco[nd] trimester of 2020, from the Ibero-American Association of Energy Regulatory Entities (ARIAE). In line with the figure, ICE generates 70% of the electricity; and the 30% left belongs to two municipal-owned companies (JASEC, ESPH), four large cooperatives (Coopeguanacaste, Coopesantos, Coopelesca, and Coopealfaroruiz) and around 30 private firms gathered in the Costa Rican Association of Energy Producers (ACOPE) (ARIAE, 2020). The role of cooperatives has been critical in ensuring access to electricity for all Costa Ricans living in rural areas. Madriz-Vargas (2016) analyzed how relevant these entities have been for rural electrification. They helped overcome obstacles in offering off-grid renewable energy in remote areas while encouraging social integration, end-user education, and local maintenance capabilities.

Figure 4: Monthly comparison of GWH energy production by company (2nd trimester 2020)



Source: Author's elaboration using *ARIAE (2020) data*

In terms of transmission, Loría et al. (2017) consider ICE a natural monopoly. It is the only institution in charge of the transmission grid's operation, construction, maintenance, and expansion. Noteworthy, the authors remark on the role of a central American transmission grid, "*Sistema de Interconexión Eléctrica de Los Países de América Central*" (SIEPAC), which connects Costa Rica to its neighbouring countries, allowing to resell energy surpluses. Finally, in the commercialization and distribution stage, ICE is dominant, but cooperatives significantly benefit from each other. The electric sector has a strict and complex regulatory framework that will be analyzed later.

The country's fossil fuel sector is also centralized; in this case, the "*Refinadora Costarricense de Petróleo* " (RECOPE) is the monopoly in charge of oil imports and distribution. Founded in 1961, RECOPE is in charge of allocating imported fossil fuels- in the form of end-use products- received from big producers like the United States (RECOPE,2016). The most demanded end-use products are diesel and gasoline, but they are now reaching skyrocketing prices. ICAP (2021) claimed that the country's institutional architecture of the market disrupts even more hydrocarbon prices. Almost 80 % of those products are consumed in the transport sector, followed by the industry sector (IEA,2019). Costa Rica is ranked first in Central America in the use of private vehicles, with an average of 175 passenger cars per 1000 people (Helgi Library, 2021). Transportation is the most emitting sector, 5.7. million tons of CO2 are emitted by the national transport sector (Ritchie and Roser, 2020), accounting for more than 40% of the total emissions (Our World in data,2021).

4. Data and Research Methods

4.1. Research Design

A qualitative research design guided the research procedures of data collection and analysis by analyzing the different components of the Costa Rican energy system and its role in enabling or impeding the emergence of green hydrogen as a niche. According to Denzin and Lincoln (2018), qualitative researchers "*study things in their natural settings, attempting to make sense of, or interpret, phenomena in terms of the meanings people bring to them*" (2000:3). Henceforth, this study opted for a qualitative research design as it aims to interpret the different perspectives of stakeholders regarding the emergence of green hydrogen in Costa Rica. Considering how underexplored green hydrogen is, a case study seems the best option. Ritchie (2003) argues that case studies gather multiple perspectives together while rooted in a unique context which is crucial for the comprehension of the researched phenomena (p.76). Flick (2018) adds that the subject of study could be persons, social communities, organizations, or institutions. Under these assumptions, a single case study fully suits this paper, as the aim is to explore a new phenomenon where there is not much information available. This is the case with emerging technological niches like green hydrogen in Costa Rica. The goal of case studies is associated with exploring, testing existing theories, and developing new theories under repeated patterns. The research aim of this paper is to both explore and test emerging theories, as the previous academic literature in emerging sectors in innovation systems is underexplored. This single case study will be helpful for further research as it will allow comparative studies across different countries and longitudinal research in a few years. The following section specifies the techniques used for data collection, analysis, method limitations, and ethical considerations.

4.2. Case Study

Case studies allow researchers to gain a refined perspective on reality and help understand the social actors' viewpoints and behaviours (Flyvbjerg, 2006). To expand the research regarding innovation, decarbonization, and emerging sectors, analyzing green hydrogen in Costa Rica seemed enriching due to the lack of academic research in this field and the reasons discussed next.

4.2.1. Case selection and purpose

First and foremost, Costa Rica is a country with an exemplary energy matrix, so it presents a comparative advantage regarding decarbonization. However, it still faces significant challenges in the transport sector. Analyzing how innovative solutions like green hydrogen could potentially improve the challenge that this sector faces and better exploit the good preconditions of the country towards decarbonization.

Second, it could be said that the institutional efforts toward green hydrogen during the last two years have been remarkable. Formal and informal initiatives have been drafted over the last years, from which multiple regulations have emerged with a clear emphasis on green hydrogen development. Among others, green hydrogen is part of the NDC(Contribución Nacionalmente Determinada de Costa Rica, 2020), the National Decarbonization Plan, the National energy plan (2015-2030) and the National plan of electric transport (2018-2030). The most promising opportunity for the green hydrogen niche is the draft bill nº *22392* for "*the promotion and implementation of a green hydrogen economy in Costa Rica*." This proposal includes significant fiscal incentives such as tax exemptions on equipment imports, visas for professional experts, facilities in environmental procedures, and exemptions to newly formed firms in the field. If this law is approved, the potential development of this niche will increase significantly. Additionally, the regulatory body ARESEP has suggested cheapening electricity prices for green hydrogen producers, encouraging the supply side (Lara,2022). This policy aims to develop a flexible regulatory framework that allows energy suppliers to use their energy surplus on incremental demand from electro-intensive operations, such as green hydrogen production.

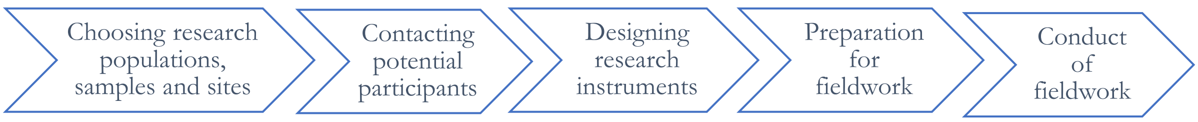
Thirdly, green hydrogen's actors have gathered around a specific location: Guanacaste, which raises the question about potential agglomeration economics or clustering effects. Franklin Chang is a Costa Rican ex NASA astronaut that launched his company "*Ad Astra Rocket,*" first based in Houston and afterwards in his motherland. In 2006, Ad Astra Rocket opened its subsidiary in Guanacaste province "*to bring a piece of Franklin's technological achievements back to his country of origin*" *(Ad Astra,2021).* In 2010 Ad Astra started Costa Rica's green hydrogen journey and aimed to turn Guanacaste into a technological hub (Ad Astra,2021).

Noteworthy, during this research, elections took place, which means that interviewees' perspectives faced uncertainty regarding the prospects of the institutional initiatives. The two potential winning candidates were Jose Maria Figueres, from *Partido Liberación*; and Rodrigo Chaves from "*Progreso Social Democrático*". Most interviewees perceived that Figueres would be more likely to bet on green hydrogen than its competitor. Both participants refer to green hydrogen's potential in their political agenda. On the one side, Figueres was very clear about its commitment to decarbonization, promising, among other initiatives, to promote a generation expansion plan that would include private generators and develop a recharging network for fuel cell vehicles. He also specified his interest in promoting hydrogen for the cement industry and producing green ammonia (Figueres,2022). On the other hand, Rodrigo Chaves presented a different view; he commits to developing zero-emission fuels to replace diesel, including green hydrogen and biomethane, but without specific measures. Besides, he emphasized the potential of Costa Rica to become the "first *Green Data Center in the world,*"; and he is committed to ending fossil fuel boilers (Chaves, 2022).

4.3. Data collection

This case study is the result of fieldwork in Costa Rica. Qualitative methods allow for collecting two kinds of data that complement each other: verbal and non-verbal data, and there are different instruments to do so. In this case, verbal data was gathered through interviews with the sample participants; and complemented by the non-verbal data collected in the field to exploit the advantages of contextualizing. Figure 5 shows the different steps taken for collecting data before its analysis. The following sections specify each of these stages of this paper.

Figure 5: Interview procedure



Source: Author's elaboration adapted from Ritchie (2014).

4.3.1. Sampling strategy

Visiting the field will allow collecting data and approaching the research population, which should be first identified for determining sampling strategies accordingly. Noteworthy, this paper does not intend to generalize the results through a representative population sample, as in most qualitative methods, the sampling is non-probabilistic (Ritchie, 2014).

The sampling strategy chosen for this paper is "*purposive*" by most authors. Bryman (2012) remarks that this approach involves choosing participants strategically to answer the research questions. This approach is imperative to establish selection criteria that differentiate individuals by categories and later determine their prioritization. Furthermore, the author considers a set of multiple purposive sampling approaches that can be considered. In this paper, the researcher guided its decisions following the maximum variation sampling to ensure diversity across the different dimensions of interest. Moreover, new interviewees revealed the relevance of additional actors that could be of interest during the fieldwork, and a few of them were interviewed. This mechanism is known as snowball sampling, and it results from asking participants for the address of engaging potential stakeholders. The notion is to target a few very rich cases of different nature, covering the different features of the topic and depicting how they interrelate with each other.

It is difficult to specify the best sample size in qualitative research, but Bryman (2012) suggests it shall not be so small to impede data saturation but not too large to allow deep case-oriented analysis. In this study, 17 participants were interviewed, allowing them to meet these conditions. The set of interviewees allowed what Flick (2018) referred to as "*theoretical saturation,*" which means that no relevant findings are being revealed by adding data, so the researcher cannot develop new properties per category. *Table 2* shows the sampling approach, including the criteria used to choose the specific actors that compose the so-called sectoral innovation system. In line with the table, we distinguish energy suppliers, Industry, experts, institutions, investors, and international actors. Choosing different sample units with certain characteristics allows for identifying how the perspectives of this niche change across stakeholders. In this case study, the interviewees were chosen based on published reports and considering the members of the "*Alianza por el Hidrógeno*," a formal alliance composed of Costa Rican public and private firms that commit to working towards green hydrogen development.

The Green Hydrogen niche includes different stakeholders depending on their role in the overall energy sector. On the one hand, as renewable energy is crucial to make hydrogen production green, energy suppliers are included in the sample from both the public and the private sector. Considering the renewable energy matrix that Costa Rica holds, this is a potential market opportunity for this first category. Green hydrogen can also apply to different industries such as transport, chemicals, fertilizers, or steel at different supply chain stages. Hence, the second category includes the demand side by interviewing interviewees working in interesting industries.

Moreover, the study included experts to understand better the market structure and the dynamics of this niche. Additionally, institutional actors were interviewed as they frame the sectoral innovation system through laws and public policies. Finally, it is worth considering the actors who have contributed financially to developing this niche, distinguishing between internal investors and international actors. All these actors were further analyzed, considering if they are public or private. Noteworthy, these categories are not mutually exclusive, but they present different knowledge levels, and their involvement in the green hydrogen niche varies.

Table 2: Sampling Approach

Sample Type	Sampling criteria	Examples
Energy suppliers	It includes public and private renewable energy suppliers and those importing fossil fuels.	Private and public firms generating hydropower energy.
Industry	Includes different actors demanding green hydrogen for its industrial use.	Firms working in the transport and touristic sector.
Experts	People who have drafted detailed market research about the green hydrogen niche in Costa Rica.	Consultants
Institutions	Participants working in the higher positions of public institutions who promote public policies that promote the use of green hydrogen.	Employees of the Environment Ministry
Investors	Private companies investing in the green hydrogen niche.	Investment Banks
International Actors	Members of International Organizations that have promoted the development of the green hydrogen niche through funding, technical assistance, and alliances.	Development Banks, Cooperation agencies

Flick (2018) assured that collecting verbal data is the central methodological approach in qualitative research. He emphasizes the need to make well-founded decisions when choosing alternative methods according to the research aim and the target group. The researcher carefully chose the sample to be interviewed to make this decision properly to design the interview procedures later accordingly.

4.3.2. Interview procedure

Firstly, the participants were contacted through different mechanisms: e-mails, LinkedIn, calls or referred by another interviewee. About 35 people were contacted initially requesting to schedule interviews, of which 16 accepted. Overall, the response rate is considerably high, as more than 50 % of the people contacted replied by accepting to participate. Interviewees and CINPE members contributed significantly to this research by providing specific contacts of research interest. Besides, during the research process, a few experts were willing to talk about the research; although they did not participate in the interviews, they provided contacts and advice. Once participants agreed to collaborate with the research project, arrangements were made to confirm their consent, adapt to their availability, and make the research accessible.

The interview guide was structured to explore participants' views about the potential barriers and opportunities coming from the energy sector in Costa Rica and their prospects about green hydrogen's decarbonization potential. Appendix C shows the interview's blocks (although split into two sections based on the structure). In the first block, interviewees introduced themselves and their company's role in the energy sector. Later, questions aim to capture how they contribute to decarbonization. The following questions tackled green hydrogen as an example of innovation for decarbonization, including questions for drafting the innovation biography and their view on GH2 usage. The last blocks touched upon actors' networks, GH2 barriers, and opportunities to scale up.

Flick (2018) exposed the alternative structures that interviews can present to collect verbal data from open answers or more structured opinions. This paper uses semi-structured interviews, as they allow to compare and explore different topics with flexibility. Ritchie (2003) emphasized that this interview design requires the interviewer to follow a set of preestablished questions while allowing respondents to expand through follow-up questions. This instrument is the most suitable due to the innovative status of the topic, which requires rich and detailed information from experts to compare the individual perspectives of different actors. Ritchie (2014) recognized that the instruments required for designing the research instruments included: screening instruments, letters to selected sample members, and a topic guide. The latter is also referred to as the "interview guide", and it is understood as a set of questions, which in this case vary between structured and open-ended. To design this questionnaire, researchers from the Autonomous National University of Costa Rica double-checked the questions to ensure their adequacy to the country's context.

The questionnaire's design followed Kvale's (1996) criteria for being a successful interviewer. The author included the need to be knowledgeable, structured, gentle, clear, sensitive, open, steering, critical, remembering, and interpretative. One helpful strategy that allows testing these criteria is doing a pilot interview with one of the participants that allow the researcher to adapt the interview guide after trying it in the field. After these tests, the resulting Interview Guide (see Appendix B) included two sections: one with multiple open-ended questions and a second one with structured tables to fill.

The interviews lasted between 45 minutes and 1 hour, depending on the availability and length of interviewees' responses. Interviews were conducted with each participant separately, besides a few cases with two participants. Many companies remain working remotely, so there was a preference for taking interviews online. Out of 16 interviews, 8 of them were in-person, and the rest took place online through zoom (see *Table 3*), which is half of the sample. When interviews took place in person, participants chose their preferred location to ensure their comfortability; the most common choices were their own offices or cafes. Flick's (2018) suggestions allowed realistic time estimation, so the researcher accounted for 90 minutes per interview to account for travel or unexpected reschedules.

Interviews provide verbal data from transcriptions of recorded audios and researchers' notes. The researcher's phone recorded in-person interviews, and the platform Zoom recorded online interviews. Before every interview, a consent form was given to participants (see appendix B) to ensure they were allowed to record the interviews while informing them about the confidentiality agreement that guarantees that their names remain anonymous throughout the entire study. Transcriptions were done immediately after interviews took place using Word Online as a tool. All the interviews were translated to English for the analysis, as they took place in Spanish, the interviewees' mother tongue. Table 3 shows the interviews conducted for this study, including their category, name, number of participants, setup, and date.

Table 3:Interviewees and respective settings (own elaboration)

Code	Entity name	Attribute	Set-up	Date
Group 1: Green hydrogen niche actors				
NS1	Ad Astra	Private firm-H2 supply	Face-to-face	07/04/2022
NS2	Ad Astra	Private firm-H2 supply	Online	21/04/2022
ND1	Relaxury	Private firm- H2 demand	Online	30/03/2022
ND2	Invermaster	Private investor	Online	31/03/2022
ND3	Las Catalinas	Private firm- H2 demand	Face-to-face	01/04/2022
Group 2: Green energy sector				
SPU1	Instituto Costarricense de Energía (ICE)	Public company	Online	25/03/2022
SPU2	Refinadora Costarricense de Petróleo (RECOPE)	Public company	Online	10/03/2022
SPR1	Coopeguanacaste	Private- cooperative	Face-to-face	22/03/2022
SPR2	Asociación Costarricense de Productores de Energía (ACOPE)	Private generators	Face-to-face	25/03/2022
Group 3: Institutions				
I1	Ministerio de Energía y Medio Ambiente (MINAE)	Governing body	Online	25/03/2022
I2	La Autoridad Reguladora de los Servicios Públicos (ARESEP)	Regulatory body	Face-to-face	13/04/2022
Group 4: international actors				
IA1	Anonymus	Multilateral organization	Face-to-face	17/03/2022
IA2	La Fundación Costa Rica Estados Unidos para la Cooperación (CRUSA)	Bilateral organization	Online	21/03/2022
IA3	German Society of International Cooperation (GIZ)	Cooperation agency	Face-to-face	24/03/2022
Group 5: NGOs and local associations				
As	Asociación Costarricense por el Hidrógeno (ACH2)	Academic association/NGO	Face-to-face	24/03/2022
Group 6: Industry experts				
IE	HINICIO	Consultor	Online	04/04/2022

4.3.3. Interview Topics

The final interview guide includes two broad sections: open-ended questions and a second structured part. See the Interview Guides in Appendix C, in English and Spanish, for the detailed set of questions. They are described next with the expected time given in brackets: Before starting each interview, the researcher spent some time with the interviewee to introduce herself and the project to ensure that participants feel comfortable and ready to share their thoughts.

Section I: Open-ended questions (30-40 min)

This first section includes four sub-sections: The national decarbonization plan, the emergence and evolution of green hydrogen networks, and the barriers and opportunities for the niche development. The first two parts allow capturing the degree of involvement of each actor in the decarbonization process and the green hydrogen evolution. Afterwards, the two additional sections depict how the different actors interrelate and the typical expectations, the perceived barriers and how this technology can be escalated. The choices of questions changed depending on which sector the interviewee was working in. Participants working exclusively in the energy sector can answer different questions than those working in institutions.

This section has two fundamental purposes. First, to depict what Butzin & Widmaier (2012) call "Innovation Biography", a method that allows depicting innovation processes based on detailed insights from the interviewees who experienced innovation emergence and growth. This method requires careful triangulation across interviews and documents to create a coherent story. This biography combines historic milestones, the key actors and the networks that connect them. The second goal is to identify the barriers that interviewees perceived in both the energy and transport sectors. The discourse differs significantly if the actors were public or private in this case.

Section II: Structured questions (10-15 min)

The second part of the interview includes three parts, as shown in Appendix C. The researcher printed the different tables to give to interviewees during face-to-face meetings. Likewise, these figures were filled by sharing the screen in online interviews. There are three main parts to fill. First, participants were asked to order hierarchically the different uses of green hydrogen in Costa Rica based on their feasibility. There are five categories: (1) heating; (2) aviation and shipping; (3) land transportation; (4) power system; and (5) chemical feedstock and processes. This question allows us to analyze how the actors' expectations differ regarding the potential use of green hydrogen in different industries while comparing this context with the rest of the world. Secondly, participants received a table to fill the importance of different kinds of knowledge (scientific, technical, management, and market) to develop this niche. This second table depicts how knowledge is transferred in the existing networks. Finally, a table gathered a set of institutional factors (i.e., social acceptance, regulations, international standards). Interviewees reflected if they were promoting, impeding, or not involved in developing the green hydrogen niche. All these structured questions allow a better comparison of the differing perspectives based on clear answers. However, all the responses were complemented by the respondent's explanation given out loud.

4.3.4. Observations and non-verbal data

Being in the field allowed the researcher to collect non-verbal data from complementing interview data. The researcher used Participant Observation, which Flick (2018) explains as the mechanism that "*simultaneously combines document analysis, interviewing of respondents and informants, direct participation and observation, and introspection*." Hence, the researcher should be involved in the field and gather data in a research diary with constantly updated notes about general perceptions, specific interviews, and observations from visits to the field. There are different types of observation depending on the purpose; in this case, the goal is what Ritchie (2014) refers to as *familiarization*, which aims to understand behaviours, processes, and events within their naturally occurring context. These observations complement interview data and are collected in multiple ways, including field notes, visual data, and written documents.

The researcher gathers observations from a renewable energy plant associated with a demonstrative material of hydrogen production and use. The author also visited a small town, offering to rent a green hydrogen car per hour. These observations are later specified in the following sections, but the mechanisms used for collecting them are worth mentioning. Ritchie (2014) remarks on the need to document observations through fieldnotes taken on-site, being very specific and avoiding keywords that could be later difficult to interpret. A few pictures were taken in the field to better capture these observations, always with the interviewees' consent. These visual records are instrumental for the researcher to understand the complexity of innovative technologies such as green hydrogen.

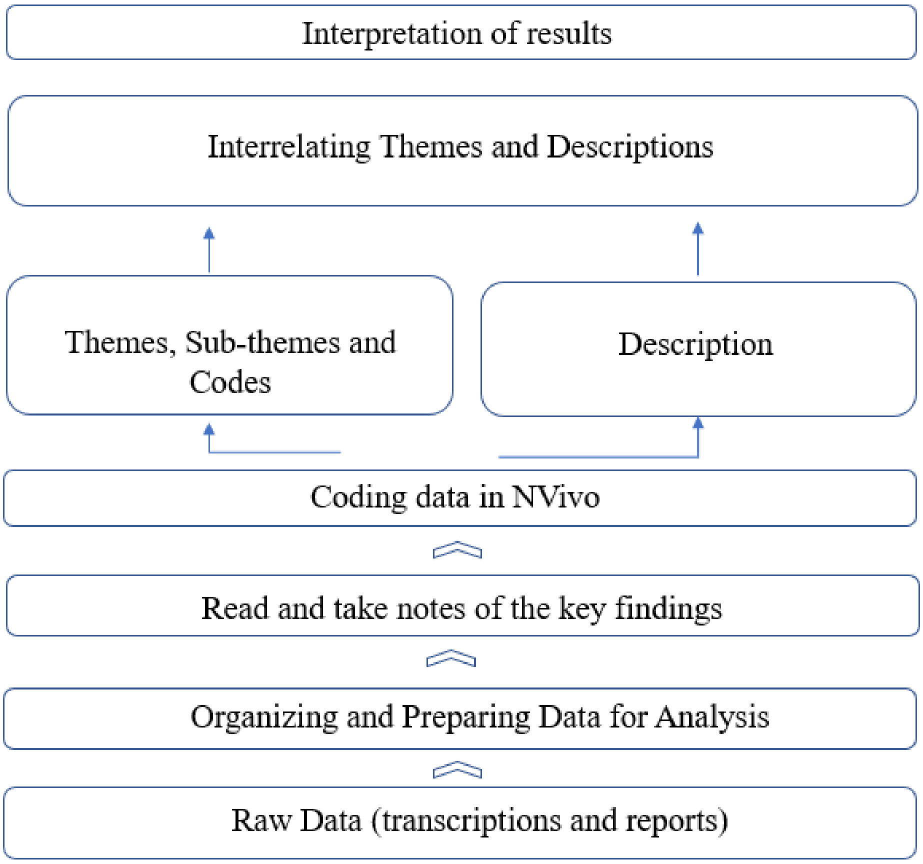
Later, relevant documents were also analyzed to frame the research topic and verify the validity of the verbal data. The researcher analyzed published documents such as the National Decarbonization Plan, the green hydrogen roadmap, and detailed market reports about this niche in Costa Rica. Besides, interviewees also authorized the use of specific documents considered relevant. All these data gathered are used to triangulate data, which Flick (2014) defines as the sole method to increase the findings' validity. The researcher wrote daily notes in a field diary and photographs to strengthen data validity. Besides, experts from the team CINPE were consulted throughout the entire research to validate the findings by cross-checking information. Green hydrogen industry experts validated some figures like Table 6 and Table 7 to ensure their accuracy.

4.4. Analysis of qualitative data

The recorded interviews provided raw verbal data when transcribed. After each interview, debriefing took place to assimilate the obtained data and complement transcriptions with notes. To analyze the qualitative data, the researcher followed the steps proposed by Creswell (2014) (See Figure 6). The first step is to organize data for its analysis, review the accuracy of the transcriptions and include notes that highlight the essential findings per interview. To complement this step, the notes from the research diary permitted a better interpretation of the interviews' verbal data. Notes were particularly relevant to elaborate information from online interviews with technical issues or those recordings from in-person interviews with background noises.

Once this is done, the coding process starts. Coding transcriptions can be laborious and time-consuming, so using the computer software NVivo accelerated this practice. Coding implies simplifying interview content for more accessible analysis. To do so, Gerson and Damaske (2020) suggested drafting a list of theoretical codes to establish a baseline and let trends and patterns emerge during the analysis. In the analysis, theory guided the main themes and sub-themes, and interviews provided the codes based on frequent keywords, arguments, and concerns. Table 9 (See Appendix D) presents an overview of the themes in the shape of a codebook.

Figure 6: Stages of qualitative data analysis



Source: Authors' elaboration based on Creswell (2014)

Lastly, these themes guided the data analysis, which required contrasting data at every level, using different within-case and across-case analysis techniques. It is not easy to preestablish the best analysis tactic before having the data, but in this case, selecting dimensions and looking for within-group similarities coupled with inter-group differences might be adequate (Chaminade,2021). Verbal and non-verbal data would be the primary sources. Verbal data were contrasted with secondary data for data triangulation through document analysis of policy briefs or administrative laws to ensure veracity. Table A8 (See Appendix A) shows the plan for the practical on-site implementation in Costa Rica, which lasted about seven months.

4.5. Limitations

The researcher is aware of the study's limitations that may endanger the validity and generalizability of the results. Even though it is not the aim of the research to capture generalizable results, the format and the sample size threaten the results' external validity, mainly due to bias at different levels. Firstly, the sample selection may be affected due to snowball sampling; Ritchie (2014) warns about the possibility of interviewees recommending people to show a specific approach. To address this issue, the method included interviewees from different categories to capture contrasting views, especially between supply and demand. Furthermore, interviews entail researcher and interviewee bias simultaneously. For the first case, qualitative researchers are often bound to their interpretation of evidence, whereas quantitative methods let econometric methods directly show empirical evidence. Mitchell (2018) considers that the main threat for the researcher is to fight the tendency to be personally involved with the interviewees as it implies being empathetic. To address this limitation, the fact that the researcher did the study in the field was beneficial to understanding the cultural differences present in the Costa Rican context.

On the other hand, Creswell (2014) claims that interviewees' responses to the questionnaire are based on their views, threatening the results' external validity. The author explains that participants tend to present "*social desirability bias*, " which is the data distortion resulting from adapting answers to socially acceptable beliefs. Besides, the mere presence of the researcher may also influence the responses. Noteworthy, all the interviews were conducted in Spanish. As the publication is in English, there might be a reduction in the meaning of some concepts lost in translation (van Nes et al., 2010).

Overall, the Covid-19 pandemic indirectly limited the proper development of this research, as multiple companies were remote working, making in-person interviews less likely to occur. Online interviews can be less informative as non-verbal data is somehow missed. As technical issues often occur, the researcher put additional efforts into preparing online meetings, ensuring proper connectivity, and avoiding background noise to address this issue. Noteworthy, it seems that remote interviews may have raised the availability of the busiest participants, as it requires less time, and hence it can also be seen as a benefit. The sample included participants from very high positions in big companies and institutions, individuals who do not tend to have many available times for interviews. As a result, there were relevant actors for the research that did not reply, impeding the direct collection of primary data that would have been crucial for a better understanding. Additionally, due to approach changes that occurred during the research process, the sample did not target many actors from the transport sector, leading to an incomplete perspective of reality. However, most participants referred to the transport sector particularities in the interviews, so the content was indirectly included.

4.6. Ethical considerations

The research should be carefully thought out to avoid ethical issues at every stage, from the study's design until the publication of the results. Ritchie (2014) stressed the importance of four essential items: informed consent, avoiding harm in data collection, doing justice to participants when analyzing the data, and respecting confidentiality in writing the results. In this case, keeping interviewees' names anonymous is especially important for those working in public institutions. Creswell's (2014, p.132) suggestions helped ensure that the research holds the essential ethical considerations and overcome the possible threats throughout the entire analytical process. Firstly, the participants knew the purpose of the study and how data would be used. After receiving their acceptance from participating in the study LUSEM, a standard consent form will be sent specifying that their "*participation in the research is voluntary and thus they are free to refuse to participate and withdraw from the research at any time*." (See Appendix).

The interviewee's identity remains anonymous, but its pertinence to a particular company is included unless specified. Some participants refused to appear in the representation of their company, so a set of codes allowed to ensure the confidentiality terms to avoid putting the interviewee in an uncomfortable position. In addition to this, the researcher allowed interviewees to ask to review a thesis draft before publishing to ensure that they felt comfortable. None of them demanded this, making the quotes more realistic, but most were interested in accessing the final publication.

Noteworthy, many interviewees insisted on having the interview online, as they remained working remotely. Therefore, the researcher offered from the beginning both set-ups and adapted them to the participant's preferences. Marhefka, Lockhart, and Turner (2020) were very clear about the need to allow participants to choose freely between in-person or online interviews to avoid uncomfortable situations.

5. Results and Discussion

Theoretical standpoints guide the empirical analysis of this study from sustainability transitions, which allows us to interpret the interview data to answer the main research question: *How is the Costa Rican energy system shaping the development of the green hydrogen niche?* Green hydrogen is an eco-innovation attempting to disrupt traditional regimes. Bento (2010) argued that pollution-intensive technologies dominate under a socio-economical context that only benefits the existing paradigm, raising barriers to avoiding a challenge in the status quo. An innovation biography is delivered to better understand the GH2 niche in Costa Rica, gathering its historical milestones and the actors involved. The interview data were analyzed intending to diagnose how green hydrogen can decarbonize Costa Rica, what are the existing barriers in the system, and the opportunities for improvement. A final reflection is included about the niche chances to develop. Through the entire analysis, the notion of "technological niche" is understood as "*the space in which new technology is protected from the harsh selection environment while it strengthens itself through learning processes"* (Cecere et al.,2014)

5.1. The green hydrogen niche

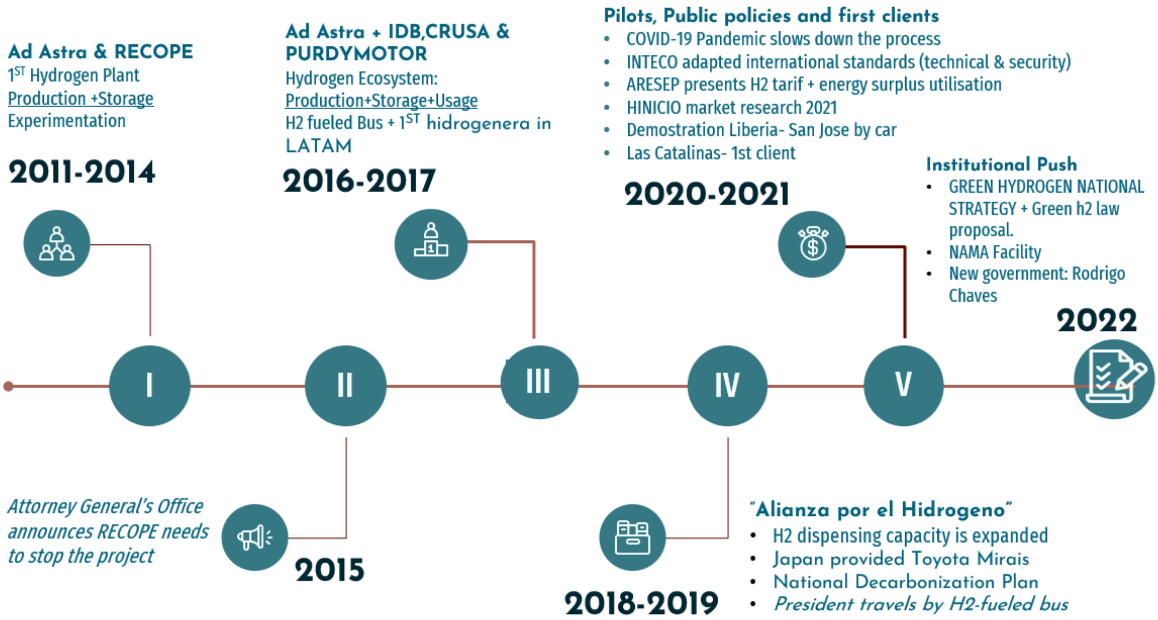
First and foremost, it is crucial to identify how green hydrogen could be perceived in innovation. Hydrogen is not a new technology, "*it has been produced for more than 100 years, so there are clear regulations defined globally. What is innovative is to produce it from renewable energy sources and named it green hydrogen.*" Likewise, Interviewee *ND2* added that what is new is *"the shift from seeing it as a gas for industrial purposes to a daily-use application."* Under these assumptions, it could be assumed that green hydrogen is a technological innovation that results from the urgency and the efforts made toward decarbonization at multiple levels. Hence, it is not a pure invention but rather a technological innovation that results from significant changes along its entire value chain. First, its generation must be renewable, and secondly, its applications have now been expanded to innovative solutions for decarbonization. As shown in section 1, GH2 requires institutional innovations. Hence, this may imply an entire reconfiguration of the sector.

5.1.1. Niche emergence and development

Interviewee *LA3* wondered, *"To what extent were things thought out this way or is it a sum of many coincidences?"* a valid question to reflect upon, considering how fast the Costa Rican green hydrogen niche has been promoted during the last decade at least theoretically. To clearly understand how this niche emerged within the energy sector, interviews included a reflection on the historical milestones in determining the origin. The verbal data from this section is analyzed following Butzin & Widmaier's (2012) research procedure to construct innovation biographies. The author pointed out three dimensions to guide the analysis: (1) time and space, (2) knowledge dynamics and (3) actors' network. Data was later triangulated and ensemble to constitute green hydrogen innovation biography, including a territorial dimension and the spatial origin of knowledge. *Figure 7* shows the historic milestones obtained from the interview data and verified with official sources.

Interviewees' reflections on the historical milestones that green hydrogen entailed in the Costa Rican context were relatively consistent. Regarding its origin, most interviewees assigned the merit of this innovative niche to the private sector efforts, with a particular focus on the case of Ad Astra Rocket, which is said to be responsible for bringing this technological innovation to the country. Many participants conceived that Franklin Chang was the sole responsible for this niche emergence. Unlike most entrepreneurs, Franklin established his innovative project in Liberia (Guanacaste) instead of in the capital. Interviewee NS2 explained two reasons for this decision. First, because the CEO *"saw in Guanacaste an area with many potentials, and he had the vision to decentralize the development focused on San Jose"*. Secondly, he specified multiple features that made Guanacaste strategic for the green hydrogen niche, remarking: (1) *renewable energy potential*, (2) *human capital*, (3) *an international airport,* and (4) *tourism*. These features could be considered "regional capabilities", which Neffke et al. (2011) refer to as factors determining which activities are more or less likely to emerge in a particular context.

Figure 7: Innovation biography of Green Hydrogen in Costa Rica



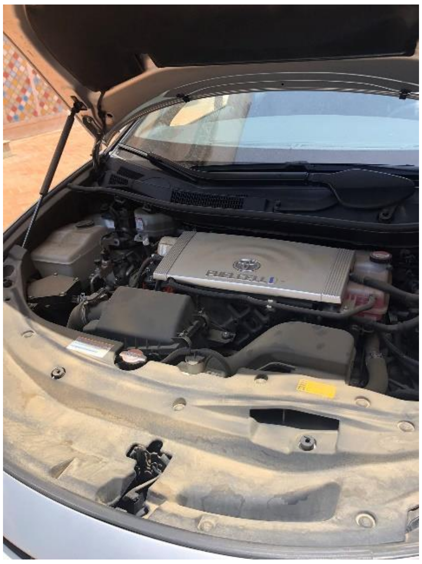
Source: Author's elaboration based on interview data and triangulated data.

The time frame in which the green hydrogen niche has been developed started in 2011 when Ad Astra Rocket signed with RECOPE to start research on the production and storage of green hydrogen and integrate the lessons in an experimental plant (*SPU2* and *NS2). The* project was perceived as promising; technical knowledge from experts in the private sector was combined with the public resources and extended network of RECOPE. Both actors worked for hand in hand, and the plant came into operation in December 2013, when green hydrogen was produced and compressed to a pressure of 700 atmospheres for the first time. (*NS2*). This pilot plant could produce 1kg of hydrogen per day. Interview *IA1* emphasized that this project started with ongoing trials and aimed to learn how hydrogen was produced and develop expertise based on constant testing. When everything seemed to be working smoothly, the Attorney General's Office ruled that "*the Costa Rican Petroleum Refinery (RECOPE) could not participate in projects involving alternative energies and biofuels*." (Rojas,2015). Hence, due to legal barriers and institutional dealignment, RECOPE needed to abandon their actions in green hydrogen sadly. *SPU2* assured: "*We have been trying to support a bill in the Legislative Assembly for about seven years*", and they perceive that public opinion might harm it.

After this unfortunate incident, Ad Astra founded alternative partners that made possible the continuation of the project from 2016 onwards. In 2017, Ad Astra completed its ecosystem by including the usage of green hydrogen thanks to an imported hydrogen-fueled bus and the first hydrogen vehicle dispenser in Latin America (*NS2*). This bus was used for demonstrations in 2018 when the ex-president Carlos Alvarado travelled around the country in the hydrogen-fueled bus to strengthen its commitment and visibility to the "*National Decarbonization Plan*". A historic milestone occurred in 2018 when the "*Alianza por el Hidrógeno*" was founded by all the actors who presented interest in green hydrogen in a way. *IE* admired the role of this association "*they have a collective of governmental and other private entities that have sat down and said, "Hey look, our country has potential in green hydrogen. What are we going to do about it?. The political intention already exists. I think that this is one of the greatest milestones a country can have.*" The same year, the "*Asociación Costarricense por el Hidrógeno*" (Costa Rican Association of hydrogen) was founded to promote green hydrogen more academically (*As*). Images 1 and 2 show examples of prototypes and teaching materials used by this association to promote green hydrogen and train students to strengthen human capital. This association also works as a network for multiple firms to align their efforts.

Images 1 and 2: Hydrogen fuel-cell car prototype; and miniature hydrogen fuel cell charger. Both objects are teaching material used by ACH2. The researcher took photos during a field trip.

In 2020, the COVID-19 pandemic slowed down the development of this technology in a sense, but alliances kept rising. Purdy motors received fuel cell cars from the giant Japanese firm Toyota, and Ad Astra acquired its first clients with the help of Relaxury (a firm that provides mobility solutions for high-end tourism). In 2020, the luxury condominium named "Las Catalinas", based in Guanacaste started to offer a rental service for the hydrogen-fueled Toyota Mirais, charged in Ad Astra's ecosystem in Liberia. Images 3 and 4 show this fuel-cell vehicle and its interior. These cars have increased diffusion; Ad Astra also used them to prove the efficiency of their technology by travelling from Liberia to San Jose with a full tank in 2021.



I*mages 3 and 4: Toyota Mirai in las Catalinas. The researcher took the photo during a field trip.*

In 2021, green hydrogen gained legitimacy as international actors got involved and competitors emerged worldwide. The enablers mentioned in the previous section explained the acceleration of institutional initiatives in 2021 for green hydrogen promotion. Among others, it is worth mentioning: (1) the "tropicalization" of international standards by INTECO; (2) ARESEP published the "surplus utilization law"; (3) MINAE updated the executive decree of the law on the rational use of energy (7447) promoting efficient equipment imports to include hydrogen production equipment (*Interviewee I1).*

During the time that this research was conducted, promising events occurred. Noteworthy, *NS2* was enthusiastic, explaining their new alliance with Mesoamerica: "*This venture with the company Mesoamerica (...) aims to demonstrate the economic viability of this technology. With them, we are securing the sources of investment and the customers who would use these vehicles."* Other interviewees perceive the potential for scaling-up Ad Astra's technology thanks to its new ally's resources and network. Moreover, in May, the preliminary tariff that ARESEP suggests for hydrogen is 7cent/kwat (*I2*). Overall, a consulting firm is already drafting the "National strategy for green hydrogen". Interviewee *IE* conceives this as strategically valuable "t*he roadmap is like that transition between our study and the national reality; it is the missing link.".* Finally, the prestigious group of donors named NAMA Facility[2] (2021); accepted Costa Rica's proposal to develop a green hydrogen economy. *IA3* explains that "*with the acceptance of the NAMA facility Costa Rica (…) will receive some money for a hydrogen feasibility study, which costs a lot (...). hydrogen experts' costs 800-900€ a day easily*".

Overall, green hydrogen emerged as an innovative solution for tackling issues in the energy and transport sector, depending on the value chain stage. First, green hydrogen deploys a solution for Costa Rica's energy surplus. Secondly, it can provide an innovative solution for decarbonization at multiple levels, particularly in the transport sector in the Costa Rican case.

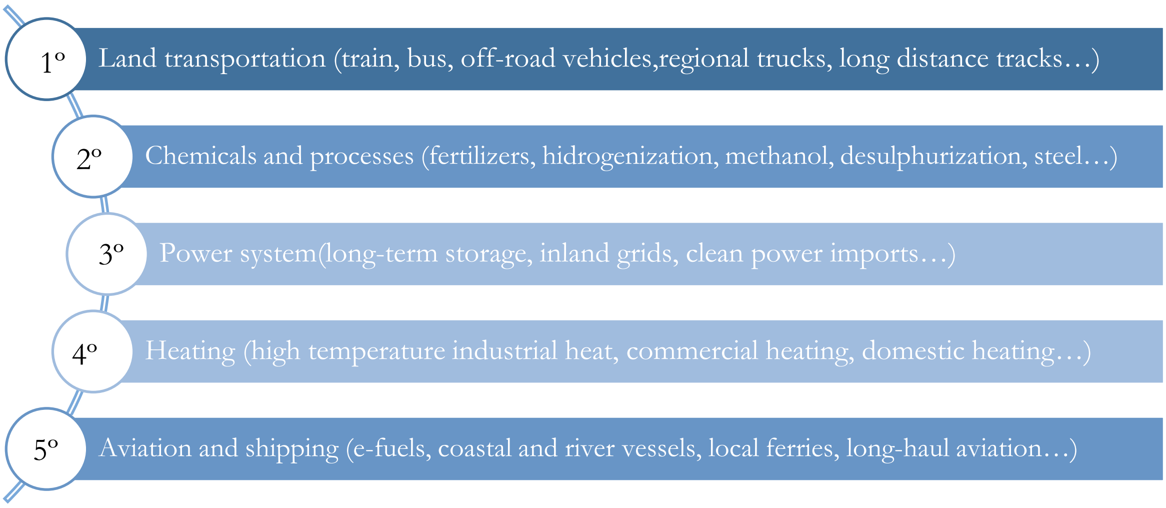
5.1.2. Hydrogen value chain and Decarbonization

Green hydrogen can be implemented in different spheres to foster the decarbonization of the economy, ranging from transportation to industrial heating and chemical processing. This section aims to answer: How can Green Hydrogen contribute to decarbonizing Costa Rica? Overall, in line with the innovation biography and the actors' map, it is easy to see a clear strategy in the Costa Rican context: decarbonizing transport, as it is the heaviest emitter. There are two key stages along the value chain on which actors are keen: hydrogen production with renewable energy and green hydrogen use for transport. As *IA1* remarked, this approach would be double beneficial, as it helps to decarbonize the most emitting sector while disregarding fossil fuel imports.

To better understand the potential hydrogen applications, interviewees built a hierarchy of the feasibility of each H2V possible application. *Figure 8* shows the results based on the most repeated choices among interviewees.

[2] NAMA Facility combines donors from the European Commission and UK, German and Danish ministries, who manage funding to support developing countries initiatives aiming to implement climate protection measures. The goal is accelerating decarbonization.

Figure 8: Green Hydrogen feasibility in the Costa Rican context based on interview data.



Source: Authors' Elaboration based on Interview Data.

99% of respondents agreed about positioning land transportation as the first option without a doubt, which makes sense considering the ongoing projects and the pilot studies that have been published. To be more specific, most interviewees were optimistic about the potential of heavy-duty or long-distance transport, mainly when applied to closed loops. For instance, *NS2* is planning to provide services for food distribution companies, while *ND3* plans to acquire GH2 vehicles for employees' daily routes.

Respondents also agreed about positioning aviation and shipping as the least feasible and hence in the fifth position. Noteworthy, the latter has been referred to be "the holy grail", although far from doable. *IE* adds that it will align with Costa Rica's environmental philosophy; it would be excellent marketing for conscious tourists to sell net-zero travelling to Costa Rica. Multiple experts were also very optimistic about the potential of synthetic or e-fuels. *IA1* was very optimistic in explaining how synthetic fuels or e-fuels work:

> *By combining Carbon Capture Storage with hydrogen, we can produce synthetic fuels, which would seem to me as a game-changer. I can generate many hydrocarbons (jet gasoline, diesel, etc.), which will not require changing vehicles or transport infrastructure.*

For the case of heating, multiple respondents thought about domestic heating, which will not apply to Costa Rica for climate reasons, diminishing its position in the hierarchy. Meanwhile, respondents with more experience in the field were aware of the potential of using hydrogen for high-temperature industrial heat. *I2* disclosed that "*the demand is almost minimal; only Acerolmita and three cement factories use hydrogen*". Regarding the attitudes towards GH2 use as a power system, responses varied for chemicals and processes, although they always remained in the second or third position. The latter could benefit different sectors, such as agricultural (fertilizers), but this has not caught enough attention. As *NS1* pointed out, *"The challenge is how to grow demand and supply hand in hand."*

5.2. Barriers to the development of the green hydrogen niche.

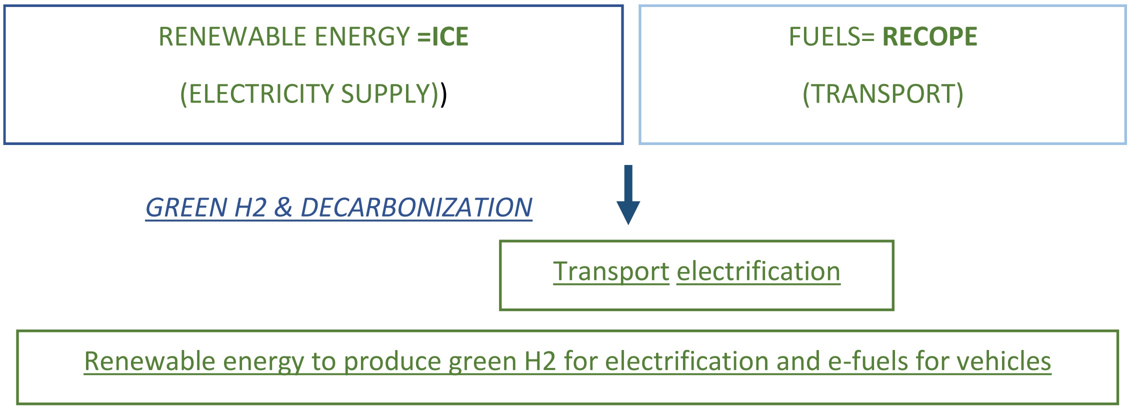
5.2.1. The current regime in the Energy and Transport system

Green hydrogen has the potential to disrupt the existing socio-technical system by reshaping the industry structure. As an eco-innovation, green hydrogen may face more substantial barriers as it requires actors' co-evolution (Cecere et al., 2014). The different stakeholders might evade cooperating to boost these innovations because of interdependences and complementarities across the different parts of technological systems (Dijk et al.,2011). Interviewee *NS1* perceived substantial complementarities and served as a motivation for the following section:

> *Hydrogen and decarbonization came to break the current paradigm and institutional organization, not only in Costa Rica but also elsewhere. Before, energy was divided into transport and electricity, where transport was oil, and the rest of the electricity came from hydropower. Today, decarbonization and electrification combined both sectors. Institutionally, Costa Rica was divided into ICE for electricity and fuels for* RECOPE. *There is an institutional gap regarding transport electrification and green hydrogen production.*

This assumption awakens multiple uncertainties at the sectoral and institutional levels. *Figure 9* shows the changes that decarbonization poses to the current structure. It could be said that green hydrogen production relies on the energy sector, and its use affects the transport sector (among others).

Figure 9: Institutional dilemma since decarbonization and green hydrogen emerged



Source: Author's elaboration.

Many interviewees perceived specific resistance in the energy and transport systems that make transitions difficult. *ND1* observed "ideological barriers" coming from the state-owned agencies in the energy sector: "*they feel threatened by technological changes, so they raise entry barriers*". Likewise, *I2* discerned "*capacity barriers*" among electricity distribution companies, referring to the limited role of private producers. Interviewees mentioned that disrupting this system is particularly difficult in the transport sector. *IA2* pointed out that "*innovations are required at all levels. (…) sustainable transport is not only about technological innovation (…), but also about innovations in the way we think about transport systems.*". *SPU2* added a clear need to redefine urban mobility and the public realm to make these changes possible. Overall, most participants were aware of the difficulties faced by innovative solutions for decarbonization.

These arguments follow Cecere et al.'s (2014) claims about the difficulty of escaping from pollution-intensive technologies. The authors considered three key categories that explain why existing sectors can lock in and impede innovation development: (1) Cost-related factors, (2) Stakeholders, and (3) Niche complexity. The following section analyzes the energy and transport sectors based on interviews and reflections to identify what impedes innovation promotion within the energy and transport sector. *Table 4* presents these categories with the interviewees' main concerns. It is worth mentioning that the sample participants do not include many active members from the transport sector, so the perceptions regarding that sector might be limited. Thus the conclusions need careful be interpretation.

Table 4: Lock-in categories in Costa Rica's energy and transport sector.

	Lock-in category	Costa Rica
Energy sector	Cost-related factors	Electricity prices Equipment
	Stakeholders	- Structural - Institutional discoordination - Outdated financial and legal instruments
	Niche complexity	Low Diffusion
Transport sector	Cost-related factors	Infrastructure Vehicles
	Stakeholders	- Opposition groups - Administrative slowness
	Niche complexity	"Chicken and the egg"

Source: Author's elaboration based on Cecere, Corrocher & Gossart & Ozman (2014)

Cost-related factors:

This category refers to the arguments given by the actors that form the existing socio-technical regime to reject investing in eco-innovations based on the transition costs, in this case, clean energies and sustainable transport. For the case of green hydrogen, objections emerged regarding multiple costs, but mainly electricity prices, hydrogen infrastructure, storage, and transport (*SPR1*). Additionally, the monopolistic structure of the Costa Rican energy sector relies almost entirely upon ICE's decisions. *I2* revealed that this institution's significant debt is a barrier to innovation investment: "*Ice's concern is not to develop new production projects but to see how its depts will be paid off*".

Meanwhile, participants were concerned about new infrastructure costs and vehicle prices in the transport sector. *ND2* assured: "*the cost of vehicles was absurdly high. I can tell you that they have come down, but in 2018 a bus made in Europe was almost €800,000; today they are around €400,000 (…)"*. During the research, fossil fuel prices increased heavily due to the Russian invasion of Ukraine, a topic that concerned most interviewees. Considering what *ND2* remarked, *"We will succeed when the cost of hydrogen at least has parity with diesel",* it might be the case that this recent event diminishes cost-related factors.

Stakeholders

Other significant sources of lock-in and self-reinforcing processes relate to coordination effects at the level of organizations, policymakers, and society. Interview data suggests that the energy sector may present "organizational inertia", especially regarding state-owned companies. Multiple interviewees alleged that outdated laws and financial instruments cause the main obstacles to innovation from emerging in the energy sector. *SPU2* specified that "*the law that governs the actions of* RECOPE *as a state-owned company was created in 1981, almost 41 years ago. Is a law that at the time did not foresee that the company would venture into the development of alternative energies*." RECOPE tried to get involved in innovative solutions in alternative energies without success.

Moreover, *IA1* pointed out low structural flexibility, *IA2* added that the monopolistic companies tend to be "*extremely reluctant to move fast*", and *IA3* perceived ambivalent positions from state-owned firms. There are different opinions regarding how the sector structure relates to innovation, but what has been consistently mentioned is the lack of institutional coordination and the limited participation of the private sector. *ND3* gave an example of lock-in in the transport sector: "*There is a private oligopoly of public transport in Costa Rica, formed by very powerful companies (...) they put a lot of pressure on the authorities (...) for projects not to move forward, as they go against their status quo*". This might be related to a perceived "*administrative slowness*", shown in examples like the eternal project to build a regional train has been pending for 20 years (*SPU2* and *IA1*).

An interesting point to be noted is that most interviewees were reluctant about the role of academia in the development of green hydrogen. *NS2* claimed that scholars in Costa Rica diffuse negative inputs about green hydrogen, emphasizing its low energy efficiency. Most interviewees emphasized a clear need to form human capital to make technological innovations like hydrogen sustainable (*AS*). GIZ and Ad Astra urged to include green hydrogen in university education programs and technical training to prepare students to operate the systems. To this end, *IA1* recognized the importance of institutions like INA as key potential actors.

Niche complexity

Eco-innovations tend to struggle to gain support during their initial stages. Cecere et al. (2014) explain that the lack of know-how and environmental information strengthens risk aversion. For example, *SPR1* lacked knowledge about green hydrogen, claiming that the business model and the costs that hydrogen entails remain unclear. Cooperatives, in general, seemed reluctant to get involved in green hydrogen production, referring to their lack of resources and knowledge as the main reason. Knowing that companies like ICE and RECOPE have accessed detailed information regarding GH2, the diffusion within and between sectors seems to be low. A first step is breaking with the existing reinforcing processes in the sector and fostering transparency and collaboration.

Niches are perceived as complex because they are different from "dominant" or standard designs or technologies. For example, the diffusion of electric cars is an arduous task, as they need to align with their old competitors in price, design and efficiency. The thought part of technological diffusion is to engage regime actors and ensure that they need to understand everything about the technology, which is why Dijk et al. (2011) conceived hybrid cars as the first stage for e-cars diffusion. Interviewee ND1 complained about the low penetration of hybrid cars due to the lack of incentives as one of the reasons why transport decarbonization is so slow in Costa Rica.

Multiple stakeholders (especially those outside the sample) perceive green hydrogen as a very complex technology. The difficulty of the infrastructures, transportation, and storage of GH2 is what concerned interviewees the most. Oltra and Saint Jean (2009) perceived the same list of concerns as a barrier to fuel cell car expansion. Another common argument among regime actors who rejected innovations is Noailly's (2007) *"the chicken and the egg problem"*. *SPU1* argued about how problematic this notion is: "*We have to wait for the technologies to reduce its price, and on the other hand, develop an infrastructure of charging stations that do not yet have enough customers to operate profitably*."

5.3. Windows of opportunity for green hydrogen in Costa Rica

The previous section shows that Costa Rica's energy and transport sectors perceive Cecere et al.' s (2014) path-dependence and reinforcing processes. The actors promoting GH2 have been trying to diffuse its use and show its feasibility. This section aims to answer the research question: *How can the green hydrogen niche disrupt the existing socio-technical system?* A helpful paper to answer this question is Ruggiero et al. 's (2017) "*Strategic Niche Management theory*" (SNM), which tackles the gap between R&D and market introduction. The authors urged to enhance three interrelated processes for niches to scale up: (1) meet expectations, (2) expand social networks, and (3) enhance learning processes. Most of these processes are now occurring in Costa Rica, so there is a clear need to analyze the potential opportunities that could emerge.

To better suit the formative nature of GH2, it seemed coherent to analyze Gosens, Gilmanova, and Lilliestam's (2021) "*windows of opportunities*". The authors focused on cleantech firms' *opportunities windows;* this case study may apply similarly. Building on Lee and Malerba (2017), Gosens et al. (2021) divided windows into technological, demand, and institutional. Noteworthy, this paper uses the notion of windows to explain how a small niche in Costa Rica can unlock the socio-technical regime rather than focusing on industrial catch-up cycles. *Table 5* gathered interview data to compare the theoretical results per window of opportunity and the Costa Rican practical examples.

Table 5: Windows of opportunities in Formative Sectors. The author's elaboration is based on Gosens, Gilmanova & Lilliestam (2021)

	Theory	Green Hydrogen (GH2)	GH2 Costa Rica
Technological	- Limited stocks of relevant experience - Competing, possibly radically different designs	Relevant experience and dominant designs in grey hydrogen, but its green alternative implies radical changes.	Stock of experience: Domestic= Ad Astra Dominant designs: Foreign= adapted with INTECO
Demand	- Limited demand , preferences to be determined -- Logistic demand growth pattern	GH2 presents several users and consumers along the value chain.Big demand opportunity when diffusion increases.	- Alternative vs GH2 at different levels. - Demand remains tiny, only transport and tourism are using GH2. Potential for green ammonia, fertilizers and e-fuels deserves attention. - Roadmap could foster geographical expansion
Institutional	- High impact of government interventions - No clear standards or certification for product design or performance.	Several institutional initiatives happening worldwide to accelerate GH2. Standards are still developing, although technical and security equipments could be updated from grey h2	- Informal: Multiple national plans, - Collaboration culture and political will - Formal: Market formation policies -Standards: Not aware, but able to prove its "green" origin

Technological windows

Lee and Malerba (2017) perceived radical innovations as technological window openers that could disrupt the existing system. Green hydrogen might have enough features to disrupt the regime as it is. NS1 exemplified an interesting innovation that may apply. *"The key to afford to scale up is to commercialize the by-products of hydrogen production. (...) Green hydrogen results from the electrolysis of water, so (...) High purity oxygen is also produced". IA1* added that these byproducts have multiple industrial applications. This consideration may overcome economic issues locked in the development of this technology.

The arduous task for GH2 is to align with the dominant design in the sector (Cecere et al., 2014). The problem gets more complex as formative sectors present unclear dominant designs, which are still under construction (Gosens et al., 2021). Another determinant to open technological windows stands on the stocks of experience, which tend to be limited in the early stages. To identify where experience is and the sources of knowledge, interviewees reflected on the origin of technical, scientific, market, and management knowledge within the green hydrogen niche (See Appendix C Section II). Evidence suggests that the technical and mechanical knowledge is fully concentrated in Ad Astra. The firms' scientific knowledge could be considered imported from Houston. In contrast, their technical knowledge is combined with domestic efforts, as *IA1* asserted: "*When the plant was built, we did exercises on generating hydrogen, pressurizing the tank, compressing the hydrogen, and throwing it on purpose (simulating an emergency) (...). In this way, we learned most operational processes on our own.*"

It seemed clear that international actors and industries influenced the niche's development. For example, the IDB or GIZ funded technological improvements such as Ad Astra's plant upgrade, which will allow filling car deposits thoroughly from now on. However, Costa Rica presents a comparative advantage due to: (1) its energy matrix; (2) its potential to increase its installed capacity (new constructions or reactivation of private projects) (*ND2*). Other interviewees perceived infrastructure advantages, as it has several free-trade zones. *IE* and *IA1* argued that these areas could be suitable for green hydrogen ecosystems, as they would provide services for all the companies working there.

These examples may show the phenomena Gerschenkron (1962) called "*the advantage of backwardness*", which refers to the mechanism through which latecomers could benefit from global pools of knowledge. However, Abramovitz (1986) warned that latecomers would not benefit if the absorption and accessibility of international knowledge were not ensured. Interviewees mentioned an example of knowledge absorption based on the tropicalization of GH2 international standards. "*Tropicalize*" is to adapt products, standards, and technologies to tropical climates. *IA1* explained that INTECO was in charge of this process due to "*an inter-institutional hydrogen plan that assigned a commission to tropicalize the technical standards."* Thanks to this commission, international standards were easily adapted to the Costa Rican context, allowing the GH2 niche to expand in new value chain stages, like equipment production. Among other options, *IE* suggested *"specializing in the production of electrolyzers, which is the best way to generate added value".* Engaging in this new value chain stage could be a clear technological window to consider.

Demand window

Lee and Malerba (2017) defined this window as the *"opportunity provided by the creation of a new demand*" (p.345). Galvan (2021) argues that the green hydrogen's momentum is now as there might be a demand increase resulting from cost reductions paired with ambitious national net-zero goals. In this analysis, it is essential to consider that the demand differs along the value chain. First, the demand needed to produce GH2 targets, renewable energy suppliers. The Second stage combines various sectors (i.e., transport, fertilizers...); that demand GH2 for multiple uses. Thirdly, consumers demand end-use products such as fuel cell vehicles or green ammonia. The latter stage is tiny in Costa Rica, so it was left outside the analysis. This complex demand structure confirms that GH2 is what Gosens, Gilmanova, and Lilliestam (2021) call a formative sector because demand is limited, and preferences are unclear. The authors focused on technological alternatives; geographical and temporal development of market demand as the key features to analyze in formative sectors. Each of them is discussed next.

Interviewees reflected on the second stage of demand, ranking the core sectors that could potentially benefit from GH2 by their feasibility in Costa Rica. This data guided this section's analysis of market preferences for technological alternatives. *Table 6* was filled following "*green hydrogen ladder*" perceptions of the potential substitutes that GH2 faces at each level depending on its usage (Liebreich, 2021). The last columns include the differentiator factors and the Costa Rican approach; dark blue cells show each case's potential "winners".

Alternative technologies are diesel, electric, and hybrid cars in the transport sector. Each technology suits certain types of vehicles: "*In light transport (...) it is convenient to use electric vehicles with batteries, while in heavy or long-distance transport hydrogen is better.*" (Interviewee IE). Hence, focusing on heavy-use transport will open a window if diffusion takes place.

Furthermore, this niche has a clear opportunity to expand as most of its potential usages are not being implemented in Costa Rica and do not present apparent alternatives yet. Multiple interviewees were optimistic about: synthetic fuels, green ammonia, fertilizers, and energy storage uses. (*IA1, As, IE...*).

Table 6: Technological alternatives to green hydrogen peruse; expectations for Costa Rica.[3]

Usage	Green Hydrogen	Alternative	Difference	Costa Rica Approach
Transport (heavy-duty & light)	Heavy-duty	Electricity/Batteries for Light transport	Energy efficiency	Now: Fuel cell bus and Toyota Mirai Future: Heavy-duty transport; off-road
Chemicals and processes	Ammonia and fertilizers	Biomass/ Biogas	No alternative	Now: Steel (Numar) and medical devices. Future: fertilizers, e-fuels, green ammonia
Energy storage /power	Long-run & high volume	Batteries for short-run & small volume	Energy efficiency for volume	Now: hydro & geothermal as a base dispatch & back up for VRES. Future: back-up for renewables
Industrial Heat		Gas LP	Price, energy efficiency, and NO emission	Now: Cement Future: H2 as a substitute for LPG and heavy fuels like bunker & fuel oil.
Aviation and shipping	E-fuel	Biofuel	They will complement each other	Only aspiration, "Utopia."

GH2 presents competitors from alternative technologies in the first stage of the supply chain. Costa Rica's energy surplus is sold to neighbouring countries in the regional market-SIEPAC. However, I2 threatens potential demand losses on the frontiers. Hence, the need to relocate this energy surplus together with ARESEPs may be opening a clear window.

[3] Table content reviewed by a green hydrogen industry expert.

Green Hydrogen could benefit from this momentum, but there might be more parties interested in using it for heavy electricity activities, such as "green data centres" and "cryptocurrencies farms" (*I2*). International actors also showed interest in using this surplus to establish hydrogen production plants in Costa Rica. However, the volume of energy required would entail rethinking how sustainable the redistribution of resources could be (*SPU1*).

Regarding the geographical and temporal development of market demand, it is essential to highlight that the geographical location of the existing demand has been concentrated in Guanacaste. *Relaxury* is the intermediary between Ad Astra and the users, who gather in a luxury condo named Las Catalinas and a nearby hotel complex. A potential barrier to growing the market is the limited availability of the infrastructure for fueling. As ND3 indicates, the fuel cell cars need to limit the scope of usage as it needs to be recharged in Liberia. For demand to be expanded geographically, supply may need to do the same due to technical dependencies. NS2 disclosed:

> *There should be at least one hydrogen plant in San José so that vehicles can travel from Liberia, refuel there, and continue. This way, we can motivate investors and companies to start populating the country with hydrogen stations to develop a hydrogen infrastructure at the national level.*

The innovation biography (see section 5.1) provides a detailed timeline of the historical milestones to understand the temporal development of the market demand. Demand has not changed much over time, but diffusion and strategic alliances may encourage new actors to bet on GH2. End-users are still learning what GH2 is. Interviewees claimed that citizens used to fear the GH2 technology, relating its use with explosion risks (*ND2*). *Figure 10* showed that 53% of the participants perceived *social acceptance* as a neutral factor for GH2 development, mainly due to the lack of knowledge, but there is no opposition anymore. The first end-users in Costa Rica have tried the fuel-cell cars Toyota Mirai, and *ND3* mentioned that their rental service has already gained the attention of curious tourists. ND3 was hopeful about the new generations' role; *Millennials* tend to be environmentally conscious and hence more interested in this kind of innovation. This incoming group of end-users, coupled with an increasing diffusion, may open a demand window at the end of the GH2 value chain.

Institutional/public policy window

Lee and Malerba (2017) argue that the institutional window can be opened through public intervention in the sector or radical institutional changes. The authors distinguished formal public policies from informal declarations of purpose (i.e., declarations, national plans, or targeted goals). Notably, Gosens, Gilmanova, and Lilliestam (2021) conceived the disruptive power of institutional actions particularly relevant in formative sectors, compared to their limited impact in mature sectors. The authors distinguished government interventions and technical standards as the critical window openers.

Regarding informal commitments, Costa Rica's latest national plans were ambitious for decarbonization and green hydrogen development among governing bodies. However, *NS2* seemed to be reluctant about the National Decarbonization Plan impact, as it was published four years ago in 2018, and it still lacks intense action. Even though there is a "*National Green Hydrogen Strategy*" and a roadmap under construction, interviewees were optimistic and expectant about it. In theory, it is supposed to be published in the second semester of 2022. Carlos Alvarado ruled the government when these plans were published, and he travelled around Costa Rica in the fuel cell hydrogen bus. Noteworthy, this investigation took place during national elections. The new government concerned multiple interviewees, raising the question about the continuity of the ongoing initiatives. *ND2* showed this feeling of uncertainty and asserted: "*I hope the next government maintains this decarbonization vision. Because it plays a fundamental role, where they are direct public policies, incentives, and fiscal benefits, that is where the economy goes.* On April 4th, Rodrigo Chaves was elected president so that the institutional framework might change. This raises the question about the inclusion of green hydrogen in the political agenda; if it persists that may be feeding the openness of institutional windows

***Table 7: Institutional Initiatives that encouraged Green Hydrogen in Costa Rica*[4]**

Name	Type	Authority	Year	Status
Green Hydrogen tariff (0,07 USD/kWh).- Resolution RE-0008-IE-2022	Tariff	ARESEP	2022	In force
National Green Hydrogen Strategy	Roadmap	MINAE	2022	Pending
Policy for surplus resources use in the National Electricity System to develop a green hydrogen economy. (Policy Executive Decree N° 43366)	Public policy	MINAE and ARESEP	2021	In force
Law for promoting and implementing a green hydrogen economy in Costa Rica. File NO. 22.392 (Executive decree N°43273-MP)	Law draft	Legislative Assembly (if approved, ARESEP tariffs)	2021	Pending
National Determined Contribution	Formal Commitment	MINAE	2020	In force
Technical Committee for determining green hydrogen technical standards	Technical regulation	INTECO & MINAE	2020	In force
National electric transport plan 2018-2030	Formal commitment	MINAE, DGM & SEPSE	2019	In force
Law for the transformation of RECOPE for the contribution to the energy transition- Expedient N.° 21.343	Law draft	Legislative Assembly	2019	Pending
National Decarbonization Plan	Formal Commitment	MINAE	2018	In force
Law N° 9518 Incentives and promotion for electric transport	Law	MINAE, MOPT & ARESEP (tariffs)	2018	In force
Official list of exempted goods according to Article 38 of the Law on the Regulation of the Rational Use of Energy, Law No. 7447 of 03 November 1994 and its amendments- N° 41121-MINAE-H	Tax exemption	MINAE	2018	Updated to include H2 production
Inter-institutional Action Plan to promote the use of hydrogen in the transport sector. (Directive N° 002-MINAE)	Formal Commitment	MINAE & other	2018	In force
National Energy Plan 2015-2030	Formal Commitment	MINAE	2015	In force

Source: Author's elaboration after interview and public document analysis

[4] Table content double checked with experts from Costa Rica's institutions.

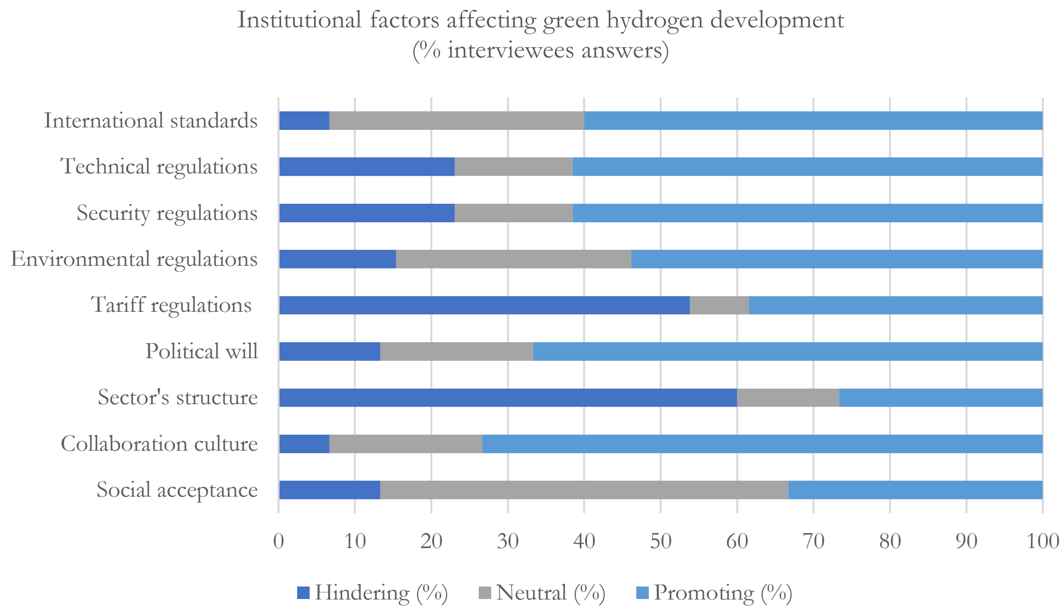
Gosens, Gilmanova, and Lilliestam (2021) emphasized the importance of "market-formation policies" regarding formal public interventions. Table 7 gathers policies, law bills and formal commitments that interviewees conceived as crucial for decarbonization and the promotion of green hydrogen. The data from this table was cross-checked with public documents and experts. Costa Rican authorities like MINAE, ARESEP, or INTECO have overseen the drafting and publishing of these policies and regulations. The first efforts toward decarbonization began with the new government entering into force in 2018, but the specific bills for green hydrogen have been concentrated in the last two years. Tax incentives for hydrogen equipment imports, the energy surplus usage law, the hydrogen tariff (7ct/Kwat), and INTECO's tropicalization of international standards have recently entered into force. Interviewees were particularly excited about the potential opportunities of ARESEP's upcoming H2 tariff and the energy surplus utilization law. The potential benefits from each of them are yet to occur, so they deserve attention as they might open institutional windows of opportunity.

Regarding the role of technical standards, Gosens, Gilmanova, and Lilliestam (2021) claim that they tend to be unclear in formative sectors. However, in the case of the hydrogen industry, the standards require adjustments from the old scheme constructed for grey hydrogen so that it might be a faster process. For example, the certification CertifHY already exists in Europe to ensure the green origin of hydrogen. For that matter, Costa Rica may present a comparative advantage, as its hydrogen can be easily certified based on its renewable energy matrix. Additionally, once INTECO is done "tropicalizing international hydrogen standards to be used here" (*IA1*), Costa Rican equipment will soon meet all security and technical standards. *IE* claimed that acquiring these certifications will potentially allow Costa Rica to enter the so-called "premium market" in countries with restrictions on the emissions of the products they import, such as green ammonia. Hence, institutional windows may also be fostering demand windows in a way.

5.1. Green hydrogen path-breaking opportunities

Interviewees reflected on how institutional factors (see Appendix C, Section II) promote, hinder, or do not affect green hydrogen niche development. *Figure 10* summarizes the participants' answers in percentages, providing an overview of their perspectives on what is crucial to scale up and the main impediments. Regarding the potential hindering factors, interviewees refer to the sector's structure (60%) and the tariffs (53%). For the first case, the structure of the energy sector is said to promote green hydrogen development in terms of production and use (*A, SPU1*). However, its monopolistic nature impeded interested actors from joining the niche. Tariff regulations were initially perceived as a hinder due to the high electricity prices, but most interviewees were hopeful about the newest incentives (see innovation biography).

Figure 10: Interviewees' perspectives on the role of institutional factors in the development of green hydrogen



Source: Author's elaboration based on interview data, structured part.

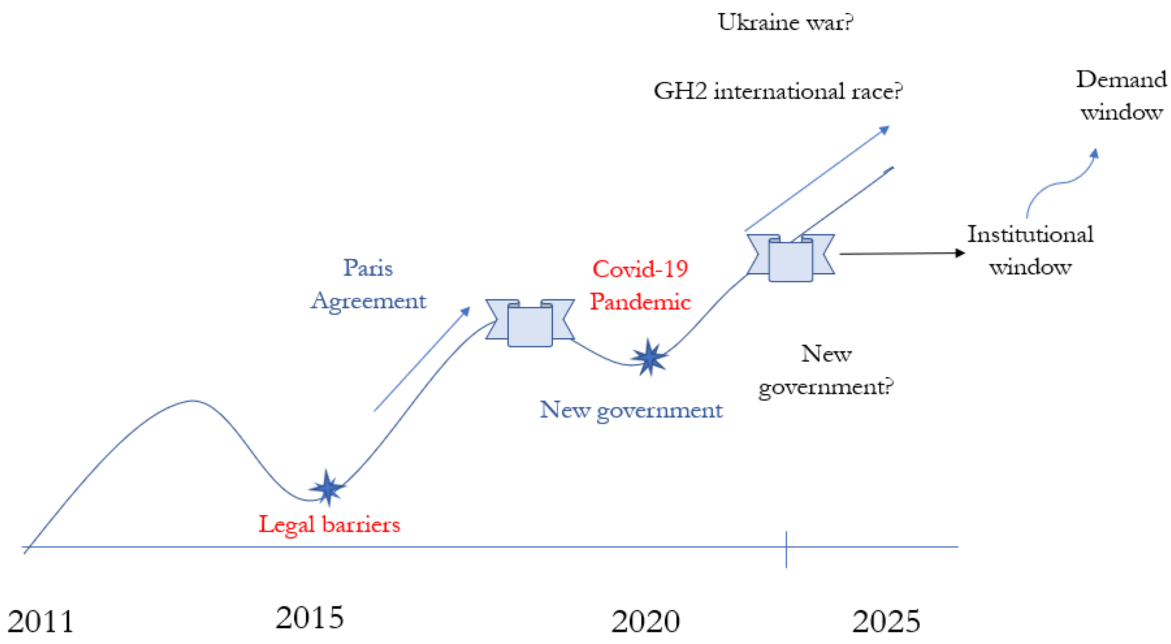
Concerning the factors promoting green hydrogen development, 73% of interviewees insisted on the importance of a collaboration culture. Participants' perspectives align with Clarke and Roome's (1995) assumptions about the crucial role of networks in fostering incremental environmental changes. As *IA3* explains, predisposition feeds the awareness that green hydrogen needs "*to generate the demand, you have to bring in the supply and generate the market mechanisms to make it accessible."* With regards to the role of political will, 66% were optimistic, which suggests that there might be a government-driven knowledge base under construction, a crucial factor for Korea, Choi, Park & Lee (2011). International standards and technical and security regulations were also perceived as the primary enablers, while social acceptance is neutral. This overview allowed the researcher stakeholders' expectations, which Budde, Alkemade & Weber (2012) regarded as crucial to accelerating technological niches.

Expectations may also shape which windows of opportunity could be promising. Lee and Malerba (2017) defended technological windows as critical for industries to forge ahead. However, the level of maturity and the sector at stake also determine how these windows can evolve. Gosens, Gilmanova, and Lilliestam (2021) argue that institutional windows might be more effective for emerging sectors than mature ones. Meanwhile, Yap and Truffer (2019) contend that actors from latecomer environments- like Costa Rica in the GH2 sector- would benefit if they actively create new windows through innovative institutional initiatives. What could be the case in Costa Rica?

The Green hydrogen niche is trying to enter an immature sector so that it may face frequent and drastic changes during its development. During the last ten years, what Geels (2017) refers to as "landscape pressure" has influenced when windows open and close. With this research, windows are not conceived in catch-up cycles but with a more internal view. Hence, more simply, the evolution of the firm Ad Astra Rocket represents the green hydrogen niche; and the energy and transport sector form the socio-technical regime. Moreover, some events have destabilized the system during the last years in what Geels (2002) calls "landscape pressures". Figure 11 presents some of the events that have impacted the green hydrogen niche in a preliminary form. The innovation biography (see section 5.1.1) provides an overview of the historical milestones of the niche, which aligned with this figure. Events like the COVID-19 pandemic, a change in the government, the Ukraine war or electricity and fuel skyrocketing prices; can destabilize the regime and potentially open a window. According to Lee and Malerba (2017), windows could open in the same industry simultaneously or sequentially; this case may present a sequence.

In light of the findings, most participants sounded hopeful about the potential impact of the new public policies and tariffs. However, there is a barrier concerning the energy sector structure, so an institutional window would be able to open if significant structural changes took place. Most interviewees indicated the urgent need to promote public-private associations to integrate all the potential actors that could help boost this niche. Furthermore, the change of government may also pose a challenge. If some public policies succeed, that may open a demand window. First, it might attract demand from other sectors and other countries. Evidence showed that Costa Rica presents a comparative structural advantage and can benefit from knowledge spillovers regarding technological windows. However, the main issue concerning technological advances is costs and infrastructure, requiring more time.

Figure 11: GH2 niche development, windows and landscape pressures



Source: Author's elaboration based on interview data

There is an external pressure included in Figure 11 named *GH2 international race*, and it refers to the interviewees' perspectives on the industry competition. There seems to be a race across countries to be the leaders in this formative sector. Interviewee IA2 assured that "*the first to arrive is the one that gets the most out of the technology.*" As Gosens, Gilmanova, and Lilliestam (2021) warn, a window that may open in an industry does not mean that companies will benefit immediately; it also depends on internal efforts. External pressure can encourage niche players to build industry-specific capabilities. Balancing niche efforts with institutional windows at the regime level could create room for expanding the green hydrogen sector until it becomes a viable alternative to decarbonizing transport.

6. Concluding remarks

This research contributed to the limited literature about green hydrogen and sustainability transitions towards net-zero goals, framing the study in an understudied context: Costa Rica. The research design restricts the generalizability of the results mainly due to potential bias, sample size, and the lack of technical estimations. Notwithstanding these limitations, the study suggests that interviews add value to the field's current exploration and limited academic attention. From a theoretical point of view, this paper contributes to depicting eco-innovations dynamics to learn how they can be path-breaking, especially in formative sectors like clean-tech.

Green hydrogen is a potential tool for transport decarbonization in Costa Rica and worldwide, but a cautious interpretation is required, as this is only one piece of a big puzzle. Even if this technology could help decarbonize certain sectors, perceiving it as the only solution might be a mistake. As Geels (2017) highlights: "*there is no "one-size-fits-all" blueprint for accelerating low-carbon transitions*", which means that solutions shall be individually tailored to the problems that affect each sector, and its specific context. Strategic pilots and roadmaps are crucial to ensure proper technological implementation. Costa Rica's GH2 niche is currently tiny, but additional defies will appear if it manages to scale up, raising questions about how sustainable GH2 massive deployment could be. For instance, some interviewees were concerned about the extensive electricity demand from foreign investors willing to establish a green hydrogen plant, as it may require resource distribution. Likewise, GH2 production requires distilled fresh water, and Guanacaste is a region with water stress, which means scaling up may have a social impact.

The current study explores how the Costa Rican energy sector shapes green hydrogen's development. Building on Cecere et al. (2014), Costa Rica's energy and transport sector seems to face multiple barriers. First, cost-related issues regarding hydrogen production equipment, storage, transport costs and particularly electricity prices. Secondly, the stakeholders that compose each sector concentrate power in a few hands, leading to outdated financial and legal instruments, administrative slowness, institutional discoordination, and overall structural challenges. Thirdly, the green hydrogen niche is perceived as complex due to low diffusion between and within sectors. These categories reinforce the existing processes that lead to system lock-ins and path dependence across stakeholders. Green hydrogen is a technology that could be path-breaking, but there seems to be an institutional gap regarding who would oversee this new sector. Despite its limitations, the study certainly adds to our understanding of the mechanisms to overcome these barriers and manage the green hydrogen niche to develop in Costa Rica.

The research also identified potential windows of opportunity for GH2 based on Gosens, Gilmanova, and Lilliestam's (2021) theory. Three windows are analyzed to identify how external pressures could destabilize the existing regime and make some space for the green hydrogen niche in Costa Rica, inspired by Geels's (2017) MLP framework. For the niche to profit from the potential windows, internal efforts need to coincide, and the expanding network that Costa Rica is building may be a good starting point. Furthermore, this central American country has a comparative advantage due to its clean energy matrix, environmental reputation, energy surplus, and low installed capacity. Those factor endowments combined with the knowledge spillovers from leading countries (Gerschenkron,1962) could lead to fast GH2 technological advances.

The final reflection on section 5.1. concluded that the institutional might be the first to open among the three windows, thanks to the new market formation policies and the upcoming national roadmap. Afterwards, demand windows could appear at different stages of the value chain. The existing project focuses on GH2 appliances for land transportation, as Costa Rica's approach; but it also explores how other sectors could benefit from this technology. Still, there are many unanswered questions about how and who should start using this technology. Nevertheless, both scholars and interviewees emphasized the importance of distinguishing when GH2 would be the only solution; and when it may play a complementary role with batteries or biogas.

The findings of this study have an array of future practical implications for green hydrogen development. Pisu and Villalobos (2016) perceived poor intermodal connections in the transport sector as well as an aversion to private sector participation. The first step might be tackling this issue by promoting public-private collaboration to overcome structural flaws assuming the legal complexity. Moreover, GH2 could create employment, so it is crucial to prepare human capital for making this technology sustainable, so reinforcing the link with academia could help.

Multiple challenges were identified in the study, raising many questions needing further investigation. Ad Astra seems to be the sole driver of green hydrogen. Its stakeholders have emerged around Guanacaste, so it could be interesting to investigate how this project expands and depicts if it gives birth to a geographical cluster. Further work is needed to predict how green hydrogen competitors could benefit from the energy surplus tariff (i.e. data centres) or how inputs like oxygen could impact this niche. These results add to the rapidly growing field of green hydrogen and decarbonization, and it sets a starting point to expand the academic work in this specific context.

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8. Appendix

8.1. Appendix A: On-site implementation

Table A8: Plan for the practical on-site implementation

November	• Research Proposal: refine the research question and narrow the aim and scope.
December	• Design Interview Guide • Do a pilot interview for time estimation
January	• Deliver methodology section • Prepare for the fieldwork: research diary, voice recorder…
February	• Attend CINPE seminars to specify the details of the Innovative Practice in San Jose. • Start contacting participants and networking.
March	• Interviewing participants, real-time recording, and immediate transcriptions. • Participant observation- aim to visit Hydrogen power source.
April	• Interviewing participants, real-time recording, and immediate transcriptions. • Coding transcriptions in NVivo.
May	• Analyzing qualitative data in NVivo; interpreting results, and writing discussion. • 13th May: Final draft • 27th May: submit the final thesis
June	• 6-10th June: Presentation

8.2. Appendix B: Consent Forms

8.2.1. Consent Form (Spanish)

La tropicalización del hidrógeno verde:
Un estudio de caso en Costa Rica

Esta entrevista forma parte de un proyecto de investigación para la tesis sobre el sistema sectorial de innovación en el que se integra el hidrógeno verde en Costa Rica. El proyecto está financiado por la Fundación Crafoord y se lleva a cabo en la Universidad de Lund (Suecia), como parte del Máster en Innovación y Desarrollo Global Sostenible. El proyecto también cuenta con el apoyo de CINPE, centro de investigación adscrito a la Universidad Nacional de Costa Rica (UNA).

Este proyecto pretende identificar los actores más relevantes que conforman el sistema de innovación sectorial en el que se ancla el caso del hidrógeno verde como vector energético. Los elementos clave que componen un sistema de innovación sectorial son los actores, las redes, la base de conocimientos y las instituciones. Esta nueva tecnología ha sido analizada en múltiples informes a nivel estadístico, y actualmente se incluye enmarca en iniciativas nacionales como el Plan Nacional de Descarbonización o el futuro Plan Nacional de Hidrógeno. Sin embargo, desde el punto de vista académico no existe un marco teórico claro en el que se especifique la dinámica que ha seguido esta tecnología y el proceso de innovación del sector. Esta investigación tratará de reunir no sólo a los actores relevantes a nivel nacional, sino también a los internacionales, que últimamente han sido notablemente útiles en términos de financiación. Para ello, se basará en datos recogidos a través de entrevistas semiestructuradas con los actores de diferentes ámbitos como el sector privado, el sector público, organizaciones multilaterales o las cooperativas

El proyecto está dirigido por la estudiante de maestría Marta Hergueta y supervisado por la profesora Cristina Chaminade.

Formulario de consentimiento para la entrevista - entrevistas individuales

La entrevista se grabará digitalmente y el entrevistador tomará notas. Tanto las notas como las grabaciones serán confidenciales. Dado que las entrevistas pueden conllevar riesgos al hablar de información sensible, trataré de mitigar dichos riesgos mediante una estricta protección de los datos en un entorno de software protegido por contraseña. Sólo el director del proyecto y los investigadores de este tendrán acceso a las notas.

Su identidad personal permanecerá en el **anonimato**. No se le atribuirá directamente ninguna opinión en ningún documento que se elabore a partir de las entrevistas. Sin embargo, el nombre de su empresa o institución puede aparecer en el informe, a menos que usted indique explícitamente lo contrario.

La información recogida en este estudio se utilizará para contribuir a la tesis. Se presentará como tesis de máster y también podrá aparecer en forma de informe, ponencia para un coloquio y/o artículo científico publicado.

Consentimiento

Por la presente, acepto participar en esta investigación en las condiciones arriba indicadas.

Entiendo que si decido participar en este estudio, mi participación es libre y voluntaria, y tengo derecho a retirar mi consentimiento para participar o a interrumpir mi participación en cualquier momento sin penalización ni consecuencias negativas.

Acepto que se grabe mi participación en el estudio Si ☐ No ☐

Nombre del participante	Firma del participante	Fecha
…………………………	………………………..	……………………

Si tiene alguna pregunta sobre sus derechos como participante de la investigación en algún momento respecto al estudio, contácteme a través del correo ma7705he-s@student.lu.se o por WhatsApp al número +34634209556, o por teléfono +50663108245. El contacto del correo de la supervisora es: cristina.chaminade@ekh.lu.se

8.2.2. Consent Form (English)

The tropicalization of green hydrogen: A case study in Costa Rica

This interview is part of a thesis research project on the sectoral innovation system integrating green hydrogen in Costa Rica. The project is funded by the Crafoord Foundation and is carried out at Lund University (Sweden) as part of the Master in Innovation and Global Sustainable Development. The project is also supported by CINPE, a research centre attached to the National University of Costa Rica (UNA).

This project aims to identify the most relevant actors that make up the sectoral innovation system in which the case of green hydrogen as an energy vector is anchored. The key elements that make up a sectoral innovation system are the actors, networks, knowledge base and institutions. This new technology has been analysed in multiple reports at the statistical level. It is currently included in national initiatives such as the National Decarbonisation Plan or the future National Hydrogen Plan. However, from a theoretical point of view, there is no clear theoretical framework specifying the dynamics of this technology and the innovation process in the sector. This research will attempt to bring together the relevant actors at the national and international levels, which have recently been remarkably helpful in terms of funding. For this purpose, it will be based on data collected through semi-structured interviews with actors from different fields such as the private sector, the public sector, multilateral organisations and cooperatives.

The project is led by Master's student Marta Hergueta and supervised by Professor Cristina Chaminade.

Interview Consent form – individual interviews

The interview will be digitally recorded, and the interviewer will take notes. Both notes and recordings will remain confidential. We are aware that these interviews may include risks by discussing sensitive information. These risks will be mitigated by strict data protection in a password protected software environment. Only the project leader and the researchers in the project will have access to the notes.

Your personal identity will remain anonymous. No views will be directly attributed to you in any document that may be produced from the interviews. Quotes may be used discretely. However, your firm's name or institution may be known in the report unless you explicitly indicate otherwise.

The information gathered from this study will be used to contribute to the thesis. It will be presented as a master thesis and may also appear in the form of a report, a paper to a colloquium and/or a published scientific paper.

Consent

I hereby agree to participate in this research under the conditions above.

I understand that if I decide to participate in this study, my participation is free and voluntary. I have the right to withdraw my consent to take part or stop my participation at any time without penalty or negative consequences.

I hereby agree to the tape recording of my participation in the study Yes ☐ No ☐

Participant name	Participant signature	Date
……………………………….	……………………….	……………………

If you have any questions about your rights as a research participant or are dissatisfied with any aspect of the study, you may contact Marta Hergueta on the email ma7705he-s@student.lu.se or the WhatsApp number XXXX or mobile XXXX. The thesis supervisor is Professor Cristina Chaminade, and her contact email is: XXXX

8.3. Appendix C: Interview guide

8.3.1. Section I: Open-ended questions (Spanish)

Introducción del proyecto y presentación- Innovación sectorial en las energías limpias de Costa Rica: Un estudio de caso sobre el hidrógeno verde.

Formulario de consentimiento y grabación

Introducir los bloques siguientes

Introducción de la empresa/ persona

- ¿Cuáles son sus responsabilidades en X?
- ¿Podría describir brevemente el papel de X en el sistema costarricense de energía?

Descarbonización

- ¿Cómo ha contribuido X al plan nacional de Descarbonización?
- ¿Quiénes son los principales actores en el proceso de descarbonización?
- En su opinión ¿Qué innovaciones pueden contribuir a descarbonizar CR?
- ¿Qué papel juega X en estas innovaciones que ha mencionado? (I.e.: regulador, financiación, apoyo técnico, infraestructura...)

Ahora quisiera centrarme en el caso del Hidrógeno verde como una de esas innovaciones.

- ¿Cuál ha sido el papel de X en la promoción de producción e innovación de Hidrógeno verde? Si no ha estado implicado - ¿Por qué no?
- ¿Qué actores destacaría en la emergencia y desarrollo de este nicho? ¿y en su financiación?
- ¿Cuáles son los principales hitos en el desarrollo del H2 verde en Costa Rica (en una perspectiva histórica)?
- ¿Cuáles son sus perspectivas a futuro?
- Hasta las fechas, los estudios publicados sobre esta tecnología califican estas iniciativas como “nicho” de mercado ¿Por qué cree que el H2 verde sigue siendo un nicho?

- Entre estos posibles usuarios ¿Dónde se concentra la demanda de H2 verde en Costa Rica?

Redes

- ¿Con que actores colabora X en el proyecto de Hidrógeno verde? ¿De qué manera?
- Dónde se encuentran ubicados estos actores (regional, nacional, internacional)

Barreras y oportunidades

- ¿Cuáles son las principales barreras que impiden el desarrollo del H2 verde?
- En el contexto global, ¿Qué oportunidades tiene Costa Rica para aprovechar el gran potencial del hidrógeno verde?
- ¿Cómo podría escalarse el uso de esta tecnología?
- ¿Qué pediría a las autoridades políticas para mejorar esto?
- ¿Hay algo que no haya preguntado y que en su opinión sea importante para entender el desarrollo del H2 verde en Costa Rica, en el marco del Plan de Descarbonización?

8.3.2. Section I: Open-ended questions (English)

Project introduction and presentation - Clean energy sector innovation in Costa Rica: A case study on green hydrogen.

Consent form and recording

Enter the following blocks

Introduction of the company/individual

- What are your responsibilities in X?
- Could you briefly describe the role of X in the Costa Rican energy system?

Decarbonization

- How has X contributed to the national Decarbonisation plan?
- Who are the main actors in the decarbonisation process?
- In your opinion, which innovations can contribute to decarbonising CR?
- What role does X play in these innovations (e.g. regulator, financing, technical support, infrastructure...)?

Now I would like to focus on the case of Green Hydrogen as one of these innovations.

- What has been the role of X in promoting green hydrogen production and innovation? If it has not been involved - why not?
- Which actors would you highlight in the emergence and development of this niche and its financing?
- What are the main milestones in the development of green H2 in Costa Rica (from a historical perspective)?
- What are its future prospects?
- Published studies on this technology qualify these initiatives as a "niche" market. Why do you think green H2 remains a niche?
- Where is the demand for green H2 concentrated in Costa Rica among these potential users?

Networks

- With which actors does X collaborate in the green hydrogen project? In what way?
- Where are these actors located (regional, national, international)?

Barriers and opportunities

- What are the main barriers to the development of green H2?
- In the global context, what opportunities does Costa Rica have to take advantage of the great potential of green hydrogen?
- How could the use of this technology be scaled up?
- What would you ask policymakers to do to improve this?
- Is there anything you have not asked that is important to understand the development of green H2 in Costa Rica in the framework of the Decarbonization Plan?

8.3.3. Section II: Structured questions (Spanish)

Existen una serie de aplicaciones del h2 en distintos sectores. A continuación, se presenta una lista que resume los principales sectores que podrían beneficiarse. ¿Cómo ordenaría estas categorías opciones de forma jerárquica en función de su viabilidad en Costa Rica? Por favor explique el porqué de su elección.

- Calefacción (calor industrial de alta temperatura, calefacción comercial, calefacción domestica…)
- Aviación y envíos por mar (barcos costeros y fluviales)
- Transporte terrestre (tren, autobús, camiones regionales, vehículo todoterreno…)
- Sistema de energía (almacenamiento a largo plazo, red insular…)
- Procesos y químicos (fertilizantes, hidrogenación, metanol, desulfuración, acero…)

¿Añadiría alguna más?

REDES

- ¿Qué tipo de conocimiento considera que es más importante para el desarrollo de este nicho en la actualidad? – Utilizar este cuadro

Tipo de conocimiento	Importancia
Conocimiento científico	1 2 3 4 5
Conocimiento técnico	1 2 3 4 5
Conocimiento de gestión	1 2 3 4 5
Conocimiento del mercado	1 2 3 4 5
Otro	1 2 3 4 5

- ¿Existe este conocimiento actualmente en Costa Rica?
- ¿De dónde viene cada uno de estos conocimientos?

BARRERAS Y OPORTUNIDADES

Rellene el siguiente cuadro según su opinión respecto a cómo una serie de factores institucionales dificulta, promueve o no aplica para el desarrollo de esta tecnología.

Factores institucionales	Dificultando	Neutro	Promoviendo
Aceptación social			
Cultura de la colaboración (los actores están dispuestos a ayudarse)			
Estructura del sector			
Voluntad política			
Regulaciones			
- Tarifarias			
- Ambientales			
- Seguridad			
- Técnicas			
Estándares internacionales (ej. Certificaciones)			

8.3.4. Section II: Structured questions (English)

There are several h2 applications in different sectors. Below is a list summarising the primary sectors that could benefit. How would you rank these categories of options hierarchically in terms of their feasibility in Costa Rica? Please explain the rationale for your choice.

- Heating (high-temperature industrial heat, commercial heating, domestic heating...)
- Aviation and shipping by sea (coastal and river vessels)
- Land transport (rail, bus, regional trucks, off-road vehicle...)
- Energy system (long term storage, island grid...)
- Processes and chemicals (fertilisers, hydrogenation, methanol, desulphurisation, steel...)

Would you add any more?

NETWORKS

- What kind of knowledge do you think is most important for developing this niche today? - Use this table

Type of knowledge	Importance
Scientific knowledge	1 2 3 4 5
Technical knowledge	1 2 3 4 5
Management knowledge	1 2 3 4 5
Market knowledge	1 2 3 4 5
Other	1 2 3 4 5

- Does this knowledge currently exist in Costa Rica?
- Where does each of this knowledge come from

BARRIERS AND OPPORTUNITIES

Fill in the following table according to your opinion on how a series of institutional factors hinder, promote or do not apply to the development of this technology.

Institutional factors	Hindering	Neutral	Promoting
Social acceptance			
Collaborative culture (actors are willing to help each other)			
Sector structure			
Political will			
Regulations			
- - Tariffs			
- - Environmental			
- - Safety and security			
- - Technical			
International standards (e.g. certifications)			

8.4. <u>Appendix D: Codebook</u>

8.4.1. Codebook

Table 9: Codebook

Themes	Sub-themes	Codes	Nº References
Barriers	Cost-related factors	Economic	3
		Infrastructure	7
		Price	12
	Niche complexity	H2 transport	1
		Low demand	1
		Market dynamics	1
		Resource redistribution	2
			3
	Stakeholders	Academia	9
		Human capital	9
		Institutional uncertainty	1
		Lack of alignment	6
		Limited Participation	15
		Low legal security	1
		Low Political support	1
		Old financial mechanisms	1
		Opposition	2
External pressure		Climate change	1
		Energy Independence	2
		Oil prices	3
		Race	4
How to scale up		Economic needs	17
		Technical needs	18
Innovation biography		Cluster	7
		Historic milestones	46
		Innovation	13
		Network	22
		Transport decarbonization	6
Verbal data from tables	H2 USES	Alternative fuels	4
		Aviation	3
		Chemicals	1
		Heavy-duty transport	8
		Industry	4
	Institutional Factors	Collaboration culture	15
		Energy sector structure	16
		International standards	12
		Political will	15
		Regulations (Environmental; Security; Tariffs; Technical)	55
		Social Acceptance	15

	Knowledge sources	• Technical • Scientific • Market	5 3 8
Windows of opportunity	Demand window	• Demonstration • Diffusion • Energy surplus • Exports • International Funding	7 10 10 13 6
	Institutional window	• New government • Private sector • Public policies • Public-private collaboration • Strategic alliances	7 6 3 2 3

	Technological windows	• Comparative Advantage
		  ○ Environmental reputation
		  ○ Exemplary energy matrix
		  ○ Size
		  ○ Strategy
		• Innovative solutions
		• Value chain
			36
			9
			9
			6
			12
			8
			5