SM1 SUPPLEMENTARY MATERIAL

CHAPTER 3

Identifying opportunities and risks based on the case of Ceará

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This is the supplementary material to Chapter 3 of the Ph.D. Thesis by Clara Rabelo Caiafa Pereira, entitled "Structural change in a green hydrogen economy: socioeconomic and climate change implications", to be defended at the Eindhoven University of Technology on the 6th of February of 2026.

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SM1.1. Statement of positionality of the researchers

The research team comprised three researchers, two Dutch nationality and one of Brazilian nationality. This mix of nationalities allowed researchers to better understand some contextual information and navigate cultural differences in this research. The researchers recognize that the choice of case study was probably partially influenced by the nationalities of the researchers and the attention they see the case receiving in their countries.

All three researchers have experience in working with climate, energy, and development/industrial policies and projects in developing countries, both from a research and practitioner position. All of them have an active engagement with international cooperation projects and processes, and have in many different circumstances experienced situations where concerns about trade-offs between economic development and climate policy were framed as a barrier to promoting sustainability transitions and economic development in developing countries.

This awareness about the importance of addressing synergies and trade-offs between economic development and climate goals to enable ambitious climate action, together with the belief that international cooperation in innovation and technology transfer should avoid past failures to enable developing countries to promote development and technological catching up, were personal motivations for choosing this topic. The researchers acknowledge that these motivations probably had some influence on the choice of focusing in these two aspects of sustainable development instead of other relevant areas such as health benefits and gender equality.

SM1.2. Information on interviews and coding procedure

Interviews were conducted with stakeholders throughout the green hydrogen value chain in Pecém. Sample size was defined based on saturation while ensuring representativeness across stakeholder types. The list of interviews can be found in Table II.1. Interviews and documents were coded using Nvivo.

Table SM1.1 – List of interviews

#	Date	Stakeholder type	Origin
1	18/05/2022	Industry Association	Local
2	18/05/2022	Industry Association	Local
3	19/05/2022	Government	Local
4	20/05/2022	Project Developer	Local
5	20/05/2022	University	Local
6	26/05/2022	Government	National
7	26/05/2022	Government	National
8	26/05/2022	Technical Education	Local
9	31/05/2022	University	Local
10	01/06/2022	Project Developer	Multinational
11	09/06/2022	Government	Local
12	18/08/2022	Consultant	International
13	20/09/2022	Technology provider	National
14	20/09/2022	Port	Local
15	21/09/2022	Industry Association	National
16	22/09/2022	Potential Green Hydrogen User	Multinational
17	22/09/2022	Potential Green Hydrogen User	Local
18	18/10/2022	Technology provider	Multinational
19	21/10/2022	Port	Local

20	24/10/2022	Government	European
21	18/11/2022	Port	European

Each interview took between 45 minutes and 1h30 minutes. Interviews were recorded and transcribed, after which interviewees read and approved the transcript. All participants signed an Informed Consent Form (ICF), which was approved by the ethical committee of the university of affiliation from the researchers. The ICF declared that data would be anonymized and quotes that could lead to the identification of interviewees would be avoided or that their explicit consent would be requested otherwise. Interviewees were given the choice of conducting the interview in their native language in case of insufficient proficiency in English. Most of the Brazilian interviewees opted for conducting the interview in Portuguese, while interviewees working internationally declared to be comfortable with the interview in English. There was a preference for in-person interviews, but some interviews were conducted online when an in-person meeting was impossible.

Interviews were conducted in a semi-structured format, where interviewees had a high degree of freedom to formulate their answers around five broad questions:

1. In your opinion, what are the main economic opportunities associated with the green hydrogen hub in Pecém?
2. In your opinion, what are the main opportunities for promoting sustainability (i.e. climate change mitigation, energy transitions) associated with the green hydrogen hub in Pecém?
3. What are the challenges to materialize these opportunities?
4. Can you identify any risks associated with the implementation of the green hydrogen hub in Pecém?
5. What can be the role of international cooperation in leveraging opportunities and helping to mitigate risks?

Transcripts were coded on Nvivo in three rounds: a first round, consisting of an explorative phase to identify from an inductive approach what were the main issues at stake and whether any adaptations were needed in the analytical framework; a second round where codes had been pre-defined based on the analytical framework and the inductive round of coding (i.e. influencing factor, project characteristic, opportunity, risk, synergy and/or trade-off across goals and scales); a third-round, after the first draft was ready and reviewed by all co-authors (approximately 6 months after the second round of coding), to double check that all relevant points were addressed in the paper and that no further adjustments were needed in the framework.

Coding of documents followed the same procedure as the coding of transcripts.

SM1.3. Full overview of technology, project and context characteristics

SM1.3.1 Background on the green hydrogen hub at Port of Pecém, Ceará, Brazil

The Green Hydrogen Hub at the Port of Pecém was created in 19 February 2021 via the signature of a MoU between the Government of Ceará (represented by the Secretariat for Economic Development and Employment - SEDET), the Industry Association of the State of Ceará (Federação das Indústrias do Estado do Ceará - FIEC), the Complex of Pecém (Companhia Industrial e Portuária do Pecém – CIPP), and the Federal University of Ceará (UFC). The memorandum established a Working Group to coordinate actions within the state aiming at the implementation of a green hydrogen hub in Ceará (Interviews 1, 2, 3, 5, 11, 14, 15, 19, 21). The government of Ceará mentions two aims driving the development of the hydrogen hub: 1) to become a global player in production, distribution and Green Hydrogen export; and 2) to contribute to the reduction of levels global CO2 emissions as well as to the socio-economic, technological and environmental development of Ceará (Secretariat for Economic Development and Employment, 2022c).

The Working Group signed in December 2021 a contract to jointly elaborate a Master Plan for the Green Hydrogen Hub in Ceará. This master plan would comprise two deliverables: 1) a study identifying existing public policies that can support or hinder the development of a green hydrogen hub in Ceará, including main gaps and recommendations; and 2) a techno-economic feasibility study for the green hydrogen hub in Pecém to identify the best technology options for production, transport and storage of green hydrogen, estimate national and international demand, analyse skills requirements, identify risks and infrastructure gaps, among others.

In addition to the local Working Group, the elaboration of the master plan also received technical and financial support from the Port of Rotterdam and the German bilateral development agency GIZ. A Brazilian consultant with extended living and working experience in Germany has also been supporting the process (Interviews3,8,15,19,21). Ceará will also be receiving support from the World Bank to prepare its infrastructure for receiving the green hydrogen hub (Interview 3)(Secretariat for Economic Development and Employment, 2022b; World Bank, 2023).

Over 20 MOUs have been signed between future project developers and the Working Group by September 2022 to set the main lines, plans and expectations about the hub. These add up to over 20 USD billions in investments announced in the implementation period 2022-2025 (Interviews). The majority of MoUs was signed with multinational companies or Brazilian companies from other states (Table SM1.1). MoUs often include clauses establishing that investors would undertake efforts to source goods and services locally, even though not legally binding (Interviews4,11,14,19). Given announcements in these MoUs, around 9GW of installed electrolysis capacity is expected by 2035, mainly under giga-scale projects (Interviews1,3,15, Figure2).

Table SM1.2 – List of MOUs signed with the Government of Ceará up to November 2022. Elaborated based on Quintela (2022), Secretariat for Economic Development and Employment (2021, 2022d), Secretariat for Infrastructure (2021), as well as Interviews 3, 11, 15 and 19.

	Company name	Company Origin
1	Enegix Energy	Australia
2	White Martins/Linde	Brazil/United States
3	Qair	France
4	Fortscue	Australia
5	Energias de Portugal (EDP)	Brazil (Ceará)/Portugal
6	Neoenergia/Ibérdola	Brazil/Spain
7	H2Hellium	Brazil (Rio de Janeiro)
8	Eneva	Brazil (Rio de Janeiro)
9	Hytron	Brazil (São Paulo)
10	Diferencial Energia	Brazil (São Paulo)
11	Engie	France
12	Total Eren	France
13	Transhydrogen Alliance	European
14	AES Brasil	Brazil (São Paulo)
15	Cactus Energia verde	Brazil (Rio de Janeiro)
16	Casa dos Ventos	Brazil (Ceará)
17	H2 Green power	United Kingdom
18	Energy Vault SA	Switzerland
19	Nexway	Brazil (São Paulo)
20	Mitsui	Japan

21	ABB	Swedish-Swiss (Factory in South and South-East of Brazil)
22	CaetanoBus	Portugal

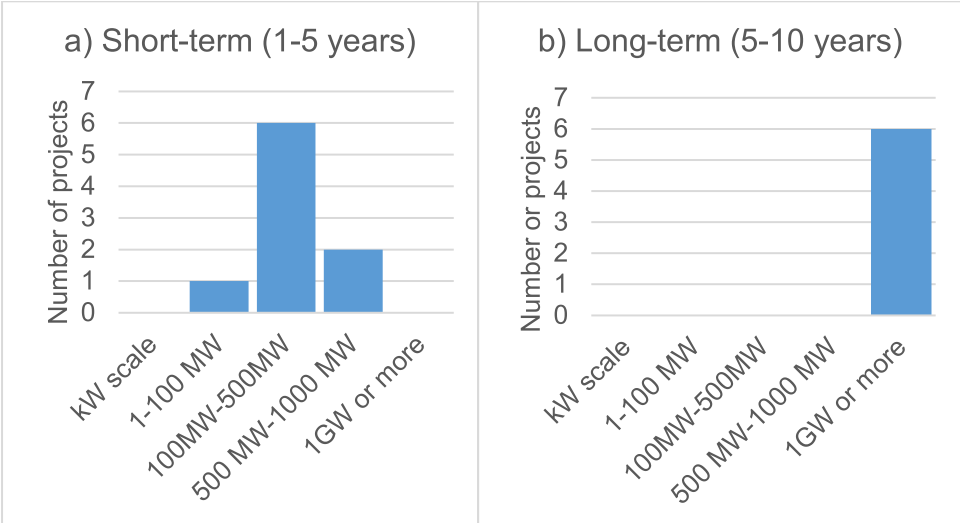

Figure SM1.1 – Capacity of electrolysis projects announced for the HUB H2V in Pecém until September 2022. Elaborated based on Quintela (2022), Secretariat for Economic Development and Employment (2021, 2022d), Secretariat for Infrastructure (2021), and Interviews 3, 11, 15 and 19.

SM1.3.2 Technology factors

Green hydrogen still has a higher cost than fossil-fuel based hydrogen and other low-carbon alternatives (IEA, 2022; IRENA, 2022b). Renewable power cost is the main cost driver, hence reducing renewable energy costs contributes to reduce costs. Other drivers for cost reductions are innovations to improve performance and efficiency, deployment to increase scale, and larger electrolyser plants (IRENA, 2022b).

High electrolyzers' costs has implications for configuration of green hydrogen projects. Firstly, it means electrolyzers need to operate for as many hours as possible in order to pay back investments within a reasonable period (Interviews 4, 12). And indeed, studies looking at hybrid systems in the Northeast of Brazil have concluded that green hydrogen produced only from curtailment events is currently not economically feasible, despite high availability of renewable energy (Macedo & Peyerl, 2022; Nadaleti et al., 2020). Moreover, electrolyzers require less maintenance and have a longer life time (and hence lower life time costs) when they operate continuously instead of being switched on and off (Interview 15). These two aspects demand stable electricity inputs throughout the entire day. If projects are not connected to the grid, this would require over dimensioning wind and solar parks, increasing final levelized costs (Interview 4).

Electrolysis is a capital intensive activity, highly automated and hence with low employment factors. For example, a 20MW plant would require only 1-2 operators per shift (Interviews1,4,15) (NREL, 2018). Electrolysis is also a complex activity, involving high pressure controlled systems, which requires high levels of technical skills and capabilities (Interview8). Nevertheless, it would be considered less complex than fossil fuel based production via Steam Methane Reforming (SMR), implying that workers in fossil fuel production could relatively easily switch to jobs in electrolysis plants(Interview 3).

For long-distances, hydrogen can be transported by pipeline as compressed gaseous hydrogen or by ship. To transport hydrogen by ship, it has to be either liquified, converted to ammonia or to liquid organic hydrogen carriers (IRENA, 2022a). Transport costs are determined by the transport distance as well as the size of the production plant, with shipping being more attractive over long distances (IRENA, 2022a). The need to convert hydrogen to ammonia and the high energy needs to keep temperatures low (-253°C) increase costs for shipping, while technologies for liquid organic hydrogen carriers are under early stages of development (IRENA, 2022a). Due to transport challenges, a more cost-effective alternative would be to shift production of large scale industrial consumers such as iron (and steel), synthetic fuels, and fertilizers, to places where green hydrogen production would be abundant and at lower cost, and then ship the industrial product to final consumer markets (IRENA, 2022a).

SM1.3.3 National context

Brazil has high shares of renewable energy in its energy matrix: in 2020, 84% of total electricity generation and 46% of total energy supply came from renewables (IRENA, 2022c). Renewable electricity generation came from hydropower (64%), biomass (9%), onshore wind (9%) and solar (2%) (IRENA, 2022c). Bioenergy is a main pillar of Brazilian energy supply, accounting for 30% of primary energy, and includes a widespread use of biofuel applications for power generation and transport (Gils et al., 2017).

This high availability of renewables provides Brazil with a CO_2 emission factor for electricity and heat generation about four times lower than the global average (95 tCO_2/GWh against around 400 tCO2/GWh) (IRENA, 2022c). Importantly, large share of hydropower means Brazil has a substantial capacity of dispatchable power and hence additional storage is not a constraint for further expansion of VRE shares in the grid (Gils et al., 2017).

The Brazilian National Energy Plan for 2050 estimates a renewable energy potential around 17 times bigger than the projected total energy demand for 2050, although subject to uncertainties in demand estimation and actual feasibility of resource exploration (EPE, 2020). The greatest potential for solar and wind is in the North-East region (Centro de Pesquisas de Energia Elétrica – CEPEL, 2017; Pereira et al., 2017).

However, some argue that high shares of renewables often ends up delaying more ambitious efforts from the part of the national government, due to a discourse saying that Brazil is already doing enough (Basso, 2018). Indeed, planned capacity expansion for Brazil also includes an increase in Oil and Gas capacities (EPE, 2020), motivated by the full exploitation of the Pré-Sal reserves discovered in 2006 (Interviews 6 and 7). Moreover, Brazil lacks strong, credible, decarbonization targets and policies (Climate Action Tracker, 2022) (Interviews).

This context also impacts choices regarding technological routes for hydrogen production in Brazil (Interviews 6 and 7). The Brazilian energy planning office from the Ministry of Energy and Mining, the Empresa de Pesquisa Energética (EPE), has published several technical notes to guide the elaboration of the Brazilian National Hydrogen Plan (EPE, 2021b, 2021a). They emphasize the need for a hydrogen strategy that valorises Brazil's competitive advantages and hence call for a "rainbow strategy", that would encompass hydrogen from all Brazilian energy sources: not only solar and wind, but also natural gas, bioenergy and hydropower. According to two coordinators of these studies, a "low-carbon" hydrogen strategy would be more adapted to the local conditions than one that ended up leading to "technological lock-ins" into the green hydrogen route, since it would allow Brazil to take the most advantage of its natural resource endowments and existing capabilities, and hence enjoy greater political support (Interviews 6, 7). Indeed, the national electrolyzer manufacturer offers not only electrolyzers for producing hydrogen based on solar and wind, but also systems integrated to hydropower, as well as options for producing hydrogen from bio-ethanol (Interview 13).

Brazil hydrogen innovation policy dates from over 25 years ago (EPE, 2021b; GIZ, 2021). Innovation efforts have led to the creation of several spin-off companies, including the national electrolyzer manufacturer Hytron, the establishment of research labs, and over 10 pilot-and-demonstration projects on topics like storage systems, production from hydro-solar hybrid systems, fuelcells, bio-hydrogen production, among others. RD&D activities are concentrated mainly in the Southeast and Northeast (34%) regions, South (22%), Center (7%) and North (3%)(GIZ, 2021). R&D funding is majorityly (68%) public or publicly-oriented (GIZ, 2021). This is mainly due to a federal law (Lei 9.991/2000) establishing that 0.75% of all revenues from companies from generation, transmission and distribution go to a fund for research to the benefit of the power sector, managed by ANEEL, the Brazilian Electricity Regulatory Agency. In 2021, the National Council on Energy Research (CNPE) published a resolution establishing hydrogen as a priority for public and public-oriented R&D (EPE, 2021b). The ANEEL program is now funding the first pilot-and-demonstration project in Pecém developed by EDP (Interview 10). Important to note is that projects funded by ANEEL are required to use national technologies and share knowledge and results (Interview 10).

The idea that hydrogen should contribute to the development of the national industry is also emphasized in the EPE technical note (EPE, 2021b). Brazil has several factories from manufacturers like ABB and WEG that could supply parts and components across the value chain, except for the stacks that would have to be imported (Interview 13). Nevertheless, most of these factories are located in the South and South-East regions, including for assembly of the electrolyzers (Interview 13). This is due to the fact that industrial production in Brazil is heavily concentrated in these regions (Confederação Nacional da Indústria, 2022).

This implies that domestic hydrogen consumption and decarbonization potential in Brazil would most likely be in the South-East region. This is not only where most of industries and economic activities are (Confederação Nacional da Indústria, 2022), but also where 40% of the population lives (Instituto Brasileiro de Geografia e Estatística - IBGE, 2022), resulting in an energy consumption that is half of total national energy consumption (EPE, 2021c). Nevertheless, Brazil has not yet any directive or even estimations for the potential national consumption of hydrogen (EPE, 2021b; GIZ, 2021). In fact, hydrogen has historically not been included in the energy planning or decarbonization scenarios (Interviews)(EPE, 2020, 2021a). As a result, there is currently no local market developed for the consumption of green hydrogen – or green any products such as green steel –, and also high levels of uncertainty about potential markets in the future (GIZ, 2021).

SM1.3.4 Local context

The state of Ceará is located in the North-East region of Brazil, which is the region with the lowest Human Development Index (HDI) and income per-capita (0.711 and R$517/month against national averages of 0.778 and R$ 834). This means that the average income per capita in Ceará in 2017 was about half of the one from states in the South and South-East such as São Paulo (R$1130), Rio de Janeiro (R$960) and Rio Grande do Sul (R$1073)(UNDP et al., 2022).

Due to its geographical location, Ceará has a high availability of renewable energy resources, together with a daily complementarity between solar and wind and a low seasonality (Government of Ceará, 2022). This increases the output of renewable electricity per unit of installed generation capacity, helping to reduce input costs for the electrolysis process. The area where Ceará is located has the potential for a relatively low cost for green hydrogen production. IRENA (2022b) estimates a levelized cost of hydrogen (LCOH) of 1.5-2 USD/kgH_2 in 2030, even when considering water scarcity. For Europe, in comparison, ranges are between 2-5 USD/kgH_2, while most of the continent is in fact considered not eligible (IRENA, 2022b).

Aiming to ensure that the energy transition brings socio-economic opportunities for the local community, the government of Ceará established a local energy transition plan in May 2022, which includes green hydrogen (Interviews 1, 2 and 3). The plan is called Plano Estadual de Transição Energética Justa do Ceará, or Ceará's State Plan for a Just Energy Transition (DECRETO Nº 34.733, DE 12 DE MAIO DE 2022., 2022). Ceará also has an incentive program for the renewable energy generation productive chain (PIER) that aims to promote the development of a local renewable energy value chain. In addition, the state of Ceará offers several other tax benefits to foster industrialization, including a 10-year 75% exemption on state-level taxes for industrial production, as well as programs such as the Industrial Development Fund (FDI) and the Industrial Development Incentive Program (PROVIN) (Secretariat for Economic Development and Employment, 2022a).

The Port of Pecém is located in a free-trade zone. The ZPE Ceará offers multiple tax incentives for both national- and internationally acquired goods, including for import, income and value-added taxes (ZPE Ceará, 2022). These benefits together with state-level incentives can lead to up to 35-40% reduction on both capital and operational expenditures of investment projects in Pecém (Interviews)(CIPP, 2022). Ceará's location would make it more challenging to transport green hydrogen domestically in Brazil, given a lack of transmission infrastructure (GIZ, 2021) and the long distances to consumption centres in the South-East (e.g. over 3,000km for road transport from Pecém to São Paulo). Regarding the Port of Pecém in itself, 30% of the port is owned by the Port of Rotterdam from the Netherlands. This offers a direct connection to what is expected to be one of the main import corridors for green hydrogen in Europe (Interviews) (Port of Rotterdam, 2022, 2023).

Moreover, the Port of Pecém is surrounded by an industrial complex with companies that could play a role across the green hydrogen value chain. For instance, in the upstream, there is the Brazilian wind blade manufacturer Aeris Energy, the biggest wind blade manufacturer in Latin America and supplier for turbine manufacturers such as Vestas, Nordex, Siemens Gamesa and the Brazilian WEG (Aeris, 2023). Vestas has an assembly factory located around 70km from the Port (Vestas, 2023). Downstream, there are seven steel manufacturing companies. These include the Companhia Siderúrgica do Pecém (CSP), formerly a joint-venture between the Brazilian Vale and two South-Korean companies, but which was acquired in July by the multinational Arcelor Mittal(ArcelorMittal, 2022), as well as multinational companies like Gerdau and White Martins. It also has two cement factories that could be potential consumers of green hydrogen. There are also four power plants in the complex: two coal-fired (EDP and Eneva) and two gas-fired (Enel and Petrobras), who could become both producers and consumers of green hydrogen(CIPP, 2022).

SM1.3.5 International aspects

There are different types of international actors involved in different ways in the development of the hub. Firstly, the Port of Rotterdam is a partial owner of the Port of Pecém and has been sharing knowledge and experience on how Port areas in Europe are preparing to become green hydrogen valleys. It has also been provided support in creating the connection between Port of Pecém with green hydrogen trade corridors to Europe (Port of Rotterdam, 2022, 2023). Moreover, most of the MOUs signed with the government of Ceará were with multinational companies (Annex I, Table 1).

In addition, the German bilateral development agency GIZ has been conducting studies for the Working Group on the Pecém hub (Interviews3,8,15,19,21). They are also supporting SENAI-CE in defining the curriculum and priorities for technical education courses that will train people in Ceará to work in the green hydrogen value-chain (Interview 8). Germany has also been supporting the development of green hydrogen at the national level, via the bilateral cooperation project H2Brasil and the Brazil-German Alliance for Green Hydrogen. Under the latter, the Brazil-Germany Business Chamber AHK-Rio has been organizing courses and events, and supported the organization of the World Hydrogen Energy Conference (WHEC) in Rio de Janeiro in 2018 (AHK, 2021). The Dutch Consulate in Rio de Janeiro has also been offering support to Dutch companies who wish to develop businesses in the green hydrogen value-chain both in Pecém. The World Bank will be providing funding for infrastructure development in Ceará to better attend the green hydrogen hub (Interviews3,8,15,19,21) (Secretariat for Economic Development and Employment, 2022b; World Bank, 2023).

International studies from organizations like World Hydrogen Council and IRENA, as well as attendance to international hydrogen conferences, have been important sources of knowledge for the local stakeholders (Interviews, all). Moreover, several Brazilian individuals who are in the leadership of key organizations (Port of Pecém, FIEC and ABH2) have in fact had their first contact with green hydrogen while visiting or living in Germany and the Netherlands (Interviews 1,2,3,12,13,14,15,19). Moreover, developments for green hydrogen in the European Union have been key determinants for project design. The idea of the creation of a green hydrogen hub was directly inspired by the idea of Hydrogen Valleys developed by the European Commission, including the Dutch project HEAVENN (Interview 15)(HEAVENN, 2023).

The German H2Global mechanism has been pointed out as the main expected mechanism for sales of green hydrogen produced in Pecém (Interviews, all). H2Global is an auction-based mechanism with financing of the German Federal Ministry for Economic Affairs and Climate Action (BMWK) that aims to promote market ramp-up of green hydrogen products and applications on an industrial scale (H2Global, 2022). This also means that since projects aiming to compete in H2Global auctions need to meet certain product requirements and sustainability criteria based on European regulation, European regulations for green hydrogen certification are having a major influence on how projects in Pecém are designed (Interviews, all). Finally, factors like labour shortage, higher energy prices, and more stringent emission regulations and carbon pricing in the European Union were pointed out as key reasons for industries to consider shifting their production to the Pecém Industrial Complex (Interviews 12 and 16).

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