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Andrés Rebolledo
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La presente edición especial de la Revista ENERLAC se enmarca en la colaboración institucional entre la Organización Latinoamericana de Energía (OLADE) y la Asociación Latinoamericana de Economía de la Energía (ALADEE). Esta edición de la revista de publicación conjunta representa mucho más que una compilación de artículos académicos; constituye un testimonio tangible del compromiso compartido por ambas organizaciones para promover transiciones energéticas justas y equitativas en América Latina y el Caribe.

La decisión de OLADE y ALADEE de unir esfuerzos en esta edición de ENERLAC responde a la necesidad urgente de integrar perspectivas técnicas, económicas y sociales en el abordaje de las transiciones energéticas en marcha en la región. En un contexto global de transformación acelerada del sector energético, esta colaboración editorial materializa la convicción compartida de que las publicaciones académicas deben trascender la divulgación para convertirse en instrumentos efectivos de cambio.

Esta colaboración editorial reafirma un principio fundamental: el conocimiento académico en materia energética adquiere su máximo valor cuando se pone al servicio de transformaciones energéticas adaptadas a las condiciones regionales y con efectos sociales positivos. En un contexto regional marcado por profundas desigualdades, las transiciones energéticas representan tanto un desafío como una oportunidad histórica para reconfigurar sistemas energéticos de formas que contribuyan a la equidad social y el desarrollo sostenible.

ENERLAC, como plataforma editorial, se consolida así no solo como un espacio de difusión académica, sino como un instrumento concreto para la construcción colectiva de visiones energéticas que respondan auténticamente a las aspiraciones y necesidades de las sociedades latinoamericanas y caribeñas.

Es importante recalcar que una buena parte del material presentado en la presente edición, es fruto de la IX edición del evento: Latin American Energy Economics Meeting (ELAEE), desarrollado en el mes de julio en Rio de Janeiro, organizado por la ALADEE.

Invitamos a nuestros lectores—investigadores, tomadores de decisión, empresas, organizaciones sociales y público interesado—a sumarse activamente a este esfuerzo colaborativo. Las transiciones energéticas justas y equitativas que nuestra región requiere conllevan procesos sociales amplios donde el conocimiento técnico y económico dialogue permanentemente con valores éticos, aspiraciones comunitarias y visiones de desarrollo inclusivo.

Esta edición especial de ENERLAC es nuestra contribución a ese diálogo esencial. Un diálogo al que OLADE y ALADEE, desde sus respectivas trayectorias institucionales y ahora desde su alianza estratégica, se comprometen a enriquecer con investigación rigurosa, análisis independiente y perspectivas diversas.

EDITORIAL ALADEE

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Esse número especial da Enerlac é fruto de uma parceria entre Associação Latino Americana de Economia da Energia (ALADEE) e a Organização Latino-Americana de Energia (OLADE). O número traz artigos selecionados que foram apresentados no 9º Encontro Latino Americano de Economia da Energia (ELAEE). O 9º ELAEE foi realizado no Rio de Janeiro de 28 a 31 de julho de 2024 e faz parte dos congressos regionais da International Association of Energy Economics (IAEE). O Encontro contou com 10 plenárias temáticas em que participaram especialistas internacionais e 174 artigos que passaram por chamada de seleção foram apresentados.

O tema do encontro foi "Transição Energética, Mercados de Energia na América Latina e Caminhos para o Desenvolvimento: Descarbonização da Economia Global". Foram debatidos os desafios da transição energética no mundo, em um cenário de conflitos geopolíticas e incerteza de suprimento energético. Esse cenário impacta a América Latina, oferecendo dificuldades e oportunidades. A região conta com abundância de recursos renováveis e as novas tecnologias, como o hidrogênio verde, podem favorecer a liderança da região no processo de descarbonização.

A parceria com a Enerlac é bastante promissora para a ALADEE cumprir seu papel de difundir o tema de Economia da Energia na América Latina. A publicação desse número especial pode ser um passo inicial para uma cooperação duradoura com a Olade e Enerlac.

Análisis biofísico del ciclo de vida en la producción de ecoladrillos en las islas Galápagos

Biophysical analysis of the life cycle in the production of eco-bricks in the Galapagos islands

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Resumen

Los recursos minerales y energéticos en las Islas Galápagos son limitados, lo que afecta las dinámicas socioeconómicas, sobre todo en la construcción de edificaciones. Los materiales de construcción deben importarse desde continente, lo que incrementa el consumo de combustibles fósiles y las emisiones de gases de efecto invernadero (GEI). Como alternativa para reducir la presión sobre el ecosistema, se ha comenzado a producir y utilizar ecoladrillos fabricados con vidrio reciclado, siguiendo los principios de la economía circular (EC). No obstante, la producción de ecoladrillos requiere energía y materiales imprevistos, lo que podría afectar su sostenibilidad. El estudio se propuso analizar los flujos biofísicos presentes en la producción de ecoladrillos en Galápagos, con un enfoque particular en las emisiones de dióxido de carbono equivalente (CO_2e) derivadas del consumo de materiales y energía. Utilizando la metodología de Análisis del Ciclo de Vida (ACV), se determinó que la producción de 16,800 ecoladrillos generó 5 toneladas de CO_2e. El uso de cemento fue responsable del 79.40% de las emisiones totales y del 62.2% de la energía utilizada. En comparación con la producción de un bloque de hormigón convencional, la energía incorporada se reduce en un 12.5%, mientras que las emisiones aumentaron en un 16.8%.

PALABRAS CLAVE: Ecoladrillos, Análisis del Ciclo de Vida, energía incorporada, huella de carbono, CO_2, economía circular, Galápagos.

Abstract

Mineral and energy resources in the Galapagos Islands are limited, which affects socio-economic dynamics, especially in building construction. Building materials must be imported from the mainland, which increases fossil fuel consumption and greenhouse gas (GHG) emissions. As an alternative to reduce pressure on the ecosystem, eco-bricks made from recycled glass have started to be produced and used, following the principles of the circular economy (CE). However, the production of eco-bricks requires unforeseen energy and materials, which could affect their sustainability. The study set out to analyze the biophysical flows present in the production of eco-bricks in Galapagos, with a particular focus on carbon dioxide equivalent (CO_2e) emissions derived from material and energy consumption. Using the Life Cycle Assessment (LCA) methodology, it was determined that the production of 16,800 eco-bricks generated 5 tons of CO_2e. The use of concrete was responsible for 79.40% of the total emissions and 62.2% of the energy used. Compared to the production of a conventional concrete block, embodied energy is reduced by 12.5%, while emissions increased by 16.8%.

KEYWORDS: Eco-bricks, Life Cycle Assessment, embodied energy, carbon footprint, CO_2, circular economy, Galápagos.

1. INTRODUCCIÓN

A nivel global, las edificaciones son responsables del 39% de las emisiones de dióxido de carbono (CO_2) relacionadas con el consumo de energía (FFLA, 2023). Mientras que solo el sector del cemento es responsable del 7% del total de las emisiones mundiales de CO_2 (Islam, et al., 2024). De acuerdo con el Banco Central del Ecuador (BCE), aunque la construcción es una industria intensiva en energía, representó el quinto sector más importante de la economía ecuatoriana, siendo que, en el año 2022 aportó con el 6.1% del Producto Interno Bruto (PIB) ecuatoriano (CCQ, 2023).

En Galápagos el desarrollo del sector de la construcción enfrenta múltiples desafíos, no solo por la fragilidad de su ecosistema, sino por la dinámica demográfica y la demanda de infraestructura. De acuerdo con los datos del censo 2022 la población y las viviendas ocupadas crecieron en un 13 % sobre las reportadas en el censo 2015. La población pasó de 25.2 a 28.5 mil habitantes, mientras que las viviendas ocupadas pasaron de 8.5 a 9.6 mil en solo 7 años. Se muestra también que el 96% (9,268) de viviendas usa hormigón, bloques o ladrillos para la construcción de paredes, y el 42.02% (4,058) tiene loza de hormigón en el techo (INEC, 2023; INEC, 2015).

Por su parte: a) la disminución de los stocks de materiales pétreos en las minas de piedra volcánica dentro del Parque Nacional (Euroclima y Mentefactura, 2020); b) la reducción en la disponibilidad de agua dulce debido a alteraciones en los patrones de lluvia y al aumento de las temperaturas (CAF, 2021); c) la alta dependencia de la importación de materiales de construcción y energía; y d) la limitada efectividad en la implementación de una matriz energética renovable, dado que el 99.48% de la electricidad proviene del diésel (INEC, 2023), son muestras de la presión que el sistema socioeconómico de Galápagos ejerce sobre su ecosistema en términos de escasez de recursos y emisiones de gases de efecto invernadero (GEI).

En este contexto, se vuelve crucial explorar estrategias que promuevan la eficiente optimización de los recursos. La construcción sostenible y la economía circular (EC) sugieren maximizar el aprovechamiento responsable y sostenible de estos recursos, en aras de fortalecer la resiliencia frente al cambio climático. Sus principios consideran aspectos como la eficiencia energética, el uso eficiente del agua, la mejora del ambiente interior y la relación con el entorno urbano y natural y la elección de materiales con baja huella ecológica que son indispensables a ser implementados en las islas (Valencia, 2018).

Esta investigación tiene como objetivo analizar los flujos biofísicos en el ciclo de vida de la producción de ecoladrillos en Galápagos para determinar su impacto sobre el ecosistema. Se analizaron las emisiones de dióxido de carbono equivalente (CO_2e), así como el consumo de materiales, agua y energía en cada etapa del proceso productivo. Al evaluar estos factores, se determinó varios indicadores de sostenibilidad sobre la producción de ecoladrillos en términos de eficiencia energética, huella hídrica y de emisión de carbono.

2. ESTADO DEL ARTE

2.1 Economía circular en la construcción

La Ley Orgánica de Economía Circular Inclusiva de Ecuador (2021) define a la EC como un modelo que busca la regeneración y restauración de los ecosistemas mediante un cambio estratégico en la producción y el consumo (Asamblea Nacional, 2021). Mientras que, el Parlamento Europeo-PE (2023) establece que la EC se trata de un enfoque de producción y consumo que involucra prácticas como el compartir, alquilar, reutilizar, reparar, renovar y reciclar materiales y productos existentes, con el propósito de generar valor agregado y, de esta manera, extender el ciclo de vida de los productos.

Específicamente en la industria de la construcción, el cambio hacia la circularidad requiere centrarse en el pensamiento sistémico para comprender todo el ciclo de vida de las infraestructuras y la cadena de valor de la construcción (Zimmann et al., 2016). Adoptar los principios de la EC y un diseño ecológico puede reducir significativamente el consumo de recursos y el impacto ambiental, promoviendo un uso más eficiente de los materiales de construcción (Munaro et al., 2020). En este contexto, un ejemplo destacado se encuentra en la isla de Bornholm, Dinamarca. Allí se llevó a cabo una investigación para explorar la creación de una cadena de valor basada en un sistema de producción y consumo de circuito cerrado. Durante este estudio, se realizaron pruebas y demostraciones de prácticas destinadas a reutilizar y reciclar residuos de construcción y demolición. Los resultados indicaron la viabilidad de casos comerciales positivos para la demolición selectiva, siempre y cuando se establezcan mercados locales para los materiales de construcción reutilizados (Christensen et al., 2022).

La EC en la construcción va más allá de la gestión de residuos e involucra toda la cadena de valor del proceso constructivo. Comienza en la etapa de planificación, considerando el espacio y las futuras circunstancias para asegurar la perdurabilidad del proyecto. En el diseño se optimizan los materiales, se reduce la generación de residuos y se adoptan prácticas como la construcción modular y elementos industrializados. Además, se planifica la deconstrucción y se fomenta el uso de productos reutilizables o reciclables al final de su vida útil (Congreso Nacional de Medio Ambiente, 2018). Así, la construcción puede evolucionar de un enfoque convencional a uno alineado con principios sostenibles.

La EC se alinea con la construcción sostenible al aplicar sus principios para gestionar de manera eficiente recursos esenciales, como energía y agua, desde el diseño hasta el mantenimiento y rehabilitación de infraestructuras, utilizando además materiales sostenibles y reprocesados con baja huella ecológica. Esto conlleva beneficios como la eficiencia energética, la optimización del uso del agua, la prolongación de la vida útil de las infraestructuras, la reducción de costos operativos y la minimización de residuos. Además, esta perspectiva impulsa el desarrollo de bioemprendimientos, fortalece la resiliencia al cambio climático y fomenta la creación de regulaciones, contribuyendo a la construcción de infraestructuras más responsables y resilientes.

En Ecuador, se han logrado avances normativos que impulsan una construcción más eficiente en términos de consumo energético. Estos avances incluyen la Norma Técnica Ecuatoriana (NTE) INEN 2506:2009 sobre eficiencia energética en edificaciones y la NTE INEN 2507:2009 sobre rendimiento térmico de colectores solares. A partir de 2011, se desarrolló la Norma Ecuatoriana de Construcción (NEC), que establece parámetros mínimos de seguridad y calidad en las edificaciones, optimiza los mecanismos de control y mantenimiento en los procesos constructivos, entre otros, y en 2018 se publicó la normativa específica de eficiencia energética (MIDUVI, 2018). En 2019, la Ley Orgánica de Eficiencia Energética fue promulgada, seguida en 2021 por su reglamento, que obliga a cumplir metas sectoriales de eficiencia energética y establece un proceso de evaluación del consumo energético para nuevas construcciones y remodelaciones (Asamblea Nacional, 2019). Estas normativas están alineadas con el Plan Nacional de Eficiencia Energética (PLANEE) 2016-2035. Sin embargo, su aplicación aún no es efectiva en todo el territorio y no contempla la cuantificación de la huella de carbono en el ciclo de vida de las edificaciones.

2.2 Cuantificación de CO_2 en la construcción

Medir y reportar las emisiones de GEI de las edificaciones es fundamental para producir estrategias significativas y rentables. Aunque las metodologías de emisión de carbono varían entre países, el marco básico suele ser el proceso bien establecido del Análisis del Ciclo de Vida (ACV). El ACV suele considerar un enfoque “de la cuna a la cuna”, en el que los productos se evalúan sistemáticamente a lo largo de toda su vida. En los últimos años, ha existido un mayor interés en los métodos de ACV para evaluar edificaciones y productos con el fin de diseñarlos de manera eficiente y con materiales ambientalmente preferibles (Fenner, et al., 2018).

A nivel internacional, se han realizado múltiples investigaciones sobre el ACV en bloques y ladrillos. Un ejemplo notable es el estudio comparativo realizado en Egipto sobre las emisiones de carbono y la energía incorporada en ladrillos secados al sol versus ladrillos de arcilla cocida a través. Los resultados mostraron que, por cada 1,000 ladrillos cocidos producidos, la energía incorporada calculada es de 4,250 MJ y el carbono incorporado de 5,502 kg de CO_2e, mientras que, para los ladrillos secados al sol, solo se necesitan 0.033 MJ de energía incorporada y se emiten 0.24 kg de CO_2e (Dabaieh, et al., 2020).

Otra investigación en Argentina, realizada por Saez y Garzón (2020), analizó la huella de carbono en bloques elaborados con polipropileno post-consumo. La metodología utilizada fue la propuesta por las Normas IRAM-ISO 14040 y IRAM-ISO 14044, que se enfocan en el ACV. Los resultados indicaron que la fabricación de un metro cuadrado del prototipo en estudio genera 11.37 kg CO_2e.

En Ecuador, la investigación de Villota (2023) calculó la huella de carbono de la fabricación de ladrillos artesanales en la parroquia Sinincay, Cuenca, utilizando la norma UNE-EN ISO 14064-1:2019. Los resultados mostraron que las emisiones directas e indirectas en la producción anual de 360,000 ladrillos artesanales fueron de 72.74 toneladas de CO_2e.

En Galápagos, aún no se han realizado estudios sobre la cuantificación de carbono en el sector de la construcción o los materiales de construcción. No obstante, se han encontrado otros estudios relevantes. Por ejemplo, en la isla Santa Cruz, el proyecto Huella de Ciudades calculó la huella de carbono. En la ciudad de Puerto Ayora, se estableció la línea de base de las huellas de carbono e hídrica para el año 2015. Las emisiones totales de GEI fueron de 45,353 toneladas de CO_2e, representando aproximadamente el 0.01% de las emisiones totales de Ecuador en 2011 reportadas en su Segunda Comunicación sobre Cambio Climático en 2011 (CAF, 2017).

El Plan Galápagos 2030, emitido en 2021, promueve la construcción sostenible y ambientalmente amigable, adaptada al contexto insular de las islas. Entre sus metas principales se incluyen la descarbonización de Galápagos y la reducción del 20% en la huella de carbono y el consumo de agua en los asentamientos humanos y las principales actividades económicas. Además, como objetivo estratégico, propone identificar oportunidades para disminuir el uso de combustibles fósiles en el transporte marítimo y el sector hotelero, mediante la implementación de estándares y normas de eficiencia energética (CGREG, 2021). Para apoyar sus metas y objetivos, es crucial realizar estudios sobre las emisiones de CO_2 en el sector de la construcción en Galápagos. Estos estudios son necesarios para comprender el impacto real de la construcción y proporcionar información valiosa para los tomadores de decisiones.

En Galápagos, se ha comenzado a producir y utilizar bloques y ladrillos ecológicos como parte de un esfuerzo por emplear materiales más sostenibles y locales. Diversos estudios han explorado el potencial de estos bloques ecológicos para el aislamiento de edificaciones y han demostrado que ofrecen un rendimiento energético superior al de los bloques convencionales (Prato & Schiavi, 2015).

Un estudio realizado en la isla de Mauricio destaca los beneficios de los bloques ecológicos en la mejora del confort térmico de los edificios. Joyram, Govindan y Nunkoo (2024) informan que la tecnología de bloques ecológicos se introdujo para reducir el consumo de energía necesario para enfriar los espacios, especialmente durante el verano, cuando las temperaturas superan los 35 °C. En otro estudio de 2015, The United Basalt Products Ltd evaluó el desempeño energético de dos edificios similares en Mauricio: uno construido con bloques convencionales y el otro con ecobloques. Los resultados demostraron que los ecobloques son tres veces más eficientes en términos de resistencia térmica. Además, el edificio con ecobloques requirió significativamente menos electricidad para enfriar el espacio en comparación con el edificio de bloques convencionales (Joyram, Govindan, & Nunkoo, 2022).

En Argentina, González (2014) documentó la fabricación de bloques de paja y arcilla para rellenar paredes envolventes en la Patagonia Andina. La energía incorporada y las emisiones de CO_2 fueron de 40 MJ y 3.4 kg CO_2e por metro cuadrado de pared cubierta con bloques de paja y arcilla, respectivamente. Estas cifras son considerablemente menores en comparación con las de los ladrillos cocidos comunes (481 MJ/m^2 de pared y 38 kg CO_2e/m^2 de pared) y los bloques de hormigón (141 MJ/m^2 de pared y 11 kg CO_2e/m^2 de pared).

Por lo tanto, los bloques y ladrillos ecológicos se han consolidado internacionalmente como una alternativa atractiva frente a los bloques de hormigón convencionales, gracias a su capacidad para mejorar la eficiencia energética de las edificaciones y su menor impacto ambiental en la fabricación. Se presume que el uso de reciclados, disminuirían la intensidad energética y sus emisiones de CO_2, sin embargo, la presencia de energía y materiales imprevistos en los procesos específicos de su producción, la tecnología y la localización pueden impactar en la sostenibilidad a largo plazo.

3. METODOLOGÍA

Se utilizó la metodología del ACV para identificar el proceso de producción de los ecoladrillos en Galápagos. El alcance abarcó desde el transporte de materiales a las islas hasta el apilado y secado del producto final, incluyendo las emisiones y el consumo de energía relacionados con productos fabricados, como el cemento. La información obtenida fue mediante un enfoque bottom up, para lo cual se estructuró un diagrama input-output de flujos biofísicos, considerando las entradas de flujos: energía (electricidad y combustibles), actividad humana, materiales, agua y las salidas de flujos: emisiones de CO_2e y residuos sólidos (Gráfico 1). Además, se identificaron los materiales y emisiones propios de las islas y los provenientes del continente.

Gráfico 1. Propuesta de ACV del proceso productivo

Fuente: Elaboración propia

Para estimar las emisiones de CO_2e, se aplicaron los principios del Protocolo de GHG, los factores de emisión del Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC) de 2006 y factores propios del Sistema Nacional Interconectado (SNI), para las emisiones, además del análisis de las tasas de retorno energético determinadas para cada subproceso.

Finalmente, se identificaron las variables intensivas, que se refieren a la cantidad de recursos asociados con la producción de un solo ecoladrillo, como la energía consumida (Joules/ecoladrillo), materiales necesarios (m^3/ecoladrillo), el consumo de agua (m^3/ecoladrillo) y el trabajo realizado (horas-trabajo/ecoladrillo). Las variables intensivas son útiles para estimar los posibles impactos ecosistémicos en las islas, ya que pueden convertirse en variables extensivas. Las variables extensivas, por su parte, reflejan el total de recursos asociados con la producción completa de los ecoladrillos, como el total de energía consumida, el volumen total de agua y materiales utilizados y las horas de trabajo empleadas.

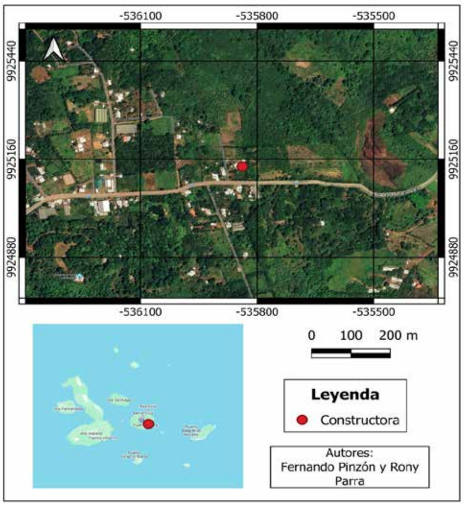
La población y muestra del estudio comprende los proveedores de mampostería ecológica disponibles en las islas Galápagos. Se identificaron dos iniciativas en Santa Cruz dedicadas a la producción de mampostería ecológica: la constructora Garden House Design (GHD) y ReciclArte. Por lo tanto, se decidió aplicar un muestreo no probabilístico por conveniencia, dada la escasez de proveedores en las islas. La constructora GHD fue seleccionada como objeto de estudio, dado que actualmente se dedica a la producción de ecoladrillos y cuenta con la maquinaria necesaria.

Se trabajó con información secundaria de diversas fuentes bibliográficas y estadísticas para complementar las brechas de datos, especialmente en lo referente al consumo de combustible desde continente hacia las islas, así como emisiones y energía incorporada del cemento. Además, se aplicaron los factores de emisión del IPCC y factores propios del SNI.

Adicionalmente, se diseñó y se levantó un cuestionario semiestructurado de entrevista in situ en el mes de marzo de 2024 que incluyó preguntas abiertas realizada a actores estratégicos presentes en los subprocesos del sistema de producción para recabar información primaria sobre los flujos biofísicos.

La constructora GHD está ubicada en Santa Cruz, El Cascajo, vía a la playa El Garrapatero (Figura 1), produce ecoladrillos a partir de vidrio reciclado y utiliza maquinaria eléctrica únicamente para dos procesos (prensado y la limpieza). Está equipada con diferentes moldes de hierro intercambiables y de tamaño variable, que permiten fabricar ecoladrillos según las dimensiones requeridas del producto final. En noviembre de 2022, alcanzaron su mayor producción con 16,800 ecoladrillos, cifra que se tomó como referencia para el estudio.

Figura 1. Ubicación del estudio



Fuente: Elaboración propia

4. RESULTADOS Y ANÁLISIS

4.1 Alcance de emisiones y energía incorporada

De acuerdo con los principios del Protocolo GHG realizado por (WRI, WBCSD, & SEMARNAT, 2005), las emisiones del estudio corresponden al Alcance 2 (emisiones indirectas de GEI asociadas a la electricidad), debido al uso de dos maquinarias para el proceso de prensado y limpieza.

El estudio también abarca el Alcance 3 (otras emisiones indirectas), que incluye las emisiones resultantes de las actividades de la empresa, pero que provienen de fuentes que no son de su propiedad ni están bajo su control. Dentro de este alcance, se identificaron dos fuentes principales: a) las emisiones asociadas al consumo de combustible para el transporte de materiales y el combustible utilizado para generar electricidad en las islas, y b) las emisiones asociadas a la producción de cemento.

En cuanto al transporte de materiales para la producción de los 16,800 ecoladrillos, el tiempo estimado de viaje desde Guayaquil hasta Santa Cruz es de 5 días (MTOP, 2021). Según la ficha técnica del buque Fusion 2, que opera en esta ruta, el consumo estimado de combustible es de 2,966 galones de diésel oil por día. Esto equivale a un total de 14,830 galones de diésel consumidos en los 5 días de viaje. El buque tiene una capacidad máxima de 373 contenedores de 20 pies y un tonelaje neto de 2,052.33 toneladas (Pacific Cargo Line, 2020). Por lo tanto, transportar una carga de 144 quintales de cemento de 50 kg (7.2 toneladas) requeriría 52.03 galones de diésel.

Para calcular el consumo de combustible en el transporte de diésel y gasolina de Guayaquil a Santa Cruz, se tomó como referencia el buque ALFA 007, que transporta 10,000 barriles de diésel (420,000 galones) y 5,000 barriles de gasolina (210,000 galones), y tarda dos días en llegar a Santa Cruz (CGREG, 2019). Según la ficha técnica del buque, tiene un consumo diario de 3,170 galones de diésel oil (Consulat, 2014), por lo que consumiría 6,340 galones de diésel en los dos días. Por lo tanto, transportar 34 galones de gasolina necesarios para transportar los materiales al interior de Santa Cruz requiere 0.342 galones de diésel. Asimismo, se requieren 17.28 galones de diésel para la generación de electricidad del proceso productivo, y su transporte desde Guayaquil requeriría 0.1739 galones de diésel.

En referencia a las emisiones del cemento, investigaciones internacionales informan que la producción de 1 tonelada de cemento Portland produce aproximadamente 900 kg de emisiones de CO_2 (Dey, et al., 2023; Benhelal, et al., 2013). Sin embargo, en la memoria de sostenibilidad de Holcim Ecuador 2019/2020, informan que la intensidad de emisiones es 552 kg CO_2 neto por tonelada material cementante (Holcim, 2021). Se va a tomar como referencia este último valor, dado que es una empresa que opera en el país. Por lo tanto, un quintal de cemento de 50 kg emite alrededor de 27.6 kg de CO_2e, y los 144 quintales de cemento necesarios para producir los 16,800 ecoladrillos generarían 3,974.40 kg de CO_2e.

En cuanto a la energía necesaria para el proceso productivo, según la investigación de (León & Guillén, 2020), la energía incorporada en la producción de una tonelada de cemento es de 3,191.95 MJ. Los principales aportes de energía provienen del uso de caliza, fuel oil y electricidad. Por lo tanto, para producir 16,800 ecoladrillos, que requieren 7.2 toneladas de cemento, se necesitarían 0.02298 TJ de energía.

De esta manera, considerando el consumo de combustibles y energía en la producción de 16,800 ecoladrillos, se requiere un total de 0.0369 TJ (Tabla 1).

Tabla 1. Energía incorporada por proceso y material

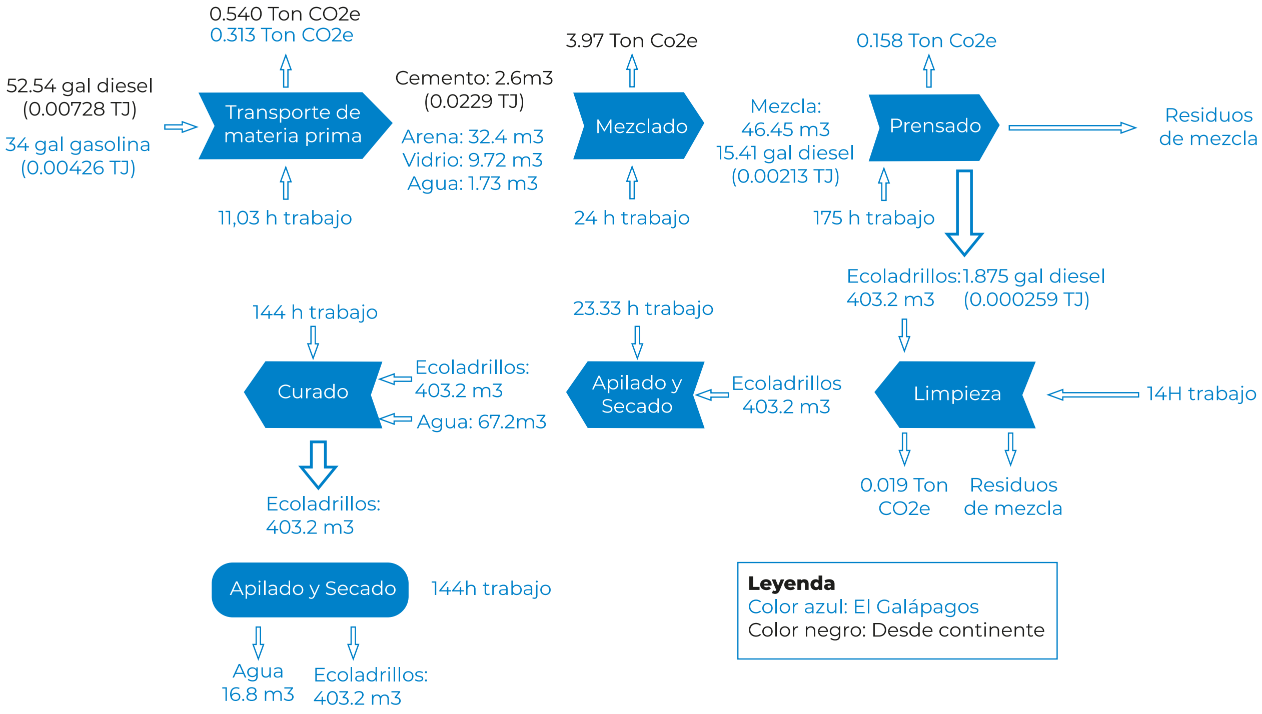
Actividad/Producto	Combustible necesario	Energía (TJ)	%
Prensado	15.41 galones de diésel	0.0021354	5.8%
Limpieza	1.875 galones de diésel	0.0002598	0.7%
Transporte de materia prima (arena, cemento y vidrio) dentro de Santa Cruz	34 galones de gasolina	0.0042662	11.6%
Transporte de cemento desde Guayaquil	52.03 galones de diésel	0.0072099	19.5%
Transporte de gasolina desde Guayaquil para la movilización de la camioneta dentro de Santa Cruz	0.342 galones de diésel	0.0000474	0.1%
Transporte del diésel desde Guayaquil para generación de electricidad	0.1739 galones de diésel	0.0000241	0.1%
Incorporado en el cemento		0.02298	62.2%
Total		0.036923	100%

Fuente: Elaboración propia con datos de GHD (2024), León & Guillén (2020) y CENACE (2020)

4.2 Análisis del Ciclo de Vida

El ACV (Gráfico 2) reveló que la producción de 16,800 ecoladrillos genera emisiones indirectas de 5 toneladas de CO_2e. Esto implica que la producción de cada ecoladrillo con dimensiones de 12cmx8cmx25cm (2,400 cm^3) emite 0.297 kg de CO_2e.

Gráfico 2. Visualización del ciclo de vida de la producción de ecoladrillos (2022)



Fuente: Elaboración propia con datos de GHD (2024)

Las emisiones indirectas relacionadas con el cemento constituyen el 79.40% de las emisiones totales y además contiene el 62.2% de la energía incorporada del ecoladrillo, es un dato relevante dado que son emisiones y energía contabilizada desde continente y que frecuentemente son obviadas en los análisis tradicionales. Mientras que la etapa de transporte de materiales, con un 17.05%, es la segunda mayor generadora de emisiones y contiene el 31.1% de la energía incorporada. Por otro lado, las emisiones indirectas relacionadas con la electricidad representan tan solo el 3.55% y contienen el 6.5% de energía incorporada, es mínimo, ya que gran parte del proceso es artesanal y se realiza manualmente.

En cuanto a los materiales, la producción de ecoladrillos se basa principalmente en agua, que representa el 60.65% del total, seguido de arena con el 28.52% y polvo de vidrio con el 8.55%. Caso contrario, el cemento constituye solo el 2.29% de los materiales utilizados.

A partir de ACV se calcularon variables intensivas y extensivas (Tabla 2). Las variables intensivas se obtuvieron dividiendo las variables extensivas entre el total de 16,800 ecoladrillos producidos. Con estos datos, se pueden estimar fácilmente los requerimientos futuros de materiales si la demanda de ecoladrillos aumenta en las islas (Autor, Bukkens, & Giampietro, 2020; Autor, Di Felice, Giampietro, & Ramos, 2018). Estos valores son importantes para discutir los posibles impactos sobre el ecosistema, dado que en Galápagos existe escasez de arena, energía y agua (Galapagos Conservation Trust, 2015).

Tabla 2. Variables intensivas y extensivas

Tipo	Variable intensiva	Variable extensiva
Cemento	0.0001548 m^3/ecoladrillo	2.6 m^3
Arena	0.0019286 m^3/ecoladrillo	32.4 m^3
Agua	0.0041030 m^3/ecoladrillo	68.93 m^3
Polvo de vidrio	0.0005786 m^3/ecoladrillo	9.72 m^3
Trabajo	0.0318667 horas trabajo/ecoladrillo	535.36 horas trabajo
Energía	0.0000022 TJ/ecoladrillo	0.0369 TJ
Emisiones de CO_2e	0.0002976 Ton CO_2e/ecoladrillo	5 ton CO_2e

Fuente: Elaboración propia con datos de GHD (2024)

Por otro lado, una jornada laboral estándar en Ecuador comprende 160 horas al mes. La variable de trabajo muestra que la producción de ecoladrillos requiere de 3.34 personas al mes para mantener ese ritmo de producción. No obstante, se ha determinado que la capacidad de producción de ecoladrillos podría aumentar considerablemente según la demanda, lo cual incrementaría la necesidad de mano de obra y, en consecuencia, fomentaría el empleo en las islas.

De acuerdo con GADM Santa Cruz (2009), en 2009 la mina Granillo Rojo tenía un volumen de 1,908,698 m^3 de material y la tasa de extracción de la mina es de 81,206.63 m^3 (DPNG, 2013). Lo que indicaría que para 2023 su volumen se reduciría a 771,805.18 m^3. Si se mantiene la misma tasa de extracción los recursos se acabarían en 9.5 años.

Para comparar los resultados, se utilizaron los hallazgos de la investigación de (Urgilés & Vanessa, 2017), quienes elaboraron el Inventario del Ciclo de Vida de un bloque de hormigón convencional en la ciudad de Cuenca. Este estudio fue seleccionado porque también consideró tanto la energía incorporada como las emisiones de CO_2 asociadas al cemento. Según su investigación, la energía incorporada y las emisiones de CO_2 para un bloque de 10cmx20cmx40cm (8,000 cm^3) son de 8.34 MJ por bloque y 0.83 kg de CO_2 por bloque.

En el presente estudio, se evaluó un ecoladrillo de 12cmx8cmx25cm (2,400 cm^3) y se obtuvieron valores de 2.2 MJ por ecoladrillo y 0.297 kg de CO_2/ecoladrillo. Si se ajustaran las dimensiones del ecoladrillo para que tuviera el mismo volumen que el bloque de hormigón (8,000 cm^3), el ecoladrillo emitiría 7.3 MJ y 0.97 kg de CO_2 por unidad. Esto significa que, en comparación con el bloque de hormigón, la energía incorporada en el ecoladrillo se reduciría en un 12.5%, pero las emisiones de CO_2 aumentarían en un 16.8%.

El uso de vidrio reciclado en lugar de otros materiales probablemente redujo la energía incorporada en la fabricación del ecoladrillo. Los materiales reciclados suelen requerir menos energía para un nuevo procesamiento, dado que ya tienen un proceso productivo detrás de ellos, a diferencia de los materiales vírgenes utilizados en la fabricación de bloques de hormigón. Sin embargo, este ahorro de energía no se tradujo en una reducción de las emisiones de CO_2; de hecho, estas aumentaron un 16.8%. Este incremento se debe a factores como el transporte de materiales desde continente y el uso de combustibles fósiles para generar la electricidad necesaria para la producción de los ecoladrillo.

5. CONCLUSIONES

La metodología empleada permitió identificar datos frecuentemente omitidos en los análisis tradicionales, como las emisiones y el consumo de energía asociados al transporte de materiales, así como las emisiones y la energía incorporada en un material. Los resultados revelaron que, aunque el cemento representa solo el 2.29% de los materiales utilizados, es responsable del 79.40% de las emisiones totales y del 62.2% de la energía incorporada. Esto refleja el extenso proceso productivo detrás de este material y resalta la urgencia de encontrar alternativas más sostenibles.

En Galápagos se están adoptando prácticas de EC en la construcción, como la producción de ecoladrillos a partir de vidrio reciclado. Esta iniciativa promueve el reciclaje de vidrio a través de la recolección voluntaria y la limpieza costera. El vidrio recolectado se transforma en polvo, extendiendo su vida útil como materia prima para otros procesos productivos, cumpliendo así con los principios del ciclo técnico del diagrama de mariposa de la EC. Además, se ha identificado en las islas la adopción de prácticas sostenibles, como la reutilización del agua de lluvia y la reutilización de los desechos.

Dado que las nuevas construcciones representarán solo el 5% del parque edificado futuro (Euroclima y Mentefactura, 2020), se concluye que el verdadero impacto de los ecoladrillos se podría lograr al implementarlos en la remodelación de las 9,627 viviendas, para mejorar su eficiencia energética. Además, deberían ser una prioridad en las nuevas construcciones y futuros proyectos inmobiliarios de las islas, lo que contribuiría a cumplir la meta clave del Plan Galápagos 2030 de reducir la huella de carbono y agua de los asentamientos humanos.

El estudio evidencia que por cada ecoladrillo fabricado se emiten 0.297 kg de CO_2e. Además, muestra la necesidad de materiales y recursos: se requieren 0.0019286 m^3 de arena, 0.0001548 m^3 de cemento, 0.0041030 m^3 de agua, 0.0000022 TJ de energía y 0.032 horas de trabajo. La demanda de estos materiales puede tener impactos en el ecosistema sensible de Galápagos, como el agotamiento de las minas y el agua, que es escasa en Santa Cruz y se destina al proceso de producción en lugar de al consumo humano. También existe la posibilidad de que, en el futuro, los materiales reciclados, como el vidrio, no cubran la demanda, lo que obligaría a importar desde continente.

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Identificación de los posibles Impactos Ambientales de la producción de hidrógeno verde a partir de proyectos eólicos offshore. Caso de Estudio: Zona Económica Exclusiva de Uruguay

Identification of Potential Environmental Impacts from Green Hydrogen Production through Offshore Wind Projects: A Case Study in Uruguay's Exclusive Economic Zone

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H2

Resumen

El presente trabajo identifica los potenciales impactos ambientales de la producción de hidrógeno verde en proyectos eólicos offshore en la Zona Económica Exclusiva de Uruguay. El Hidrógeno verde es una alternativa para descarbonizar el sector energético. La eólica offshore, dado la potencia nominal de los aerogeneradores, ofrece mayor potencial de generación eléctrica, pero conlleva mayores costos y complejidades técnicas. Se examinan las actividades durante las etapas de desarrollo, construcción y operación. A partir de la revisión de investigaciones ambientales sobre proyectos similares, se identifican los impactos ambientales principales en cada fase. Durante el desarrollo, se observan impactos como aumento de ruido, vibraciones y alteraciones en el lecho marino debido a estudios geofísicos y geotécnicos. En construcción, el dragado y la instalación de fundaciones y cables pueden suspender sedimentos, afectar la calidad del agua y aumentar el ruido afectando la fauna marina. En operación, los impactos incluyen colisiones de aves y aumento del ruido submarino. La desalinización del agua puede alterar la calidad del agua, pero conserva los recursos hídricos terrestres.

Esta investigación busca ofrecer una visión integral que sirva de base para la toma de decisiones de los responsables de políticas, los desarrolladores de proyectos y actores clave.

PALABRAS CLAVE: Hidrógeno Verde, Impacto Ambiental, Energía Eólica Offshore, Electrólisis, desalinización, Uruguay.

Abstract

This paper analyzes the potential environmental impacts of green hydrogen production in offshore wind projects in Uruguay's Exclusive Economic Zone. Green hydrogen is an alternative for decarbonizing the energy sector, although its production requires significant resources. Offshore wind, given the nominal power of the turbines, offers greater electricity generation potential but involves higher costs and technical complexities. The activities during the development, construction, and operation phases are identified. Based on a review of environmental research on offshore wind projects and green hydrogen production, the main environmental impacts in each phase are identified. During development, impacts such as increased noise, vibrations, and alterations to the seabed due to geophysical and geotechnical studies are observed. In construction, dredging and the installation of foundations and cables can resuspend sediments, affect water quality, and increase noise, impacting marine fauna. During operation, impacts include bird collisions and increased underwater noise. Desalination of water may alter the salinity and oxygenation of the water but preserves terrestrial water resources. Other impacts include noise and the risk of gas leaks. This research aims to provide a comprehensive perspective that can serve as a basis for decision-making by policymakers, project developers, and other key stakeholders.

KEYWORDS: Green Hydrogen, Environmental Impact, Offshore Wind Energy, Electrolysis, Desalination, Uruguay.

1. INTRODUCCIÓN

En los últimos años, el cambio climático y la demanda de fuentes de energía sostenibles han incrementado el interés en tecnologías renovables y bajas en emisiones de gases de efecto invernadero como la energía eólica offshore y la producción de Hidrógeno (H2) verde. Esta investigación explora dichas tecnologías, específicamente en la Zona Económica Exclusiva (ZEE) de Uruguay para identificar sus posibles impactos ambientales. El H2 verde, producido mediante la electrólisis del agua con electricidad de fuentes renovables, es un vector energético con bajas emisiones y potencial para aplicaciones industriales, de transporte y almacenamiento de energía. Ofrece una forma eficiente de almacenar energía e integrarse en infraestructuras energéticas existentes. Por otro lado, la energía eólica offshore, que aprovecha los vientos marinos, es una alternativa con bajas emisiones y ha avanzado con mejoras en la eficiencia de aerogeneradores y técnicas de construcción y mantenimiento. Uruguay, con su amplia costa, buenos recursos naturales y experiencia en energías renovables, es un candidato ideal para implementar proyectos de H2 verde y energía eólica offshore. La investigación tiene como objetivo principal identificar los impactos ambientales de este tipo de proyectos offshore dentro de la ZEE de Uruguay. Se llevará a cabo una revisión bibliográfica detallada sobre los conceptos de generación eólica y producción de H2 verde, tecnologías específicas, procedimientos de operación y mantenimiento, como también estudios de caracterización ambiental de la ZEE, para posteriormente realizar el análisis e identificación de los impactos potenciales en el medio físico, biótico y antrópico que pueden ocurrir en cada fase de un proyecto e identificar cuáles son los factores ambientales que pueden verse más afectados. Estos resultados podrían proporcionar una visión integral para ser usados como base de partida en análisis específicos e informar a responsables de políticas y desarrolladores de proyectos.

2. METODOLOGÍA APLICADA

Este estudio busca identificar los impactos ambientales de proyectos de hidrógeno verde y energía eólica offshore mediante una revisión bibliográfica que integra aspectos técnicos, ambientales y normativos. La metodología se estructuró en cuatro fases principales: revisión de conceptos básicos, revisión de tecnologías, evaluación de estudios ambientales previos e identificación de impactos clave.

2.1. Conceptos básicos del Hidrógeno Verde y la Energía Eólica offshore

El hidrógeno verde se produce mediante electrólisis, un proceso que separa el agua en hidrógeno y oxígeno utilizando un electrolizador. Para garantizar bajas emisiones de CO2, y ser catalogado como “verde” este proceso requiere energía eléctrica proveniente de fuentes renovables. (Goldman Sachs International, 2022).

La energía eólica offshore se refiere a la generación de electricidad a partir de aerogeneradores instalados en masas de agua, normalmente en océanos o grandes lagos. A diferencia de la energía eólica terrestre, los parques eólicos offshore se construyen en áreas costeras o en alta mar, es en general una ventaja que la potencia nominal de los aerogeneradores offshore es superior a la onshore. (Letcher, 2017).

2.2. Análisis de Tecnologías Asociadas

Se realizó una revisión detallada de las tecnologías utilizadas en proyectos eólicos offshore y de H2 verde, evaluando sus actividades durante las fases de desarrollo, construcción y operación de los proyectos, considerando las siguientes áreas clave:

2.2.1 Etapa de Desarrollo

La etapa de desarrollo de un proyecto eólico offshore incluye todas las actividades previas al cierre financiero, lo que puede llevar hasta tres años (BVG Associates, 2019). Un componente crítico es el Estudio de Impacto Ambiental, que implica levantamiento de líneas base y estudios específicos sobre clima, ruido, fauna marina, avifauna, hábitats, navegación, pesca, y aspectos socioeconómicos.

Los estudios del recurso eólico y datos metoceánicos evalúan la velocidad del viento a alturas aproximadas de 150-250 metros sobre el nivel del mar mediante torres meteorológicas, anemómetros y sistemas remotos como lidars y boyas metoceanográficas. Estos datos son esenciales para determinar la viabilidad técnica del proyecto. Los estudios geofísicos, geotécnicos e hidrológicos emplean técnicas no invasivas como sondeos sísmicos y batimetría para mapear el lecho marino. También se realizan perforaciones y pruebas de penetración para caracterizar el suelo y planificar las rutas de cableado submarino, asegurando la estabilidad y viabilidad de las instalaciones (BVG Associates, 2019).

2.2.2. Análisis de Tecnologías

a) Aerogeneradores Offshore: Los aerogeneradores offshore son más grandes y potentes que los terrestres, alcanzando capacidades de hasta 16 MW, como el modelo Goldwind GWH252-16 MW con rotores de 250 metros de diámetro (TGS New Energy, 2024). Su diseño maximiza la generación eléctrica en áreas reducidas, aprovechando vientos constantes en alta mar. No obstante, el transporte e instalación de componentes voluminosos y pesados plantean desafíos logísticos, que además enfrentan condiciones extremas del entorno marino, como la corrosión, las fuertes corrientes y el oleaje.

b) Fundaciones: Las fundaciones proporcionan estabilidad estructural y se clasifican en fijas y flotantes. Las fijas, como los monopilotes y estructuras tipo jackets, son adecuadas para aguas poco profundas (0-80 m). Las flotantes, ancladas mediante cables o tensores, permiten proyectos en aguas más profundas, expandiendo la viabilidad de parques eólicos en diversas regiones (Fan et al., 2022).

c) Cableado Submarino y Subestaciones: El cableado de media y alta tensión conecta los aerogeneradores a subestaciones offshore y a tierra firme. Estas subestaciones transforman la electricidad de media a alta tensión, mejorando la eficiencia del transporte energético. Su diseño robusto debe resistir la exposición a corrientes marinas y condiciones adversas (Rodríguez, 2020).

d) Electrólisis y Almacenamiento: La electrólisis es un proceso químico que utiliza energía eléctrica para descomponer agua en sus componentes básicos, hidrógeno y oxígeno. La tecnología PEM destaca en la producción de H2 verde, siendo viable para fuentes renovables intermitentes gracias a su flexibilidad y alta pureza del H2. Sin embargo, los costos elevados y los desafíos de almacenamiento, como la fragilización de materiales y el manejo de residuos químicos, requieren soluciones integradas para garantizar sostenibilidad y seguridad operativa (Calado & Castro, 2023).

e) Operación y mantenimiento: La fase de operación y mantenimiento (O&M) de parques eólicos offshore es esencial para garantizar su eficiencia y longevidad. Este proceso incluye mantenimiento planificado y no planificado. El primero se realiza periódicamente, siguiendo un calendario de inspecciones visuales, revisiones mecánicas y reemplazo de componentes desgastados para prevenir fallos. El segundo abarca reparaciones emergentes derivadas de daños por tormentas, fallos electrónicos o mecánicos inesperados, que requieren una rápida movilización de equipos especializados (Thomsen, 2012).

En proyectos de hidrógeno verde, el O&M incluye la desalinización de agua para electrólisis, compresión y almacenamiento del hidrógeno, así como la eliminación segura de residuos líquidos y sólidos generados durante las operaciones, asegurando la sostenibilidad del sistema (Calado & Castro, 2023).

2.3. Revisión de literatura científica y resultados de otros proyectos similares

La revisión de publicaciones científicas identificó los principales impactos ambientales asociados a proyectos eólicos offshore y de hidrógeno verde:

- Aves y Mamíferos Marinos: Desplazamiento, colisiones y alteración de hábitats debido a la construcción y operación, con impactos acumulativos entre proyectos cercanos.
- Peces y Comunidades Bentónicas: Modificación de comunidades por sustratos duros y arrecifes artificiales, con beneficios locales, pero riesgos de perturbaciones.
- Impactos de la producción de Hidrógeno Verde: Impactos por demanda de agua, descargas de salmuera y uso de metales raros, junto con riesgos de contaminación por fugas químicas.
- Comunidades Locales: Afectación de la pesca artesanal, conflictos por el espacio marítimo y presión sobre servicios por trabajadores externos.

Estos hallazgos establecen un marco para abordar impactos clave en futuros proyectos en la ZEE de Uruguay.

2.4. Identificación de Impactos Ambientales

Para avanzar con la identificación de los impactos ambientales se evaluaron y listaron las actividades en cada etapa del proyecto (desarrollo, construcción y operación) determinando los medios y factores ambientales asociados a cada actividad. De acuerdo con Zaror (2000), los factores ambientales son diversos componentes del ambiente susceptibles de ser modificados por la acción humana.

Los factores ambientales que se evaluarán dentro de cada Medio son los siguientes:

- Factores evaluados dentro del Medio Físico: Lecho Marino / Suelo, niveles sonoros ambientales, calidad del agua superficial, calidad del aire, temperatura del agua superficial e hidroquímica, presiones sobre los recursos naturales.

- Factores evaluados dentro del Medio Biótico: Fauna: Plancton, Bentos, Necton, Peces, Aves, Reptiles, Mamíferos Marinos, Cefalópodos; y flora acuática y flora superficial.
- Factores evaluados dentro del Medio Antrópico: Paisaje, Pesca, navegación y tráfico marítimo y terrestre.

A continuación, se identificó la relación de cada actividad del proyecto con los efectos potenciales en el Medio, así como los impactos ambientales en sus diferentes etapas. La Figura 1. muestra un ejemplo de una sección de las tablas utilizadas para la identificación de impactos durante cada fase del proyecto.

Figura 1. Sección de la tabla “Actividades que pueden ocurrir en la fase de desarrollo del proyecto, con sus posibles impactos y factores ambientales relevantes”.

Actividad	Impacto ambiental	Medio	Factor ambiental	Vinculación
Estudios geotécnicos y geofísicos	Alteración de Fauna marina	Biótico	Fauna marina	Los estudios geotécnicos y geofísicos pueden ocasionar alteración de fauna marina por pertubaciones durante los momentos de muestro.
	Alteración del lecho marino	Biótico	Fauna y flora marinas	Durante la elaboración de los estudios geotécnicos puede ocurrir posible remoción del lecho marino en diferentes áreas de estudio (Subsea Working Group, 2000)
	Aumento de los niveles de ruido	Físico	Niveles de presión sonora	Los estudios geológicos y geofísicos pueden utilizar ondas sonoras que se reflejan en las estructuras del lecho marino para recopilar datos sobre las condiciones en y debajo del lecho marino. El ruido generado por estos estudios puede causar lesiones, pérdida de audición o cambios de comportamiento, entre otros impactos, en ciertas especies marinas (Congressional Research Service, 2024)

Fuente: elaboración propia.

Posteriormente, con los resultados de las tablas obtenidas, se analizaron los impactos ambientales en función de su grado de incidencia, determinando cuáles son los que aparecen con mayor frecuencia pudiendo ocasionar mayor afectación en cada fase del proyecto y así determinar cuáles son los medios y factores ambientales más afectados.

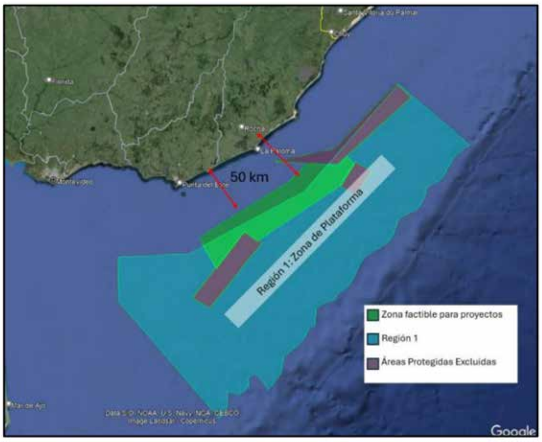
La estrategia de evaluación utilizada integra aspectos técnicos y ambientales, identificando las actividades e impactos ambientales más relevantes en cada fase del proyecto. Este enfoque no solo facilita la identificación de impactos clave en una fase temprana, sino que también ofrece una base inicial para la toma de decisiones en el diseño de medidas de mitigación adaptadas a las condiciones locales, apoyando la sostenibilidad de proyectos en Uruguay y en contextos similares.

3. RESULTADOS OBTENIDOS:

3.1. Identificación de los impactos ambientales en un proyecto ubicado en la Zona Económica Exclusiva del Uruguay

Con base en la información de la caracterización ambiental de la ZEE, se establecieron criterios para delimitar áreas factibles para proyectos y sugerir un área viable. Debido a limitaciones tecnológicas de las fundaciones fijas, se seleccionaron áreas hasta profundidades máximas de 100 m, también se excluyeron áreas protegidas a nivel nacional, rutas de buques mercantes y zonas pesqueras. La Figura 2 ilustra esta delimitación. Un mayor detalle en la delimitación necesitará de un análisis exhaustivo de la información tomando en cuenta muchos más elementos del entorno marino.

Figura 2. Delimitación de la Zona factible para proyectos eólicos offshore dentro de la ZEE.



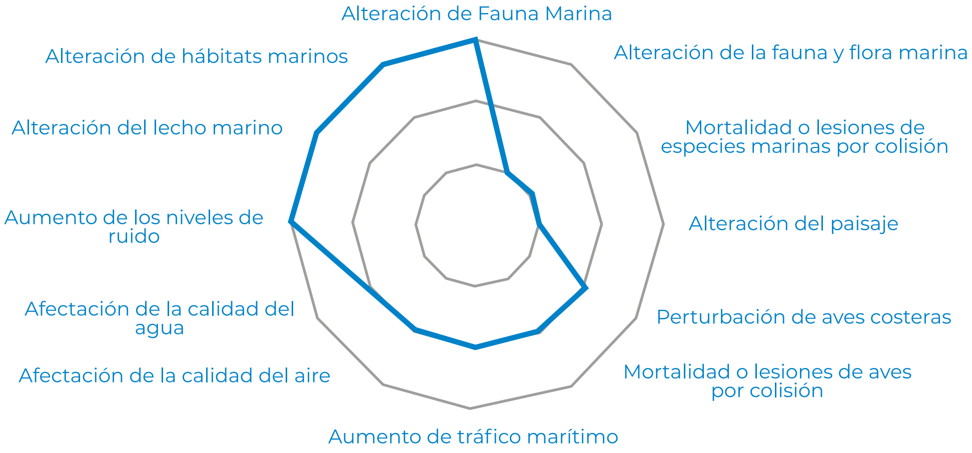
Fuente: elaboración propia.

A continuación, se presentarán los principales impactos ambientales identificados que pueden afectar la ZEE de Uruguay, para cada fase del proyecto.

3.2. Fase de desarrollo

La fase de desarrollo involucra una serie de actividades que incluyen estudios oceanográficos, sísmicos, geofísicos, geotécnicos y la instalación de infraestructuras como torres de medición de viento y boyas (BVG Associates, 2019). A continuación, en la Figura 3 se muestran los resultados de los principales impactos ambientales asociados con estas actividades.

Figura 3. Principales impactos ambientales identificados en la Fase de Desarrollo.



Fuente: elaboración propia.

Los impactos ambientales más relevantes están relacionados con el medio biótico, siendo la fauna marina la más afectada. Los niveles de ruido generados por estudios geofísicos y geotécnicos son una preocupación principal, ya que estos pueden alterar comportamientos, causar daños físicos y afectar la reproducción y comunicación de diversas especies. Estudios como los sísmicos de aire comprimido y los de alta resolución (HRG) generan pulsos sonoros que penetran el subsuelo, lo que puede impactar de forma significativa a peces, mamíferos marinos, tortugas y cefalópodos (BOEM, 2018) que pueden estar presentes en la ZEE de Uruguay.

El aumento del tráfico marítimo asociado a las actividades de exploración también incrementa el riesgo de colisiones con fauna marina, particularmente mamíferos y aves, y contribuye al ruido submarino, afectando patrones migratorios y de comportamiento de las especies (Congressional Research Service, 2024).

Adicionalmente, las actividades de instalación, como la colocación de bases para torres de medición de vientos, pueden generar remoción de sedimentos, perturbando los hábitats del fondo marino y afectando comunidades de plancton y bentos, lo que puede alterar la red trófica.

Especies como cefalópodos pueden experimentar daños en sus estatocistos, esenciales para su equilibrio, cuando se exponen a sonidos de baja frecuencia (50-400 Hz) y niveles de presión sonora de hasta 175 dB pico (Oisín, Rogério & Coca, 2023).

Otros impactos identificados incluyen la afectación de la calidad del agua debido a derrames accidentales de embarcaciones o al movimiento de sedimentos, y la alteración de la calidad del aire por emisiones de los equipos y transporte marítimo. Estas alteraciones pueden dañar ecosistemas y disminuir la biodiversidad del área de estudio (Zhou, 2019). Finalmente, aunque de menor frecuencia, la alteración del paisaje marino, influenciada por el tráfico marítimo y la presencia de estructuras temporales, puede afectar la calidad del paisaje, como también la interacción de aves y mamíferos marinos con sus hábitats. Es esencial considerar estos impactos acumulativos y sus efectos sinérgicos durante esta etapa para garantizar una planificación sostenible, en especial si se pretenden desarrollar distintos proyectos al mismo tiempo en la ZEE.

3.2.1. Medidas de Mitigación

Las medidas de mitigación propuestas se centran en minimizar los impactos en el medio biótico y físico durante la etapa de desarrollo. Para proteger el medio biótico, se sugiere implementar monitoreo visual de mamíferos marinos y monitoreo acústico pasivo mediante hidrófonos para detectar fauna cercana. Se recomienda establecer zonas de exclusión acústica alrededor de las embarcaciones y utilizar inicios suaves (soft starts) para aumentar gradualmente la potencia de las fuentes acústicas, permitiendo que los animales marinos se alejen del área antes de alcanzar niveles de ruido altos (BOEM, 2018). Además, se deben realizar pruebas preliminares de calibración de equipos para minimizar el uso innecesario de potencia y ruido.

La planificación temporal y espacial es clave, evitando actividades durante las temporadas de desove y cría, así como minimizando la superposición de estudios en áreas cercanas para permitir la recuperación de las poblaciones marinas. También se sugiere implementar cierres temporales y espaciales en hábitats críticos y rutas migratorias, especialmente para ballenas y tortugas. Es fundamental realizar estudios de línea de base con campañas de muestreo estacionales para establecer referencias detalladas del entorno marino.

Para el medio físico, las medidas incluyen la contención y prevención de derrames mediante barreras físicas, planes de respuesta rápida y equipos especializados. Se recomienda reducir las emisiones atmosféricas de las embarcaciones mediante tecnologías como filtros de partículas y catalizadores, además de optimizar rutas y operaciones para disminuir el tiempo de funcionamiento de motores y maquinaria.

En cuanto al medio antrópico, se enfatiza la planificación de tráfico marítimo mediante la definición de rutas seguras y velocidades máximas para reducir el riesgo de colisiones con fauna marina y minimizar el ruido submarino.

3.2.2. Fase de construcción

Durante la fase de construcción los impactos ambientales más relevantes están asociados con alteraciones significativas en los ecosistemas marinos. A continuación, en la Figura 4 se muestran los resultados de los principales impactos identificados durante esta fase.

Figura 4. Principales impactos ambientales identificados en la Fase de Construcción.

Fuente: elaboración propia.

Entre los impactos más destacados se encuentra el aumento del ruido submarino, generado principalmente durante la instalación de fundaciones mediante martillos hidráulicos o percutores vibratorios. Este ruido puede inducir comportamientos de evitación en mamíferos marinos como delfines, ballenas y lobos marinos, además de causar daños físicos en tejidos auditivos y otros órganos de peces y cefalópodos, todas estas especies presentes en la ZEE. La sensibilidad de estas especies al sonido, esencial para su navegación, búsqueda de alimento y comunicación, hace que estos impactos sean especialmente críticos (T. Aran Mooney, 2020). Las actividades relacionadas con el pilotaje también modifican el comportamiento de especies marinas a grandes distancias y pueden alterar patrones migratorios clave.

La instalación de cables y estructuras submarinas afecta considerablemente a los hábitats bentónicos, desplazando sedimentos, aumentando la turbidez del agua y modificando la biodiversidad local. Estas alteraciones pueden perjudicar a organismos como poliquetos, crustáceos y equinodermos, esenciales para las dinámicas ecológicas del fondo marino. Además, la turbidez incrementada afecta la penetración de luz, reduciendo la fotosíntesis del fitoplancton y alterando las cadenas tróficas marinas (Van Hoey, 2018). Según Köller (2006), los impactos en fondos arenosos pueden favorecer especies de fondos duros, pero eliminan hábitats blandos y afectan la biodiversidad asociada.

La calidad del agua enfrenta riesgos significativos debido a derrames operativos o accidentales de combustibles, liberación de sedimentos y posibles contaminantes provenientes de las actividades de construcción. Estas alteraciones hidroquímicas y físicas pueden dañar directamente a las especies acuáticas y generar impactos a largo plazo en los ecosistemas marinos. Paralelamente, las emisiones atmosféricas generadas por maquinaria pesada, buques y equipos de soldadura contribuyen a la contaminación del aire, afectando tanto a las comunidades locales como a la biodiversidad costera (Thomsen, 2012).

El incremento del tráfico marítimo y terrestre durante la construcción añade complejidad a los impactos. El transporte continuo de materiales y equipos aumenta el riesgo de colisiones entre embarcaciones y especies marinas como tortugas, aves y mamíferos marinos. Estas colisiones pueden causar lesiones graves o mortales, y el ruido generado por el tráfico marítimo afecta aún más a la fauna marina, especialmente a especies dependientes del sonido (Byrnes & Dunn, 2020). Las restricciones de navegación impuestas para garantizar la seguridad durante la construcción también pueden interferir con actividades económicas como la pesca, afectando directamente los medios de vida de las comunidades locales (Van Hoey, 2018).

Otro impacto relevante es la presión sobre los recursos naturales debido al consumo intensivo de materiales como acero, concreto, cobre y otros metales esenciales para las estructuras y membranas de los electrolizadores. Este consumo genera una huella significativa de gases de efecto invernadero durante la producción de estos materiales, incrementando los impactos ambientales del proyecto (Condon, 2023). Además, la generación de residuos, incluyendo materiales de construcción y aceites usados, plantea desafíos en su gestión, destacando la necesidad de sistemas adecuados para su recolección, reciclaje y eliminación segura (Thomsen, 2012).

Finalmente, la congestión de servicios logísticos, como los puertos, representa un desafío tanto técnico como ambiental. La selección inadecuada de puertos puede generar demoras significativas en las operaciones logísticas y conflictos con las comunidades costeras debido a impactos visuales y restricciones en el acceso a áreas públicas (Thomsen, 2012). A pesar de estos desafíos, la fase de construcción también ofrece oportunidades de generación de empleo y desarrollo económico local, creando empleos directos e indirectos en sectores como la logística, los servicios y la construcción, lo que puede contribuir positivamente al bienestar de las comunidades cercanas.

3.2.3. Medidas de Mitigación

La mitigación de los impactos ambientales durante la fase de construcción incluye un conjunto integral de medidas. Para reducir el impacto del ruido submarino, se propone el uso de pingers, dispositivos acústicos que emiten señales fuertes para alejar a los mamíferos marinos de las áreas de construcción, evitando daños en su sistema auditivo y posibles lesiones permanentes. Además, las cortinas de burbujas ofrecen una barrera acústica al generar burbujas con aire presurizado, disminuyendo la transmisión de ruido bajo el agua, aunque su eficacia depende de las condiciones del entorno marino (Thomsen, 2012, pág. 288). Asimismo, los sistemas de propulsión a chorro son recomendados para embarcaciones, ya que reducen el riesgo de lesiones en tortugas marinas y otras especies debido a la ausencia de hélices (Byrnes & Dunn, 2020).

Se deben implementar planes de contingencia que gestionen posibles derrames de aceites y sustancias contaminantes, y se debe minimizar el uso de generadores eléctricos temporales que utilicen combustibles fósiles (Thomsen, 2012). También es recomendable utilizar materiales no contaminantes, como cables libres de hidrocarburos, para evitar la liberación de sustancias tóxicas al entorno marino, protegiendo la fauna y flora local (Bastien et al., 2018). La planificación estratégica de actividades puede prevenir impactos acumulativos al coordinar varias obras simultáneas en una misma región (Thomsen, 2012).

En relación con el lecho marino, se recomienda planificar cuidadosamente las rutas de los cables submarinos para evitar áreas ecológicamente sensibles, así como enterrar los cables a profundidades que minimicen la exposición de las especies marinas a campos electromagnéticos y calor. Esto protege organismos como tiburones, rayas y peces diádromos presentes en la ZEE, además de reducir el riesgo de interacción negativa con la vida marina (Bastien et al., 2018).

Es fundamental establecer restricciones de navegación y zonas de seguridad para evitar colisiones entre embarcaciones el proyecto. Además, se debe prohibir la pesca de arrastre en las áreas del proyecto para evitar accidentes. La participación del sector pesquero en la planificación permite minimizar conflictos y asegurar un diseño que facilite la coexistencia de las actividades pesqueras y el proyecto eólico (Van Hoey, 2018).

La gestión de residuos es clave para minimizar la contaminación. Todos los desechos deben ser recolectados, reciclados o eliminados siguiendo regulaciones, como el principio de cero descargas utilizado en aguas alemanas, que obliga a retornar a tierra todo lo que no quede fijado en las estructuras offshore (Thomsen, 2012).

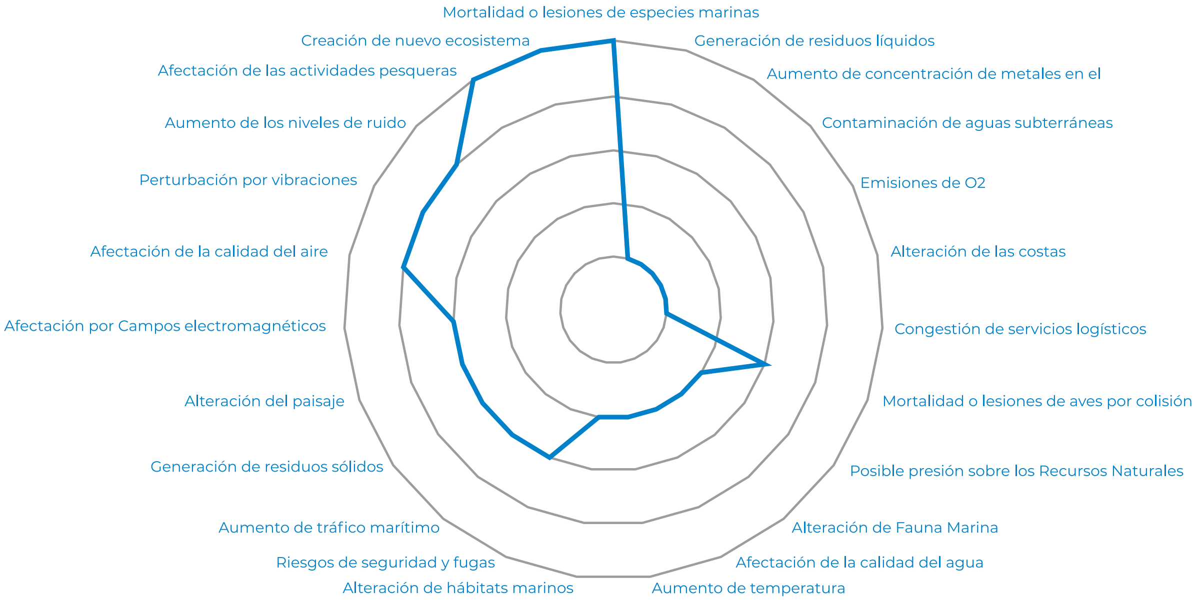
Finalmente, es esencial planificar puertos con suficiente capacidad para manejar los componentes del proyecto, establecer áreas de almacenamiento amplias, entre 60,000 y 70,000 m2 para proyectos de aproximadamente 80 aerogeneradores (Thomsen, 2012), y evitar la construcción en áreas sensibles desde el punto de vista turístico o ecológico. La implementación de centros de coordinación de tráfico garantiza un flujo eficiente de materiales y personal, minimizando la congestión y los accidentes en zonas marítimas y terrestres. Además, la gestión eficiente del uso de combustibles y lubricantes, junto con la documentación detallada del consumo de recursos, contribuye a una operación más sostenible y a reducir la huella de carbono del proyecto (Thomsen, 2012).

3.3. Fase de Operación

La fase de operación implica una serie de actividades continuas que pueden generar impactos ambientales significativos tanto al medio físico y biótico como al medio antrópico.

En la Figura 5 se detallan los principales impactos identificados durante esta fase.

Figura 5. Principales impactos ambientales identificados en la Fase de Operación.



Fuente: elaboración propia.

Entre los principales impactos identificados se encuentra la mortalidad o lesiones de aves y especies marinas por colisiones con las palas de los aerogeneradores o con las embarcaciones utilizadas en actividades de mantenimiento. Las aves migratorias, en particular, enfrentan un riesgo elevado debido a la altura y extensión de las turbinas, mientras que mamíferos marinos y tortugas pueden sufrir lesiones graves al interactuar con las estructuras (Exo et al., 2003; Ibon et al., 2022).

Otro impacto importante es el aumento del ruido y las vibraciones, que afecta negativamente a la fauna marina. Este ruido proviene tanto de la operación de los aerogeneradores y los electrolizadores como de los sistemas de transmisión eléctrica y compresión, con efectos acumulativos que pueden alterar los patrones de comportamiento y migración de la fauna marina (European Industrial Gases Association, 2018).

Los cables submarinos generan campos electromagnéticos y aumentan la temperatura del agua, lo que puede afectar a especies sensibles y alterar las condiciones térmicas del entorno. Adicionalmente, en caso de roturas, los cables podrían liberar sustancias contaminantes al lecho marino, afectando la calidad del agua y los ecosistemas locales (Bastien et al., 2018).

La desalinización del agua, necesaria para los sistemas de electrólisis genera salmuera, cuya descarga puede alterar la salinidad y la oxigenación del agua, impactando negativamente a los hábitats bentónicos y la fauna marina. Además, el uso de productos químicos en estos procesos puede incrementar la toxicidad del agua marina (Soliman, 2021).

El tráfico marítimo intensificado para mantenimiento incrementa el riesgo de colisiones con fauna marina y puede interferir con rutas de migración y actividades pesqueras. Esto último afecta tanto a la pesca industrial como a la artesanal, limitando el acceso a áreas tradicionales de pesca y provocando conflictos en el sector (Van Hoey, 2018).

En el ámbito terrestre, la instalación de sistemas de electrólisis onshore puede impactar el paisaje costero, transformar áreas en zonas industriales y generar riesgos de contaminación de acuíferos debido a posibles fugas de concentrados salinos y químicos tratados (Gurudeo, 2007).

Entre los impactos positivos se incluye la creación de nuevos ecosistemas debido a las estructuras marinas, que pueden actuar como arrecifes artificiales, favoreciendo la biodiversidad local. Además, la generación de empleo en sectores relacionados con la energía renovable y el hidrógeno verde constituye un beneficio socioeconómico significativo (Congressional Research Service, 2024).

3.3.1. Medidas de Mitigación

Las medidas se centran en reducir los efectos negativos sobre la fauna marina, las aves, los recursos naturales y el entorno físico. Para prevenir la mortalidad de aves y murciélagos por colisión, se recomienda la instalación de sistemas disuasorios visuales y acústicos, como pintar una pala de los aerogeneradores de negro para aumentar su visibilidad, lo que ha demostrado reducir las colisiones hasta en un 70%, y el uso de señales acústicas o ultrasónicas para alejar especies vulnerables (Renewable Energy Wildlife Institute, 2024). Además, se propone la reducción o apagado selectivo de aerogeneradores en momentos críticos de alto riesgo, utilizando tecnología de radar e inteligencia artificial para detectar aves y activar estas medidas automáticamente.

Para minimizar el impacto en la fauna marina, se sugiere el enterramiento de cables submarinos para reducir la exposición a campos electromagnéticos, además de usar cables trifásicos AC o sistemas HVDC bipolares con blindajes adecuados (Bastien et al, 2018). También se recomienda implementar tomas de agua subsuperficiales (depende de la región) en los procesos de desalinización, lo que disminuye el riesgo de atrapamiento de organismos marinos durante la toma de agua (Missimera, 2017). En cuanto a la iluminación, se sugiere utilizar sensores de movimiento y temporizadores para controlar la duración de la exposición lumínica, minimizando su impacto en la vida silvestre y los hábitats marinos (Byrnes & Dunn, 2020).

En el manejo de residuos líquidos, se plantean sistemas de tratamiento de aguas residuales para eliminar impurezas generadas en los procesos operativos y evitar la contaminación del agua. Para la gestión de salmuera derivada de la desalinización, se proponen sistemas de difusión diseñados para diluir la concentración salina y minimizar sus efectos sobre los ecosistemas bentónicos (Missimera, 2017). En cuanto al ruido y las vibraciones generadas por los equipos de electrolisis y compresores, se recomienda el aislamiento acústico de los mismos, el uso de cabinas insonorizadas y el mantenimiento planificado para evitar la acumulación de impactos en el medio marino (Stocker, 2023).

Además, se sugiere un enfoque de planificación estratégica para fomentar la coexistencia entre proyectos y actividades pesqueras, estableciendo restricciones específicas para técnicas de pesca de alto impacto como el arrastre, pero evaluando opciones para permitir métodos de pesca pasiva (Van Hoey, 2018). Por último, se recomienda el diseño adecuado de instalaciones para el manejo seguro de hidrógeno, incluyendo códigos y normas estrictas que minimicen riesgos de fugas e incendios (Chris LaFleur, 2023).

4. CONCLUSIONES Y RECOMENDACIONES

En Uruguay, las zonas entre 20 y 100 metros de profundidad dentro de la ZEE son técnicamente viables para la instalación de proyectos eólicos offshore, sin embargo, hay que delimitar muy bien las áreas para evitar afectar zonas protegidas o de interés cultural.

En la fase de desarrollo los impactos ambientales se concentran en el medio biótico. Las actividades preliminares, como estudios geofísicos y geotécnicos, generan ruido y alteran el lecho marino, afectando a especies como mamíferos marinos, peces y tortugas. Los equipos utilizados en estas investigaciones son invasivos, y los niveles de ruido pueden perturbar los patrones de comunicación y migración de ballenas y delfines, así como interferir en el comportamiento de otras especies marinas dentro de la ZEE.

En la construcción, actividades como el dragado y la instalación de cables submarinos alteran la turbidez del agua y liberan sedimentos, afectando la calidad del hábitat marino. El uso de martillos hidráulicos para fundaciones genera ruido y presión sonora, perjudicando a mamíferos marinos, peces y cefalópodos. Estas actividades también incrementan el tráfico marítimo, aumentando el riesgo de colisiones y afectaciones a la fauna marina.

En la operación, uno de los impactos más relevantes es la mortalidad de aves por colisiones con aerogeneradores. Las vibraciones y ruidos submarinos también afectan a la fauna marina, alterando patrones de comportamiento, reproducción y migración. Además, la desalinización necesaria para la electrólisis produce efluentes de alta salinidad y residuos químicos que alteran la calidad del agua y pueden impactar ecosistemas locales. Los campos electromagnéticos generados por los cables submarinos, aunque con efectos menores, también pueden interferir en especies sensibles.

Para mitigar estos impactos, se proponen medidas que se han utilizado exitosamente en otros proyectos, como el uso de cortinas de burbujas para reducir ruido, enterramiento de cables para minimizar campos electromagnéticos, y sistemas de tratamiento para gestionar adecuadamente los efluentes de desalinización. Además, estrategias como la planificación espacial y la implementación de tecnologías más eficientes buscan reducir impactos acumulativos y promover la sostenibilidad del entorno marino.

Los proyectos también pueden presentar impactos positivos. Las estructuras offshore actúan como arrecifes artificiales, fomentando la biodiversidad al ofrecer hábitats a diversas especies marinas. Este efecto positivo puede generar oportunidades económicas adicionales, como el ecoturismo y la investigación científica. Además, el desarrollo y operación de los proyectos offshore generan empleo en sectores como ingeniería, logística, mantenimiento y desarrollo tecnológico, impulsando industrias locales y creando un efecto multiplicador en la economía.

Este estudio sugiere un enfoque integral para el desarrollo sostenible de proyectos de energía eólica offshore y producción de hidrógeno verde en Uruguay. Las recomendaciones clave, partiendo de las lecciones aprendidas en otras regiones son:

4.1. Marco Regulatorio Integral:

En Uruguay, la falta de regulaciones específicas para este tipo de proyectos resalta la necesidad de establecer normativas claras desde las etapas iniciales de planificación. Se recomienda adoptar estándares internacionales y aprender de la experiencia de países en el sector, como Dinamarca y el Reino Unido. Dinamarca, con su planificación espacial marina y procesos de licitación competitivos, ha desarrollado un modelo exitoso para el crecimiento sostenible de la energía eólica offshore. Por su parte, el Reino Unido, mediante instituciones como el Crown Estate y políticas como el Offshore Wind Sector Deal, ha promovido la colaboración público-privada, reduciendo costos e incrementando la capacidad instalada (UK Government, 2020). Estados Unidos también ofrece un modelo basado en la planificación espacial y subastas de derechos gestionadas por el BOEM, equilibrando el desarrollo con la protección de otras actividades marinas (BOEM, 2024).

Para desarrollar proyectos offshore es fundamental obtener diversos permisos, incluyendo concesiones para el uso del espacio marítimo, autorizaciones para generación de electricidad, acuerdos de conexión a la red, permisos ambientales y licencias relacionadas con trabajos en tierra y operación de infraestructura. La ausencia de un enfoque coordinado en la gestión de estos permisos puede provocar retrasos significativos, aumentando el riesgo y la complejidad del proyecto. Por ello, se requiere un sistema eficiente, con coordinación interinstitucional, simplificación de trámites y alineación con los objetivos nacionales, para garantizar el avance sostenible de estas iniciativas.

Una estrategia efectiva para optimizar los procesos de permisos es la implementación de una Ventanilla Única, que centraliza la gestión a través de un único punto de contacto. Este modelo, aplicado exitosamente en Dinamarca y Costa Rica, mejora la transparencia y reduce los tiempos de aprobación, permitiendo una mejor coordinación entre las autoridades. Sin transferir competencias legislativas, actúa como facilitador, guiando a los desarrolladores en un marco regulatorio claro y eficiente (GWEC & IRENA, 2023).

4.2. Planificación Espacial Marina (MSP, por su sigla en inglés):

Se recomienda que Uruguay inicie el desarrollo de proyectos offshore con la implementación de una MSP con un enfoque estratégico diseñado para regular los entornos marinos mediante la zonificación y la conciliación de diversos usos del mar. La MSP busca facilitar el desarrollo sostenible de actividades marítimas, minimizando conflictos y acelerando los procesos de permisos al involucrar a múltiples partes interesadas desde las etapas iniciales (GWEC & IRENA, 2023).

La MSP promueve la colaboración entre actores clave, como la industria energética, organismos gubernamentales, sectores de conservación y comunidades locales, para tomar decisiones coordinadas e informadas. Organismos internacionales como la UNESCO, en colaboración con la Unión Europea, han desarrollado guías de referencia para su implementación, incluyendo estándares globales como el documento de 2009 sobre gestión basada en ecosistemas y la Guía Internacional de 2021 para la Planificación Espacial Marina (GWEC & IRENA, 2023).

Para Uruguay, se recomienda incluir consultas públicas desde las etapas iniciales de planificación para garantizar transparencia y consenso, especialmente con sectores como el pesquero. También se sugiere evaluar impactos acumulativos y desarrollar medidas específicas para mitigar efectos temporales como ruido, vibraciones y alteraciones en la calidad del agua y el aire, promoviendo un desarrollo marítimo equilibrado y sostenible.

4.3. Promoción de Investigaciones y Estudios:

Es crucial desarrollar líneas de base ambientales detalladas para evaluar los impactos en la ZEE de Uruguay. Se recomienda exigir estudios de línea de base a los desarrolladores y construir bases de datos digitales consultables para mejorar la toma de decisiones y la planificación futura.

4.4. Formación y Capacitación:

Uruguay debe priorizar programas de formación en tecnologías de energía eólica offshore e hidrógeno verde para los equipos e instituciones que estarán evaluando estos proyectos, fortaleciendo competencias digitales y técnicas en la fuerza laboral. Soluciones tecnológicas como las desarrolladas por WindEurope y Amazon Web Services pueden optimizar la gestión de permisos, mejorando la eficiencia y transparencia en los procesos regulatorios (GWEC & IRENA, 2023).

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Garantias financeiras: evoluções regulatórias para assegurar o efetivo descomissionamento das instalações de produção de petróleo e gás natural no Brasil

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Resumo

Diante do cenário de incertezas quanto ao futuro da indústria do petróleo e da possibilidade de responsabilização internacional em caso de poluição oceânica, países produtores de petróleo, dentre ele o Brasil, têm promovido a atualização dos seus normativos sobre descomissionamento de plataformas offshore. Assim, por meio de revisão dos principais normativos internacionais e brasileiros relacionados ao descomissionamento offshore, este artigo busca analisar o arcabouço regulatório brasileiro sobre a temática. Adicionalmente, são discutidas as principais questões a serem abordadas no processo de revisão da regulação de garantia financeira para mitigar o risco de o contribuinte arcar com o custo das operações de descomissionamento. Os resultados da análise indicaram haver falta de transparência na disponibilização de informações à sociedade sobre as atividades de exploração e produção de petróleo. Além disso, constatou-se a necessidade de aumentar a participação do sistema financeiro no provimento de garantias para o descomissionamento. Por fim, verificou-se a necessidade de o órgão regulador estabelecer parâmetros claros para a definição de estimativas de custo do descomissionamento. As melhorias propostas neste artigo pretendem contribuir para que países como o Brasil avancem em direção a uma transição energética justa, na qual os custos da transição sejam adequadamente suportados pelos seus respectivos responsáveis.

Palavras-chave: descomissionamento de plataformas, garantias financeiras, indústria de petróleo e gás natural, transição energética, regulação.

Abstract

In the face of uncertainty regarding the future of the oil industry and the possibility of international liability in the event of ocean pollution, oil-producing countries, including Brazil, have been updating their regulations on the decommissioning of offshore platforms. Thus, by reviewing the main international and Brazilian regulations related to offshore decommissioning, this article seeks to analyze the Brazilian regulatory framework on the subject. Additionally, the main issues to be addressed in the process of reviewing the financial guarantee regulation to mitigate the risk of the taxpayer bearing the cost of decommissioning operations are discussed. The results of the analysis indicated a lack of transparency in the provision of information to society about oil exploration and production activities. In addition, it was found that there is a need to increase the participation of the financial system in the provision of guarantees for decommissioning. Finally, it was found that the regulatory body needs to establish clear parameters for defining decommissioning cost estimates. The improvements proposed in this article aim to help countries like Brazil move towards a fair energy transition in which the transition costs are adequately borne by those responsible for them.

KEYWORDS: platform decommissioning, financial guarantees, oil and natural gas industry, energy transition, regulation.

1. INTRODUÇÃO

De acordo com relatórios setoriais publicados no início da década de 2020, o mundo possui mais de 7.500 instalações offshore destinadas à produção de petróleo e gás natural, distribuídas entre mais de 50 países (Loia et al., 2022). Grande parte dessas estruturas, entretanto, estão alcançando a fase final de seu ciclo de vida, sendo estimado que aproximadamente 3.000 plataformas serão descomissionadas entre os anos de 2021 e 2030, ao custo total de 100 bilhões de dólares (Lockman et al., 2023). Estima-se que o Brasil se tornará um dos principais países em termos de volume de investimento em descomissionamento, com um total de investimentos pós-2025 que deve exceder 180 bilhões de reais. Essas estimativas superam as previsões de investimentos para o Reino Unido (119 bilhões de reais) e para os Estados Unidos, de 55,25 bilhões de reais, para o mesmo período (FGV Energia, 2021).

Não obstante a fase descomissionamento ainda não ter sido experimentada por muitos países produtores de petróleo, uma vez que tais atividades são normalmente executadas em campos maduros, não se pode dizer que essa é uma etapa totalmente desconhecida pela indústria. Como todo recurso mineral esgotável, ainda durante a elaboração dos planos de desenvolvimento, é possível estimar quando os custos de produção tornarão maiores que a receita advinda da produção e, consequentemente, quando um projeto será descomissionado (Kaiser, 2019). Em razão disso, as plataformas offshore de petróleo são projetadas para ter uma vida útil equivalente ao período de produção esperado do campo onde serão instaladas (FGV Energia, 2022).

Ocorre que, em adição aos fatores técnicos que inevitavelmente conduzem ao descomissionamento, a crescente exigência de descarbonização da economia poderá acarretar o encerramento das atividades de produção de petróleo muito antes do planejado (Lockman et al., 2023). Ambientalistas e pesquisadores têm afirmado que, para alcançar as metas estabelecidas pelo Acordo de Paris e limitar o aumento da temperatura global a 1,5°C acima dos níveis pré-industriais, é necessário impor restrições à produção de combustíveis fósseis. Assim, sugerem que os países produtores de petróleo sejam obrigados a renunciar à exploração de até 60% de suas reservas (Welsby et al., 2021). Outras medidas mais concretas, entretanto, já estão sendo adotadas por países industrializados, a exemplo da proibição da venda de carros com motor de combustão interna, o que permite projetar uma redução drástica na demanda futura de combustíveis fósseis (Panetta, 2022).

Nesse cenário de incertezas quanto ao futuro da indústria do petróleo, portanto, a preocupação quanto à capacidade das petrolíferas honrarem com seus compromissos de fim de vida contratual passou a ser um tema recorrente nas agendas governamentais. Tal apreensão decorre, principalmente, do fato de grande parte dos países produtores de petróleo serem signatários de tratados internacionais que os obrigam a não causar poluição oceânica. Assim, nos termos desses tratados, caso as companhias petrolíferas não detenham recursos financeiros para desativar as instalações de produção, os países que as autorizaram poderão ser condenados a assumir os elevados custos das atividades de descomissionamento (Paterson, 2010).

Para mitigar esse risco financeiro, então, países produtores passaram a buscar medidas mais efetivas para evitar que o custo do descomissionamento venha a ser suportado por seus cidadãos pagadores de impostos, um problema conhecido no mundo econômico como externalidades (Dernbach, 1998; Mackie & Fogleman, 2016). Dentre as principais medidas para garantir a internalização dessas externalidades referentes às atividades de descomissionamento, a exigência da contratação de garantias financeiras para assegurar o descomissionamento das instalações de produção tem se mostrado uma ferramenta com potencial para evitar que danos socioeconômicos e ambientais se materializem (Parente et al., 2006). Essa foi exatamente a opção adotada pela Brasil, que recentemente promoveu atualizações em seu arcabouço regulatório, de modo a tornar mais rígidas e claras as obrigações relacionadas às atividades de descomissionamento a serem executadas ao fim do contrato (Braga & Pinto, 2022).

Tendo sido superada, então, a etapa inicial de atualização normativa, a Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) realizou em 2023 o primeiro ciclo completo de cobrança de garantias financeiras, o que torna possível analisar o processo para identificar oportunidades de aprimoramento dessa política pública. Assim, com o objetivo de situar a atualização da regulamentação brasileira dentro de um esforço global de construção de mecanismos para proteger os cidadãos de países produtores de petróleo quanto ao risco financeiro associado às atividades de descomissionamento, este artigo, por meio de uma revisão histórica, busca apresentar os principais tratados internacionais relacionados ao descomissionamento offshore.

Adicionalmente, analisando as informações publicadas pela ANP sobre o descomissionamento, serão feitos apontamentos iniciais sobre oportunidades de evolução do atual arcabouço regulatório, visando permitir que as garantias financeiras cumpram efetivamente sua função. O diagnóstico alcançado indica que o órgão regulador deve ampliar a transparência das informações prestadas à sociedade sobre as atividades de descomissionamento, além de estabelecer parâmetros claros que permitam a elaboração de estimativas confiáveis do custo dessas atividades. Além disso, foi constatada a necessidade de aumentar a participação do sistema financeiro no provimento dos recursos que garantam a execução do descomissionamento, reduzindo as possibilidades de autogarantias.

Além desta breve introdução, o presente artigo contempla mais cinco seções. Na seção dois são apresentados os principais tratados e convenções internacionais relacionados à temática do descomissionamento offshore. A seção três é dedicada a analisar a influência das normativas internacionais sobre a construção do arcabouço legal e regulatório brasileiro. Por sua vez, na seção quatro é realizada uma breve análise do primeiro ciclo de apresentação de garantias, que se iniciou em 2023. Em seguida, na seção cinco, são debatidos os principais aspectos que devem ser considerados para aumentar a efetividade da política pública em análise. Finalmente, as considerações finais apresentam os principais pontos discutidos neste artigo, com destaque para a indicação dos caminhos que a regulação brasileira deverá seguir para assegurar uma transição energética justa no país.

2. EVOLUÇÃO DOS TRATADOS E CONVENÇÕES INTERNACIONAIS DE DESCOMISSIONAMENTO

Buscando proteger o meio ambiente, as rotas oceânicas para navegação, as atividades comerciais como a pesca e os outros usos das águas marítimas, os tratados e convenções internacionais que governam importantes aspectos da indústria offshore de petróleo evoluíram consideravelmente no último século (Fam et al., 2018). Dentre os tratados internacionais elaborados nos últimos 60 anos relacionados à temática do descomissionamento offshore, três normativos merecem uma apreciação mais detalhada: a Convenção sobre a Plataforma Continental, a Convenção das Nações Unidas sobre o Direito do Mar e as Diretrizes emitidas pela Organização Marítima Internacional (Martin, 2003).

2.1. A Convenção sobre a Plataforma Continental - Convenção de Genebra (1958)

A Convenção sobre a Plataforma Continental, também conhecida como Convenção de Genebra, foi o primeiro tratado internacional relacionado ao abandonamento ou desuso de instalações marítimas. Essa convenção estabeleceu a noção e os limites da plataforma continental e os direitos e deveres do Estado costeiro relativos à exploração de recursos naturais em uma área além do mar territorial (Anderson et al., 2020).

Os principais objetivos deste normativo foram a proteção das rotas marítimas essenciais à navegação internacional e à atividade pesqueira, bem como a conservação dos recursos vivos do mar e a defesa da investigação científica. Nesse sentido, a convenção determinava que o Estado costeiro deveria manter a segurança em torno das instalações da plataforma continental necessárias para explorar os recursos naturais com o objetivo de proteger as rotas marítimas. Adicionalmente, qualquer instalação abandonada ou fora de uso localizada na plataforma continental deveria ser totalmente removida (International Law Commission, 1958).

Cabe mencionar, entretanto, que as atividades de produção de petróleo offshore ainda eram muito incipientes quando da elaboração deste normativo, sendo confinadas quase que exclusivamente a águas rasas (Hammerson & Antonas, 2016). Nesse sentido, a total remoção das instalações abandonadas ou fora de uso era uma determinação plausível de ser seguida. Entretanto, com a instalação de plataformas em águas profundas, tornou-se claro que o cumprimento do dispositivo poderia não mais ser factível. Por esse motivo, os países mais avançados na tecnologia de produção em águas profundas passaram a propor uma interpretação alternativa para a convenção, na qual apenas as instalações que pudessem causar alguma interferência injustificável na navegação, pesca ou conservação dos recursos vivos deveriam ser removidas (Paterson, 2010).

2.2. A Convenção das Nações Unidas sobre o Direito do Mar (1982)

Considerando que a indústria do petróleo evoluiu desde a Convenção de Genebra, os países produtores de petróleo membros da Organização das Nações Unidas (ONU) procuraram estabelecer um normativo menos rígido em relação ao descomissionamento. Desse esforço, emergiu a Convenção das Nações Unidas sobre o Direito do Mar de 1982, que estabeleceu uma nova ordem jurídica para os mares e oceanos, tendo como principais objetivos promover a comunicação internacional, manter o uso pacífico do oceano, o uso eficiente e a conservação dos recursos naturais, bem como a proteção do ambiente marinho (United Nations General Assembly, 1982).

No que diz respeito ao descomissionamento, essa convenção era nitidamente mais permissiva do que a Convenção de Genebra, uma vez que permitia a remoção apenas parcial de instalações offshore fora de uso. Nos termos dessa nova convenção, qualquer instalação ou estrutura fora de uso deveria ser removida. Contudo, no caso de instalações ou estruturas não totalmente removidas, a sua posição, profundidade e dimensões deveriam ser devidamente publicadas (Martin, 2003). Assim, embora não seja explicitamente afirmado que as instalações offshore pudessem ser parcialmente removidas, o documento aprovado abre espaço para esta interpretação (Fam et al., 2018).

Outra importante mudança inserida no texto dessa convenção é a indicação de que a remoção de instalações e estruturas offshore abandonadas deveria ser conduzida de acordo com padrões internacionais de aceitação geral relativos ao desmantelamento publicados por uma organização internacional competente. Assim, mais uma vez por meio de um esforço de interpretação textual, à Organização Marítima Internacional (OMI) foi concedida a autoridade de desenvolver novos padrões e diretrizes de descomissionamento em harmonia com o estágio de desenvolvimento da indústria offshore de petróleo (Anderson et al., 2020).

2.3. As Diretrizes e Normas da Organização Marítima Internacional (OMI) para a Remoção de Instalações e Estruturas Offshore na Plataforma Continental e na Zona Econômica Exclusiva

Diferentemente das convenções apresentadas anteriormente, as diretrizes da Organização Marítima Internacional não são vinculativas, sendo apenas um guia que apresenta recomendações aos países membros da OMI sobre um assunto específico relacionado ao transporte marítimo (Braga & Pinto, 2022). Entretanto, para aqueles países que promulgaram a Convenção das Nações Unidas sobre o Direito do Mar de 1982, visto que tal regulamento menciona que devem ser observadas as normas publicadas por uma organização internacional competente, as diretrizes da OMI tornaram-se de natureza vinculativa (Fam et al., 2018).

Assim, as diretrizes produzidas por esta organização, e aprovadas na Assembleia da OMI em 1989, estabeleceram que as instalações ou estruturas abandonadas ou fora de uso localizadas na plataforma continental ou na zona econômica exclusiva deveriam ser removidas, a menos que a sua não remoção ou remoção parcial fosse coerente com os padrões estipulados pelas diretrizes da OMI. Essas diretrizes, por sua vez, estabelecem que a decisão de permitir que uma instalação, estrutura ou partes dela permaneçam no fundo do mar deve basear-se numa avaliação caso a caso pelo Estado costeiro com jurisdição sobre a instalação ou estrutura. Dentre os assuntos que devem ser considerados na análise de cada caso, destacam-se “os custos, a viabilidade técnica e os riscos de lesões ao pessoal associados à remoção da instalação ou estrutura” (International Maritime Organization, 1989, p. 2).

3. A RECEPÇÃO DAS CONVENÇÕES INTERNACIONAIS PELO ORDENAMENTO JURÍDICO E REGULATÓRIO BRASILEIRO

A Convenção das Nações Unidas sobre o Direito do Mar, celebrada em 1982, recebeu a assinatura de 159 Estados-membros, dentre eles o Brasil. Entretanto, antes de ser recebida pelo ordenamento jurídico brasileiro, foi necessário a adequação do direito interno ao tratado, o que ocorreu apenas com a Lei 8.617, de 4 de janeiro de 1993, que estabeleceu o regramento brasileiro sobre o mar territorial e a zona econômica exclusiva. Finalmente, por meio do Decreto 1.530, de 22 de junho de 1995, foi declarada a entrada em vigor da Convenção no Brasil, a partir de 16 de novembro de 1994 (Fiorati, 1997).

Assim, a partir dessa data, perante o direito internacional, o Brasil passou a ser passível de responsabilização no caso de descumprimento das normas referentes ao abandonamento ou desuso de instalações marítimas, incluindo as de produção de petróleo. Por esse motivo, desde os primeiros contratos de exploração e produção firmados entre a Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) e as empresas petrolíferas, existe a determinação explícita de que as empresas contratadas são obrigadas a executar as atividades de desativação e abandono.

Por evolução regulatória, esse conjunto de atividades passou a ser denominado descomissionamento, e consiste nas atividades associadas à interrupção definitiva da operação das instalações, ao abandono permanente e arrasamento dos poços, além da correta destinação dos materiais retirados. Adicionalmente, é na fase de descomissionamento que devem ser realizadas as ações necessárias para a recuperação ambiental da área de produção, bem como tomadas as medidas para a garantir as condições de segurança para a navegação marítima (Braga & Pinto, 2022).

Entretanto, as atividades de descomissionamento são normalmente realizadas ao final do contrato, isto é, após o fim da vida útil produtiva de um campo. Assim, caso determinada petrolífera não tenha reservado os recursos financeiros necessários para executar as complexas e dispendiosas atividades de descomissionamento, e venha a se tornar insolvente, o governo do Brasil (e em última instância, o pagador de impostos) pode ser obrigado a custear as ações de descomissionamento em decorrência da Convenção das Nações Unidas sobre o Direito do Mar.

Desta forma, para mitigar tal risco financeiro, os contratos de exploração e de produção de petróleo utilizados no Brasil também estabelecem obrigações quanto à contratação de garantias de descomissionamento por parte das petrolíferas. Ocorre que, pela ausência de previsão para o início dos projetos de descomissionamento, a regulação do tema foi, de certa forma, postergada pela ANP. Contudo, a ausência uma resolução específica que estabelecesse normas claras sobre as formas de apresentação das garantias de descomissionamento criava um ambiente de insegurança jurídica e de incertezas para os contratos de concessão (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis [ANP], 2019).

O status quo, contudo, começou a ser alterado no início da década de 2010, em decorrência da proximidade do fim dos contratos assinados em 1995 entre a ANP e a Petróleo Brasileiro S.A. (Petrobras). Entretanto, a discussão sobre descomissionamento no Brasil, de fato, ganhou consistência a partir da divulgação do plano de desinvestimento da Petrobras em 2015, que previa a cessão de campos de produção “maduros”, isto é, campos que já ultrapassaram seu pico de produção. Em decorrência desse processo de cessão, os fatores de risco associados à indústria petrolífera no país sofreriam alterações, visto que entre as principais interessadas nos ativos disponibilizados pela Petrobras estavam pequenas e médias empresas, muitas dessas sem experiência prévia no setor do petróleo (Chambriard, 2021).

Assim, após várias rodadas de discussão sobre o tema das garantias financeiras para descomissionamento com órgãos de representação das empresas petrolíferas, de instituições financeiras e de outras entidades com interesse no assunto, em 27 de setembro de 2021, foi publicada a Resolução ANP nº 854/21. Tal resolução tomou como referência as mais modernas normativas internacionais sobre o assunto, estabelecendo os procedimentos relacionados às garantias de descomissionamento no Brasil. Entretanto, para permitir que todas as instituições financeiras e o próprio setor do petróleo se adaptassem às inovações trazidas pela nova regulação, a Resolução ANP nº 854/21 passou a ter plena efetividade apenas em 02 de outubro de 2023[1], passando a ser aplicável a todos os contratos de exploração e produção de petróleo e gás natural.

4. A APLICAÇÃO DO NOVO ARCABOUÇO REGULATÓRIO - PRIMEIROS CICLOS

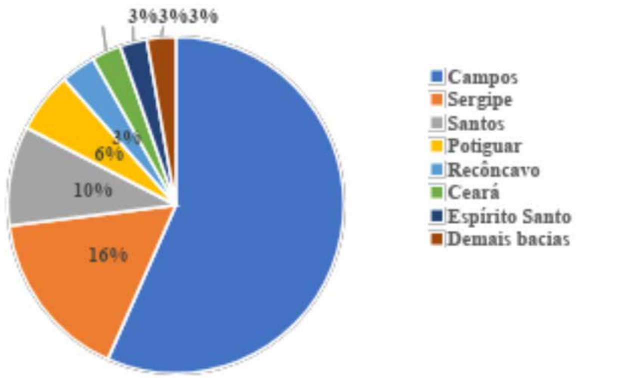
Em abril de 2023, a ANP publicou em seu sítio eletrônico o primeiro "Painel Dinâmico de Garantias Financeiras de Descomissionamento", no qual constavam todos os campos de petróleo ou gás natural em fase de desenvolvimento ou de produção no Brasil. Conforme disponível no referido painel, em 2023, um total de 396 campos estavam obrigados a apresentar garantia financeira em alguma das modalidades permitidas pela Resolução ANP nº 854/21, quais sejam: carta de crédito, seguro garantia, garantia corporativa, penhor de petróleo e gás natural, fundo de provisionamento ou um termo com atributo de título executivo extrajudicial por meio do qual a própria empresa assegura os recursos financeiros para o descomissionamento (ANP, 2023).

O valor total das garantias a serem apresentadas em 2023 foi de R$ 82,7 bilhões, o que representa 37% do custo total do descomissionamento brasileiro, que era estimado em 2023 no montante de R$ 224 bilhões. Em relação às obrigações de apresentação de garantia, os valores variavam de ínfimos R$ 50,20 (campo Piranema Sul, em devolução na bacia Sergipe) até substanciais R$ 8,8 bilhões (campo Albacora, em produção na bacia Campos). Por sua vez, no que se refere à localização, a bacia de Campos foi aquela com o maior valor a ser garantido em 2023, no montante de R$ 46,8 bilhões[2], o que representa cerca de 60% do total de garantias do ano, conforme ilustrado na Figura 1.

1.- De acordo com a Resolução ANP n° 854/21, em sua primeira versão, as contratadas deveriam apresentar à ANP, até 30 de junho de 2023, garantias financeiras de descomissionamento conforme o valor publicado no sítio eletrônico da ANP. Contudo, com a publicação da Resolução ANP 925/2023, a data limite foi postergada para 02 de outubro de 2023.

2.- Material divulgado no "Workshop de Apresentação de Garantias da ANP", em 2023, indicou um custo total de descomissionamento no Brasil na ordem de R$ 224 bilhões naquele ano. Esse valor foi atualizado pela ANP em 2024 para R$ 288 bilhões. Esses valores são próximos de estudos realizados por consultoria privadas, como a Aurum Tank, que estimou, em 2024, investimentos em descomissionamento no Brasil da ordem de R$ 306 bilhões nos próximos 30 anos (https://aurumenergia.com.br/desmontagem-de-plataformas-pode-movimentar-r-306-bi/).

Figura 1 Valor das garantias financeiras de 2023 por bacia, em percentual

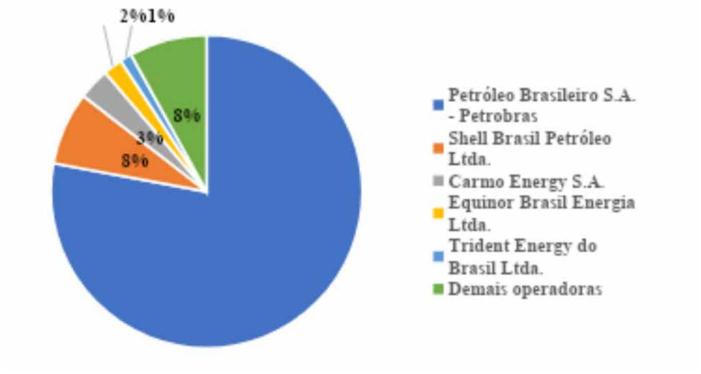


Fonte: Elaboração própria a partir de dados publicados no Painel Dinâmico de Garantias Financeiras de Descomissionamento - ANP (2023).

A representatividade da bacia do Campos no custo do descomissionamento brasileiro não chega a surpreender. Tal bacia teve produção iniciada em 1977, abrigando os primeiros grandes campos e poços produtores do offshore brasileiro, sendo ainda hoje a bacia com o maior número de campos em produção entre todas as bacias brasileiras. Contudo, a área tem apresentado uma queda progressiva de produção na última década, sendo que muitos dos campos dessa bacia estão sendo desmobilizados ou devolvidos. Assim, devido a proximidade do fim de contrato para muito desses campos, a ANP exige um valor proporcionalmente alto em garantia de descomissionamento para esses campos.

Por seu turno, em relação à responsabilidade de apresentar tais garantias, a Resolução ANP nº 854/21 determina que é obrigação da operadora do contrato apresentá-las, ainda que seja facultada às consorciadas apresentarem garantias individualmente. Por esse motivo, o Painel Dinâmico de Garantias Financeiras de Descomissionamento relaciona o valor a ser oferecido em garantias para determinado campo com a operadora do referido contrato de exploração e produção. Conforme a informação disponibilizada no painel, a Petrobras foi a operadora com o maior valor a ser apresentado, R$ 64,4 bilhões (cerca de 80% do valor total em 2023). Além dela, outras quatro operadoras apresentam valores igual ou superiores a um bilhão de reais: Shell, R$ 6,2 bilhões; Carmo Energy, R$ 2,7 bilhões; Equinor, R$ 1,6 bilhões; e Trident Energy, R$ 1,0 bilhão. Juntas as cinco empresas representaram 92% do valor a ser garantido em 2023, conforme apresentado na Figura 2.

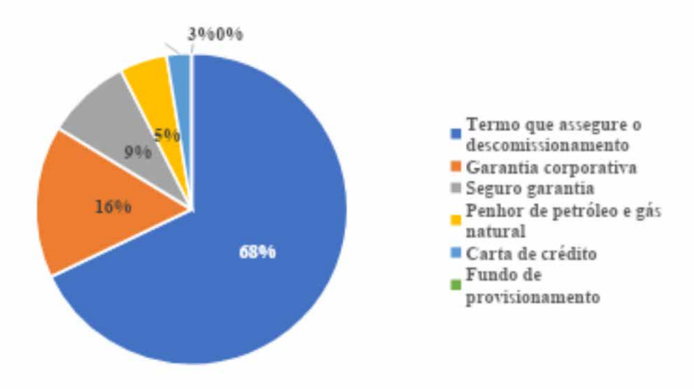
Figura 2 Valor das garantias financeiras de 2023 por operador, em percentual



Fonte: Elaboração própria a partir de dados publicados no Painel Dinâmico de Garantias Financeiras de Descomissionamento - ANP (2023).

Até o momento, ainda não foi publicado pela ANP nenhum relatório oficial que detalhe os valores recebidos pelas diferentes modalidades de garantia previstas na resolução. Contudo, Barbosa et al. (2024) apresentam a primeira análise dos resultados da regulação brasileira de garantias de descomissionamento. Conforme o diagnóstico elaborado pelos autores, em 2023, a modalidade termo que assegure o descomissionamento pela própria contratada correspondeu a 67,9% do montante recebido, tendo sido utilizada por duas empresas. A segunda modalidade com maior representação foi a garantia corporativa, correspondendo a 15,8% do valor recebido, tendo sido a modalidade escolhida por quatro empresas. Outra modalidade amplamente utilizada foi o seguro garantia, que foi a opção de 28 petrolíferas. As apólices de seguro garantia foram emitidas por nove seguradoras diferentes, totalizando 8,8% do valor assegurado. Também popular, as cartas de crédito foram a escolha de 23 empresas, que por meio de sete bancos garantiram 2,6% do total do ano. Completam o quadro, o penhor de petróleo e gás natural (4,9%) e o fundo de provisionamento (inferior a 0,1%), conforme demonstrado na Figura 3.

Figura 3 Distribuição das garantias de descomissionamento recebidas em 2023 por modalidade, em percentual



Fonte: Barbosa et al. (2024).

Tendo em vista que a Resolução ANP nº 854/21 determina que o valor das garantias financeiras deve ser atualizado anualmente, em abril de 2024, a ANP publicou o segundo Painel Dinâmico de Garantias Financeiras de Descomissionamento (ANP, 2024). Nesse segundo ano de regulação, houve um acréscimo do valor a ser assegurado, que passou a ser de R$ 92,6 bilhões, uma elevação de 12% em relação ao ano anterior. Por sua vez, esse valor passou a corresponder a apenas 32% do custo total do descomissionamento brasileiro, estimado em R$ 288 bilhões em 2024. A bacia de Campos permaneceu correspondendo a cerca de 60% do valor a ser garantido, bem como a Petrobras se manteve como a operadora responsável por apresentar cerca de 80% do valor das garantias.

Tabela 1 – Comparativo entre os valores de garantias de descomissionamento dos anos 2023 e 2024

Descrição	Ano		Variação percentual
	2023	2024	
Custo estimado do descomissionamento no Brasil	R$ 224 bi	R$ 288 bi	29%
Valor a ser apresentado em garantias financeiras	R$ 82,7 bi	R$ 92,6 bi	12%
Percentual do custo de descomissionamento assegurado por garantias financeiras	37%	32%	-14%
Participação da bacia de Campos no valor a ser garantido	57%	56%	-2%
Participação da Petrobras no valor a ser garantido	78%	80%	3%

Fonte: elaboração própria a partir de dados publicados no Painel Dinâmico de Garantias Financeiras de Descomissionamento - ANP (2023) e ANP (2024).

Válido mencionar, contudo, que dos 401 campos listados no Painel Dinâmico de Garantias Financeiras de Descomissionamento de 2024, 158 campos (39%) apresentam valores de aporte de garantia de descomissionamento inferiores em 2024 quando comparados com o ano de 2023, totalizando uma redução de R$ 9,2 bilhões. A constatação da redução do valor a ser garantido em 2024 para alguns campos, em um primeiro momento, levanta questionamentos quanto à adequação da metodologia de cálculo do valor a ser garantido anualmente definido na Resolução ANP nº 854/21. O método, chamado Modelo de Aporte Progressivo (MAP), prevê o aumento gradual do valor garantido a cada ano, visando alcançar 100% do custo total do descomissionamento ao final do contrato de exploração. Entretanto, no caso de elevações no valor das reservas provadas e prováveis (2P), de extensões de prazo do contrato, ou mesmo de reduções do custo estimado das atividades de descomissionamento, o valor a ser garantido pode diminuir, ao invés de aumentar, de um ano para o outro.

5. DISCUSSÃO SOBRE APRIMORAMENTOS DO ARCABOUÇO REGULATÓRIO BRASILEIRO VIGENTE EM 2024

Conforme mencionado nas seções anteriores, grande parte dos países produtores de petróleo são signatários de tratados e convenções internacionais que os obrigam a não causar poluição oceânica. Sendo assim, tais países são passíveis de responsabilização no caso do descumprimento dessa obrigação (Braga & Pinto, 2022). Nesse contexto, diversos países, a exemplo dos Estados Unidos e do Reino Unido, estabeleceram normas nacionais para mitigar o risco de as empresas falharem em cumprir com suas obrigações de fim de vida contratual, deixando para os governos locais (e em última instância seus cidadãos) a conta das atividades de descomissionamento (Department for Business, Energy & Industrial Strategy, 2018; Bureau of Ocean Energy Management, 2024).

Fica claro, portanto, que o cidadão é o destinatário final das políticas de garantias de descomissionamento. Entretanto, no caso brasileiro, embora a ANP tenha publicado a Resolução ANP nº 854/21 e dado um passo a mais ao disponibilizar no Painel Dinâmico de Garantias de Descomissionamento informações básicas sobre as garantias, percebe-se que informações importantes não estão sendo compartilhadas com a sociedade. Dentre tais informações, cabe destacar o custo total de descomissionamento de cada campo, o que corresponde exatamente ao risco financeiro suportado pela população em cada projeto no caso do inadimplemento do operador em relação às suas obrigações contratuais. Portanto, aumentando a transparência em relação aos dados do setor de petróleo, a ANP possibilitará que os cidadãos participem ativamente dos fóruns de discussão sobre a política de descomissionamento, evitando que essas arenas de debate sejam monopolizadas pelas empresas petrolíferas e suas entidades representativas.

Ainda no campo da transparência, ficou constatado que o Painel Dinâmico de Garantias de Descomissionamento apresenta a informação das obrigações de garantia conectada apenas aos operadores dos contratos. Contudo, considerando que a própria Resolução ANP nº 854/21 determina que em caso de consórcios todas as contratadas serão solidariamente responsáveis pela solvabilidade das garantias financeiras, é fundamental que a sociedade tenha acesso ao montante de garantias financeiras a ser ofertado por cada consorciada, não apenas pelo operador. Essa informação poderia ser útil, por exemplo, para fomentar estudos acadêmicos sobre a definição do risco financeiro máximo tolerável para cada perfil de petrolífera, bem como para a elaboração de indicadores de qualidade financeira que poderiam ser utilizados nos processos de aquisição de campos maduros, ou mesmo pelas instituições financeiras na hora da contratação das garantias.

Por sua vez, cabe reflexão mais profunda sobre a real efetividade da própria política de garantias financeira quando verificado que cerca de 90% do valor recebido pela ANP corresponde a garantias em que a própria indústria do petróleo assegura os recursos financeiros para o cumprimento das obrigações de descomissionamento. Malone e Winslow (2018), ao analisarem as recentes falências no setor de mineração dos Estados Unidos, verificam que as garantias fornecidas pelas próprias empresas (autogarantias) não funciona mais como um mecanismo eficaz de garantia financeira, devendo os governos exigirem garantia financeira mais rigorosas. No setor petrolífero, como já mencionado, verificamos os mesmos riscos de falência de empresas, visto que a crescente exigência de descarbonização da economia ameaça o futuro da indústria do petróleo, podendo limitar a capacidade de as petrolíferas concretizarem os lucros planejados para os atuais projetos de produção.

Assim, é altamente recomendado o compartilhamento dos riscos inerentes à atividade petrolífera com outros setores da economia, principalmente o setor financeiro. Nesse sentido, Parente et al. (2006) defende que a constituição de fundos de provisionamento dedicados, que acompanhem o projeto offshore ao longo de sua vida útil, seria a opção mais adequada para diminuir os riscos da produção em campos de economicidade marginal, permitindo que as atividades de descomissionamento deixem de ser encaradas apenas como o “fim de vida” de um ativo energético, mas também como uma parte fundamental da economia circular e do desenvolvimento sustentável.

No que se refere à redução do valor do aporte de alguns campos em 2024 quando comparado com o ano de 2023, percebe-se que o contratado detém uma grande discricionariedade na definição as atividades de descomissionamento que efetivamente serão executadas ao fim do contrato. Tal discricionariedade permite que as petrolíferas adotem metodologias diferentes de abandono, o que inevitavelmente acarreta diferentes custos a serem contabilizados (Barbosa et al., 2022). Nesse sentido, cabe ao regulador aprimorar as resoluções que determinam quais instalações deverão ser removidas, bem como definir claramente o método de descomissionamento a ser empregado na elaboração das estimativas de custo de descomissionamento.

Ainda no tocante aos custos, a falta de experiência dos operadores na execução de atividades de descomissionamento tem tornado as estimativas de custos extremamente voláteis. Campos operados por empresas de porte similar, em profundidades de lâmina d'água equivalentes e com produções semelhantes podem apresentar estimativas de custos diferentes devido ao nível de risco que cada empresa está disposta a assumir, especialmente em relação aos riscos de lesões ao pessoal designado para a remoção das instalações ou estruturas. Além disso, ainda há uma carência de estudos para determinar se as novas petrolíferas, que começaram a atuar na indústria após o processo de desinvestimento da Petrobras, realmente apresentam custos inferiores de descomissionamento ou se, na verdade, tais estimativas estão subdimensionadas.

Por fim, pode-se afirmar que há baixos incentivos para que as empresas apresentem os custos de descomissionamento de forma acurada. Devido à forma que o Modelo de Aporte Progressivo foi estabelecido, quanto maior o custo estimado, maior será o valor da garantia a ser apresentada anualmente. Por consequência, maiores serão os gastos das petrolíferas com a aquisição de instrumentos de garantia financeira. Portanto, em um típico dilema do principal-agente, em condições de informação assimétrica e incompleta, as contratadas têm o incentivo de apresentar custos estimados na extremidade inferior do espectro de possibilidades, objetivando reduzir seus custos operacionais (Mackie & Velenturf, 2021). Para mitigar essa questão, a ANP deve robustecer seu corpo técnico, permitindo a criação de bases de conhecimento independentes da confiabilidade das informações prestadas pelo contratado.

6. CONSIDERAÇÕES FINAIS

Conforme visto, a crescente urgência da ação climática em linha com o Acordo de Paris, juntamente com a adoção de fontes de energia renováveis e tecnologias energeticamente eficientes podem afetar significativamente o futuro da indústria do petróleo. Nesse contexto, devido a existência de tratados que restringem a poluição oceânica, governos ao redor do mundo têm sido compelidos a atualizar seus regulamentos sobre o descomissionamento de plataformas offshore para garantir que os custos dessa atividade sejam internalizados pela indústria petrolífera e, indiretamente, pelos consumidores de combustíveis fósseis, não sendo socializados com a população geral de forma indiscriminada.

Por sua vez, o governo do Brasil, país com um dos maiores investimentos projetados em descomissionamento para as próximas décadas, não se eximiu de sua responsabilidade social, e tornou mais rígidas e claras as obrigações relacionadas às garantias do descomissionamento por meio da publicação da Resolução ANP nº 854/21. Contudo, após completado o primeiro ciclo de apresentação de garantias, foi possível analisar os principais aspectos em que o arcabouço regulatório brasileiro vigente poderia evoluir para garantir que as petrolíferas assegurem os recursos para descomissionar as infraestruturas de produção de petróleo a contento.

Dentre as principais conclusões da análise, destacou-se a necessidade de a ANP aperfeiçoar a transparência das informações prestadas à sociedade sobre as atividades da indústria do petróleo atuante no país. A divulgação de informações, tais como o valor estimado do descomissionamento e a participação de cada petrolífera nos contratos de produção, permitirá que os cidadãos, como parte interessada nas políticas públicas do setor, tenham o conhecimento necessário que os habilite a participar, como stakeholders, dos fóruns de discussão sobre as evoluções nas regulações sobre descomissionamento.

Verificou-se, também, a necessidade de aumentar o envolvimento do setor financeiro no provimento de recursos para assegurar o suporte econômico das atividades de descomissionamento, como forma de reduzir o risco de as petrolíferas falharem em cumprir com suas obrigações contratuais em um cenário de rápida substituição da produção petrolífera por fontes renováveis de energia. Além disso, foi constatado ser imprescindível reduzir a discricionariedade dos contratados em relação à definição do custo do descomissionamento, por meio do estabelecimento de uma metodologia padrão e do enriquecimento das bases de dados da ANP.

Em síntese, os formuladores de políticas públicas no setor de petróleo e gás natural devem ser estimulados a ajustar os regulamentos vigentes para responder ao complexo cenário dos combustíveis fósseis, antecipando-se para proteger os cidadãos dos custos do descomissionamento das infraestruturas de produção offshore. Nesse sentido, a implementação das melhorias regulatórias propostas neste artigo contribuirá para que países como o Brasil avancem em direção a uma transição energética mais justa, na qual os custos da transição sejam adequadamente suportados pelos seus respectivos responsáveis.

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Industrial development for the energy transition in latin america: Lessons learned from wind energy for green hydrogen in Argentina

Desarrollo industrial para la transición energética en américa latina: lecciones aprendidas de la energía eólica al hidrógeno verde en Argentina

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Resumen

La transición energética se ha consolidado como una tendencia global, exigiendo una profunda transformación de la matriz energética a través de la eliminación progresiva de los combustibles fósiles y la incorporación de diversas tecnologías para la generación de energía a partir de fuentes renovables. Este trabajo analiza los procesos de aprendizaje tecnológico e innovación observados durante el surgimiento y la consolidación de la industria eólica en Argentina, con el objetivo de desarrollar hipótesis sobre la interacción entre la demanda y el ciclo tecnológico en el impulso de la innovación en tecnologías de energías renovables, como la industria del hidrógeno verde, en países periféricos. A partir de una metodología de estudio de caso, nuestro análisis sugiere que las empresas basadas en la explotación de recursos naturales podrían no ser tan cruciales en el proceso de aprendizaje tecnológico, especialmente durante la fase inicial del ciclo. En cambio, los proveedores intensivos en conocimiento desempeñan un papel más relevante en el proceso de innovación que rodea la transformación de los recursos naturales vinculados a la energía. No obstante, persisten interrogantes sobre la especificidad de los recursos naturales energéticos y su potencial para generar oportunidades para el desarrollo de redes de conocimiento locales.

PALABRAS CLAVE: Energía eólica, hidrógeno verde, ciclo tecnológico, innovación, desarrollo industrial

Abstract

The energy transition has emerged as a global trend, requiring a profound transformation of the energy matrix by gradually eliminating fossil fuels and incorporating diverse technologies for power generation from renewable sources. This paper delves into the technological learning and innovation processes observed during Argentina's wind industry emergence and consolidation to develop hypotheses about the interplay between demand and the technological cycle in driving innovation around renewable energy technologies, for example the green hydrogen industry, in peripheral countries. Based on a case study methodology, our analysis suggests that natural resource-based firms may not be as critical in the technological learning process, particularly during the emergence phase of the cycle. Instead, knowledge-intensive suppliers play a more significant role in the innovation process surrounding the transformation of energy-related natural resources. However, questions remain regarding the specificity of energy-related natural resources and their potential to create opportunities for the emergence of local knowledge networks.

KEYWORDS: Wind energy, green hydrogen, Technological cycle, innovation, industrial development.

1. INTRODUCTION

For some decades now, the energy transition has emerged as a global trend that demands an active strategy from States to transform the challenges of this process into opportunities for industrial development in emerging countries. This trend requires a profound transformation of the energy matrix, which implies the gradual elimination of fossil fuels (United Nations, 2023) and the incorporation of diverse technologies for energy generation from renewable sources. These technologies are in different stages of development and, even though their adoption and diffusion may enhance the comparative advantages of the energy sector, their impact on the technological dynamism of its associated industries is unclear. For example, wind energy has a high penetration rate in South American energy markets (IRENA, 2023a) and its diffusion, within an appropriate institutional and economic framework, has facilitated the installation of factories for blade production in Brazil and tower production in Argentina. At the same time, green hydrogen is in a phase of feedback between technological development and demonstration on a global scale. Still, countries in the region continue to outline their institutional frameworks without achieving significant technological advances, except in Chile where the country's first hydrogen fuel cell vehicle was homologated (OLADE, 2023).

In the last decade, within the framework of neo-Schumpeterian and Evolutionary theories, various academic studies have suggested that the processes of learning and innovation around industries based on the exploitation of natural resources, such as those dedicated to the generation of renewable energy (RE), are relevant for economic development. These works highlight the role that natural resource-based industries have in the technological dynamism of the network of actors that supplies them with equipment, services, and knowledge and their economic and technological relevance in South American economies. However, they also point out that there are conditions that enable these processes, which are expressed in the demand configuration, the industrial organization, the technology cycle, and the institutional context (Andersen, Marín, & Simensen, 2018; Crespi, Katz, & Olivari, 2018; Katz & Pietrobelli, 2018). This work focuses on how the demand configuration and the technology cycle of the wind energy industry, in general, may have influenced the learning and innovation processes of this industry in Argentina over the past two decades. By distilling lessons from this context, we gain insights into the current opportunities and challenges for the emerging green hydrogen sector in leveraging economic development.

2. DEMAND AND TECHNOLOGICAL LIFE CYCLES: EVIDENCE FROM WIND ENERGY FOR GREEN HYDROGEN

Over the past two decades, the renewable energy industry has witnessed two significant trends: i) a scale expansion in response to countries' efforts to achieve energy security and more sustainable economic growth, and ii) increased internationalization resulting from the export of energy technologies (Kim & Kim, 2015). A prime example of these trends is China's entry into the global renewable energy market through manufacturing equipment for wind power and solar photo voltaic energy (Gandenberger & Strauch, 2018; Kim & Kim, 2015). The promotion of national wind power demand and its role as a catalyst for competitive technology development, primarily in terms of price rather than quality, explains China's active participation in the global energy market (Lin & Chen, 2019; Gandenberger & Strauch, 2018).

However, the empirical evidence regarding the impact of demand–pull policies on the development of energy technologies remains inconclusive (see review by Lin and Chen (2019)). This ambiguity may be attributed to the varying degrees of maturity reached by different energy technologies. In their comparative study of wind power and solar photovoltaic, Kim and Kim (2015) found evidence supporting a positive bidirectional relationship between domestic R&D investment and technology export. Notably, these results were more pronounced in wind power compared to solar photovoltaic, with the latter being considered a more mature technology.

These findings about the role of demand concerning the maturity of technologies have led to the Technological Life Cycle (TLC) concept to comprehend the long-term patterns of innovation and diffusion processes within the energy matrix. According to the TLC model proposed by Anderson and Tushman (1990), the cycle begins with a disruptive discovery that opens new opportunities and technological trajectories. This is followed by a fermentation stage, where technologies compete within a highly uncertain environment. Then, the third stage sees the emergence of a dominant technological design. Finally, the fourth stage involves incremental change, where the technology gradually evolves until a new technological discontinuity disrupts the trajectory and restarts the cycle. Utterback and Abernathy (1975) present a stylized representation of the TLC akin to an inverted U, which combines considerations about the type of innovation -product or process- that predominates at each stage of the cycle. Davies (1997) later differentiates technological patterns based on whether they pertain to mass-produced goods or complex products and systems.

From the perspective of the TLC, wind power is in a phase of incremental change (Huenteler, Schmidt, Ossenbrink, & Hoffmann, 2016; Kalthaus, 2020; Madvar, Ahmadi, Shirmohammadi, & Aslani, 2019), suppliers of wind energy equipment have enhanced the quality of their products (Huenteler et al., 2016) and there has been a steady decrease in wind energy prices. Drawing on the contributions of Davies (1997), the complexity of energy technologies, and thus the associated pattern of technological evolution, is determined by two key factors: i) the complexity of the product's architecture, and ii) the scale of the production process. Huenteler et al. (2016) concluded that wind power is characterized by its complexity and by incremental changes that combine product and process innovations, with the latter predominating. It's important to highlight that the trajectory of wind power technology involves a diverse range of contributors and knowledge sources. As per the findings of Kalthaus (2020) in Germany, non-specialized and unrelated knowledge played a significant role during the fermentation phase of wind power. This can be attributed to the involvement of technicians and engineers who aimed to enhance environmental conditions and offer technical alternatives to traditional energy. In subsequent phases, the amalgamation of new, specialized knowledge, as well as related knowledge gained prominence. This suggests an impending discontinuity associated with offshore wind power, marked by the participation of shipping firms in technological development. The presence of local industries engaged in turbine manufacturing, competitive on a global scale, is a positive factor for the national wind energy sector expansion and knowledge generation in this field (Zhang, Tang, Su, & Huang, 2020). This underlines the importance of a diverse knowledge base and cross-industry collaboration in advancing renewable energy technologies.

Ampah et al. (2023) demonstrate that water-based technologies for producing green hydrogen are experiencing varied stages of evolution: photolysis is in an emerging phase, thermolysis is in a growth stage, and meanwhile, electrolysis has reached maturity. Over the past five years, significant advancements have been made in areas such as cell design, electrodes, electrolytes, electrolytics, processes, and control methods. It's worth noting that while hydrogen generation through electrolyzers is a technology utilized in industrial processes, it has not yet been widely adopted for power generation due to the need for cost reduction. Consequently, the critical points in research and development in this field include the use of renewable energies (wind and solar) as a source of electrolysis, increasing efficiency, and reducing consumption and energy costs, among others. Dehghanimadvar, Shirmohammadi, Sadeghzadeh, Aslani, and Ghasempour (2020) apply the Gartner Hype Cycle model to abroad range of renewable and non-renewable technologies to explain their stage of development. They affirm these technologies are at different phases, primarily concentrated between the disillusionment stages (photo fermentation and dark fermentation), the slope of enlightenment phase (photo electrochemical, thermochemical water decomposition, and PV electrolysis), and the final productivity stage (electrolysis, fossil fuel reforming, and coal gasification). Interestingly, none of these technologies are found in the first two stages of the Gartner Hype Cycle, which are the innovation trigger and peak of inflated expectations.

Technological development in lagging economies exhibits unique characteristics derived from the local industrial trajectory, the influence of Foreign Direct Investment, the role of Global Value Chains, and restrictions arising from compliance with international regulations and standards (Crespi et al., 2018; Katz & Pietrobelli, 2018). A comparative study between Brazil and China reveals the differential strategies pursued and their impact on knowledge generation in the wind energy field. While both countries have capitalized on the influx of foreign technology, China has oriented its strategy towards learning and developing national technology, resulting in patents and national brand turbines. In contrast, Brazil still relies on Foreign Direct Investment (Gandenberger & Strauch, 2018). In Argentina, the lack of coordination between energy policies and science and technology policies, coupled with their lack of continuity, has posed a limitation to technological development in the field of wind energy (Aggio, Verre, & Gatto, 2018; Stubrin & Cretini, 2023).

3. METHODOLOGY

This study adopts a case study approach to analyze the technological learning trajectory of the domestic wind turbine industry in Argentina. The analysis centers on two domestic firms that demonstrated the capacity to develop and, to a certain extent, commercialized their wind turbine designs. While this case study does not encompass a comprehensive historical perspective, it delves into the institutional trajectory, strategies, and technological capabilities that these two key local industry players built over the years. In addition, the research explores the economic, technological, and political landscapes that underpin the emergence of a green hydrogen industry, both on a global and national scale.

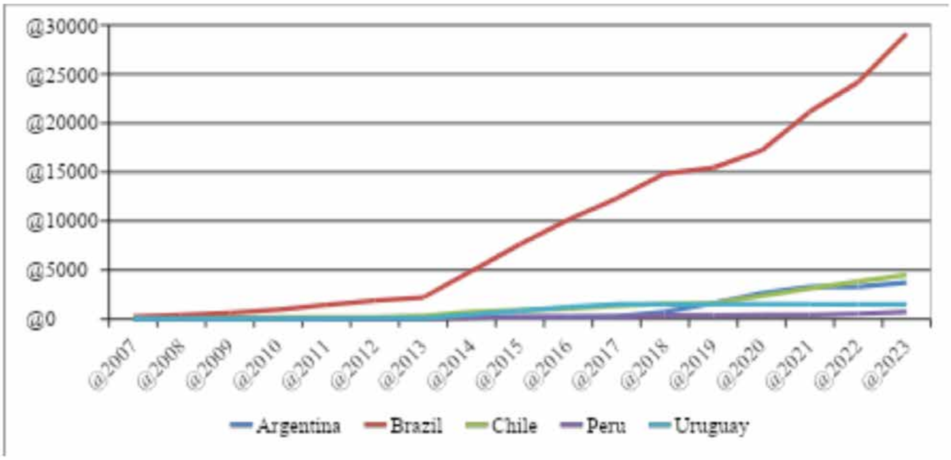
These industries were chosen due to their relevance to the energy transition agenda in South American countries and their distinct technological, market, institutional, and organizational characteristics up to the present day (Castelao Caruana et al., 2023). The analysis is based on the information collected from multiple secondary sources and semi-structured interviews with representatives from both industries.

4. WIND ENERGY TRAJECTORY

The wind energy industry emerged in the 1970s in countries like Denmark, Germany, and the United States. But it was in the late 1990s when the technology design consolidated and competition among firms began to be focused on the internationalization of technology to emerging countries (Gipe & Möllerström, 2023; Verbong, Geels, & Raven, 2008). Until then, vertical integration in wind turbine manufacturing had predominated, resulting from the organic expansion of the incumbent companies and its concentration through mergers and acquisitions (Jacobsson & Johnson, 2000). But around mid-2000, the internationalization process changed the business model giving way to the emergence of suppliers –mostly not knowledge-intensive– located in the same countries where wind farms were installed, while bigger firms continued to specialize in wind turbine design and manufacturing. So, by the decade of 2000, wind energy technology was mature, even though, as it was mentioned previously, its innovative process has remained focused on improving the product throughout its life cycle, shifting from the core sub-system to the broader range of subsystems and components that comprise wind energy (Huenteler et al., 2016). During those years, the demand for wind energy in the countries of the Southern Cone was divergent, especially in Brazil (Figure 1). Some countries, such as Argentina, Chile, Peru, and Uruguay, managed to increase their installed capacity, reaching values between 700-4,500 MW, while the rest of the countries hover around 50-60 MW, on average. The rapid increase of the wind energy installed capacity in Brazil can be attributed to the execution of national public programs specifically designed for RE, such as the PROINFA that in 2002 offered feed-in tariff schemes through 20-year contracts for wind farms, biomass, and small hydroelectric plants (Eirin, Messina, Contreras Lisperguer, & Salgado, 2022).

In Argentina, the national government implemented a program to promote electricity generation from RE sources in the late ´90 that promoted the installation of some wind farms with European technology. However, the benefits of this program were diluted with the exit from the fixed exchange rate regime called convertibility that the country went through in 2001. It was not until 2009 that the national government again promoted the installation of this type of technology with the GENREN program under the orbit of ENARSA.[1] This program tendered contracts for the electricity supply from RE sources, incorporating incentives for wind farms to develop with equipment and components produced locally. However, it had a partial impact. Even though it tendered contracts for 500 MW and obtained offers for 1,000 MW (approving 754 MW), by the beginning of 2018 only two wind farms with 130 MW had been completed, and 10 wind farms with 445 MW had started and interrupted their works. This was due to an unstable macroeconomic context that strongly conditioned access to international financing. In this context, two national wind turbine manufacturers emerged –IMPSA and NRG Patagonia – which drove the development of local suppliers.

Figure 1. Electricity Installed Capacity from Wind Energy (MW) by Country (2007-2023)



Source: own elaboration with data from IRENA (2024)

Some years later, within the framework of national Law 27.191/2016, the RenovAr program and the Renewable Energy Term Market (MATER) once again promoted the growth of wind energy demand in the country. The former was a national tender program for electricity supply contracts from ER sources that provided tax benefits associated with the incorporation of national components established by Law 27.191. The latter, also regulated by this law, is a market for electricity supply contracts from renewable sources between large users (with consumption greater than or equal to 300 KW) and generators of this type of energy participating in the Wholesale Electric Market (MEM). However, this institutional framework did not prioritize the development of domestic technology and associated local linkages (Aggio et al., 2018; Cappa, 2023), but the growth of the renewable energy sector in a complex macroeconomic context marked by energy scarcity.

1.- Energía Argentina S.A. (ENARSA) is a company owned by the national government, established in 2004 to exploit and commercialize hydrocarbons, natural gas, and electric energy.

4.1. IMPSA

At the beginning of the 2000, IMPSA (Industrias Metalúrgicas Pescarmona S.A) was a transnational company with Argentine capital[2], dedicated to developing complex hydroelectric energy projects and designing and manufacturing capital goods for these and other industries. Its advanced technological capabilities and the expansion of its production capacities beyond Latin America enabled IMPSA to access global and distant markets such as Asia, Europe and North America (Papa & Hobday, 2015). In 2003/4, with a strong commitment to innovation, IMPSA began a technological learning process for the design and manufacture of wind turbines based on its knowledge and experience in fluid mechanics and synchronous generators from the design and manufacture of hydroelectric power plants, handling of high structures and frequency conversion derived from the design and manufacture of port cranes and control systems. By 2005, when the average power of wind turbines globally was around 1.0–1.3 MW and the most consolidated European companies began to internationalize, IMPSA developed a 1.0 MW wind turbine that was tested in a wind farm in Argentine Patagonia. Although this machine did not reach a year of life due to problems in the control system, this milestone inaugurated the IMPSA Wind business unit, marking the firm's foray into the wind energy industry. However, Brazil's growing economy and dynamism of the wind market by mid-2000, compared to Argentina's economic decline and wind market halt, convinced IMPSA to shift their main wind operations and assets towards Brazil (Papa & Hobday, 2015). Given that the market was taking off in this country and that mature technologies already existed internationally, the company chose to accelerate the technological learning process by acquiring the license from Vensys, a German firm to manufacture a direct transmission wind turbine of 1.5 MW. By 2007/8 the company inaugurated its subsidiary named Wind Power and a production facility to produce wind turbines and generators in this country. Motivated by local regulations that established 60% national content, IMPSA promoted the development of local and regional suppliers that allowed the diversification of the supply chain, and the growth of the industry associated with the sector in Brazil. By 2014, IMPSA was the third producer of wind energy in this country. It was building wind farms for 480 MW and it had a contract for the manufacture, installation, and operation and maintenance of 287 generators for 574 MW for 2018. In Argentina, IMPSA developed the first wind turbine with its own technology in Latin America, called UNIPOWER® IWP-70 of 1.5 MW, which obtained international certification in 2010. This wind turbine and the subsequent ones -IWP83 and IWP-100- were manufactured in the IMPSA Argentina facilities, reaching a local content of 72 % in the IWP100 model of 2 MW. In parallel, IMPSA obtained contracts with public companies for the provision of wind turbines within the framework of the GENREN program between 2009 and 2011[3].

As in Brazil, the development of this equipment encouraged the creation of a solid network of local suppliers for the sector that included the production of towers and components of the turbines, the repair of wind blades and nacelles, the construction and protection of foundations and towers, and the manufacture of electronic controls. However, this demand was unstable over time and uncoordinated from industrial and scientific

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[2] .- Founded in Argentina in 1907, IMPSA achieved a significant international presence, operating in 40 countries and maintaining a workforce of 3,500 employees. Subsequently, by 2021, this figure had decreased to 720, and the company is currently undergoing a process of corporate restructuring.

[3] .- Within the framework of this program, two 1.5 MW wind turbines were installed in El Tordillo wind farm, one designed, built, and installed by NRG Patagonia and the other by IMPSA Wind. Both were put into operation in 2009/10, but the park began operating in the MEM in 2013. Its owner was Vientos de la Patagonia I, comprised of ENARSA and the Province of Chubut. IMPSA Wind also signed two contracts with Arauco 1 Wind Farm, owned by the state energy company La Rioja SAPEM (75%) and ENARSA, to manufacture, operate, and maintain 15 IWP-83 wind turbines of 2.1 MW and 11 wind turbines of 2 MW each. This wind farm was inaugurated in 2011. In addition, in 2015 IMPSA Wind installed 4 wind turbines of 2 MW each in El Jume wind farm, owned by the public company Energía Santiago del Estero S.A. (IMPSA, 2024; (Aggio et al., 2018).

policy (Aggio et al., 2018). Despite the various improved models that the company developed to stay at the fore front of the international industry, by 2015 the power of its IWP-100 model was lagging the offer of large international companies, which, along with other barriers, made it difficult to enter the RENOVAR (Table 1). By the end of 2016, 40% of the installed power came from turbines manufactured by companies from Denmark and 23% from France, only 27% from Argentina (Aggio et al., 2018).

Due to various financial events in Argentina, Brazil, and Venezuela, IMPSA had to restructure its capital at the beginning of 2018. Currently, IMPSA is a company dedicated to the EPC of wind farms and SFV, including the production of hydrogen, the repair of large wind equipment, and the provision of operation and maintenance services, including the application of AI for preventive maintenance.

4.2. NRG Patagonia

NRG Patagonia was created in 2006 in Argentina by domestic companies in the oil and gas industry that detected the window of opportunity posed by the absence of wind turbines adapted to the winds of Patagonia at an international level. The first Wind Farms installed in this region in the 90s showed the lack of specific information about the regional wind resources (different from the predominant in Europe) and of technology adapted to its characteristics. The company then acquired the design of a Class II turbine in Germany with software from Denmark and hired German engineering to adapt it to the requirements of the winds of Patagonia (Class I), seeking that most of the parts were manufactured in Argentina. In this way, it developed internal productive capacities to manufacture, assemble, mount, and operate Class I turbines of 1.5 MW, while the rest of the components were acquired from suppliers, many of them local. One bought the license for the electric generator abroad to be able to manufacture it in the country.

As happened with IMPSA, this technology was initially installed in El Tordillo Wind Farm in 2019/10 owned by a public company to integrate a park of 3 MW, located in Comodoro Rivadavia, Province of Chubut. However, the initiative was discontinued and given the fall in projected demand and the difficulty in accessing local public and private financing, the scaling of the prototype wind turbine for Class I winds was discontinued. However, by 2014, the company embarked on the development of a Class II team in consortium with the National University of Patagonia San Juan Bosco and with economic support from Ministry of Science and Technology for about 6 million USD. The development involved the internal capacities of the firm's engineers and external specialists from Europe. Although initially this turbine was thought of as a suitable technology to generate energy with the wind resource available in other parts of the country, given the increase in the power of foreign turbines, it became a suitable team (from 1 to 2 MW) for low-scale users – electric cooperatives, municipalities and/or small and medium-sized enterprises- located in regions with not so extreme winds[4]. This segment is a niche with potential from the creation of MATER and Law 27.424/2017 of distributed generation of low interest for large multinational companies. Currently, these wind turbines have around 50% of national components from 12 local companies. In addition to this strategy, the company created ENAT in 2016, a spin-off that capitalizes on the techno-productive knowledge and market acquired in the wind market by the firm to provide knowledge services such as detection of sites with energy resources of interest, design of wind farms or pre-feasibility analysis of connection to the electrical system.

4.- In 2021, NRG Patagonia installed a 1.5 MW Wind turbine for self-consumption by the Castelli Cooperative in Buenos Aires Province.

The analysis of this sector shows several issues. First, the specificity of the NR -winds with greater load capacity and turbulence in the Patagonia region– represented an opportunity that only some companies with a trajectory in the energy sector could identify at the beginning of the ´2000 given the low level of specialized knowledge that existed in the country about this industry. Even so, the specificity of this NR did not represent a barrier to entry for foreign companies because it is an NR with similar characteristics in other parts of the world and also in those years the global wind industry was already mature and relatively concentrated – although more dispersed than at present - and under a dynamic of innovation focused on the continuous improvement of the subsystems and components that make up wind energy, which quickly closed this window of opportunity. However, in less than a decade, the national companies analyzed managed to develop the necessary technological capacities to take advantage of this opportunity through a learning process based on internal mechanisms (existing capacities) and external (license purchase) in the case of IMPSA and merely external in the case of NRG (hiring of engineering for the adaptation of an existing design to local requirements), at least in the first stage. This learning process was supported by a timid internal demand, essentially driven by public companies, but also, in the case of IMPSA, by an external, regional, and dynamic demand.

5. GREEN HYDROGEN, AN EMERGING INDUSTRY

Green hydrogen has aroused great expectations at the global level due to its potential as an energy vector for renewable energy sources, like wind and solar photovoltaic energy. Its development could complement other sources of energy and promote the decarbonization of energy-intensive industries (steel, chemicals, cement, and transport) as well as other sectors that use hydrogen in their production processes (petrochemicals, food, and electronics) (Zabaloy, Guzowski, & Didriksen, 2021). In addition, hydrogen and its derivatives have a comparative advantage in specific applications required by sectors that need to stabilize the networks supplied by a large proportion of intermittent sources, such as solar photo voltaic and wind power (IRENA, 2023b).

Green hydrogen is produced by the electrolysis of water, which requires both the availability of fresh water and a renewable energy source. In Latin America, there is a convergence of both natural resources in their potential to produce it, as auctions in Chile, Mexico, and Brazil offer the lowest prices for wind power and solar photovoltaic energy in the world, and water scarcity is not a constraint for most countries in the region. So, the development of green hydrogen in Latin America could be an advantage for potential consumers further away from the region, such as China, the European Union or the USA, as they could compensate for the distance with cheap renewable energy and less risk of geopolitical conflict than those from closer, but more politically unstable regions.

The challenge for Latin American countries is to define how to develop the energy transition for which they have the natural resources but not the capital or the technology, considering that hydrogen production is complex and requires long-term investments that allow innovation in the construction of production plants, storage, and transportation, as well as in the electrolysers production.

Electrolysis seems to be a highly modular technology with a steep learning curve. Electrolysis could be today what solar photovoltaic energy was 0 to 15 years ago, on the verge of moving from niche to mainstream technology. While this nascent sector is still developing, electrolysers made in China are 75% cheaper than those made in the West, according to Bloomberg New

Energy Finance. This is a gap that Latin American countries should close if they are to develop a competitive hydrogen ecosystem, as they have an important endowment of natural resources for low-emission hydrogen production but are still far from the technological frontier of electrolyser production.

In Argentina, the search for insertion in this ecosystem led to the emergence of some projects promoted by public and private companies (Hychico, Y-TEC), and others by foreign companies and organizations, with varying degrees of progress. Hychico has a pilot plant in Chubut that produces 120 m3 of green hydrogen per day using wind energy, currently destined for the domestic market. The project, launched in 2008, is a spin-off of the CAPEX Company with a track record in the conventional energy sector and is an example of synergy between fossil and renewable energies: two wind farms and two electrolysers at the foot of a conventional field. At the same time, Y-TEC –a technology company of YPF and Consejo Nacional de Investigaciones Científicas y Técnicas- launched a consortium for the development of the hydrogen economy in Argentina in 2020, called H2Ar, to create a collaborative workspace between local companies interested in integrating the blue or green hydrogen value chain (YPF, 2022). On the other hand, foreign entities -such as the Australian company Fortescue Future, the Fraunhofer Institute of Germany, and the MMEX Resources Corporation of the U.S.A.- have evidenced a deep interest in promoting green hydrogen production in Argentina. These external actors have focused on studying the available natural resources and their environment – wind and water sources and topography - to assess the technical and economic feasibility of installing green hydrogen production plants powered by wind energy, proposing the emergence of hydrogen hubs in the provinces of Buenos Aires, Río Negro, and Tierra del Fuego.

Despite all these actions, there are few technical and environmental studies to assess the impact of green hydrogen production and poor standards to regulate the activity. In recent years, the international context has promoted the interest of the State, both at the national and provincial levels, but there is still no broad consensus on the benefits this sector could bring to the country, on the role of government in promoting it, and on the role of hydrogen as part of industrial policy (Castelao Caruana, et al. 2023).

The first Hydrogen Promotion Act (Law 26.123) was introduced in 2006 to promote research and development of technologies to produce hydrogen from renewable and non-renewable sources (Guzowski, Zabaloy, & Ibañez Martín, 2022), expiring at the end of 2021 due to a lack of regulation. In 2023, the national government submitted a new draft law on the promotion of hydrogen production, which was strongly criticized because of the 35% national content requirement for each project (including electrolysers and power generation equipment), the duration of the promotion scheme, the requirement to contribute a percentage of the investment to a future specific allocation fund, and the multiplicity of agencies involved in hydrogen regulation. In September 2023, the National Strategy for the Development of the Hydrogen Economy presented the basis for the promotion of low-emission hydrogen, but the change of government in December put all hydrogen-related regulations (including the draft law) on hold and does not seem to have the will to move forward, at least in the short and medium term.

Table 1. Non-exhaustive mile stones on the evolution of the wind industry at different scales of analysis

Scale of analysis	**´70**	**´90**	**2000-2003**	**2004/05**	**2006**	**2007/08**	**2009/10**	**2011**	**2013/14**	**2015/16**	**2018-2024**
International	Wind energy industry emerged	Technology design consolidated	Vertical integration in the wind turbine industry	Mature technology. Internationalization process							
Average size of wind turbines (MW)	0.1	0.3	0.75	1.5	1.5		1.8	2	2.5	3	4-5
National level		Feed-in tariffs. First wind power projects with European technology	Technological adaptation of an European wind turbine design	Creation of ENARSA			Public program GENREN			Law 27.191: fiscal benefits, MATER. Public program RenovAr	
IMPSA				Technological development of a wind turbine designed in-house (1 MW)		Creation of IMPSA Wind. Brazil as an emergent market. Acquired an European license to manufacture wind turbines (1.5 MW)	Installation of the first wind tower designed in-house (IWP70, 1.5 MW)	In Argentina 50.4 MW of wind power in stalled. International certification of IWP-83 (2.1 MW).	In Brazil: 433 MW of wind power installed and 480 MW under construction. Closure of Wind Power Brazil	Inauguration of wind turbine production plant in Argentina (IWP-100, 2 MW)	Company restructuring. EPC for renewable energy plants. AI for O&M.
NRG					Creation of the firm with capital from companies in the O&G sector		Installation of the first wind tower designed in-house (1.5 MW)		International certification of wind turbine design	Wind turbine designed in-house Class II (1.5MW). Creation of ENAT for site detection and study of its wind resource	New domestic market: decentralized renewable energy systems.

Source: own elaboration from secondary sources

6. CONCLUSIONS

This work delves into the technological learning and innovation process observed during the emergence and consolidation of the wind industry in Argentina to develop some hypotheses about the role the inter play between demand and the technological cycle may have in driving innovation around renewable energy technologies, especially green hydrogen, in peripheral countries.

This paper focuses on the trajectory of Argentina's wind industry, analyzing the technological learning processes undertaken by IMPSA and NRG Patagonia over the last two decades. Initially, these companies designed and manufactured wind turbines tailored to the unique wind conditions of the Patagonian region. We juxtapose this evolution with global wind industry trends and internal and external demand policies that influenced these learning processes. Our findings propose hypotheses applicable to understanding learning dynamics in other emerging energy industries.

The results show that despite mature technology, there remain opportunities for technological innovation when local or regional market diffusion is limited. While the accumulated technological capabilities and the learning process play a pivotal role in the initial stages, internal demand becomes central during technology's take-off phase, especially for in-house designs. Notably, external demand from countries where the technology is not yet widespread can also drive technological development. Brazil's role in IMPSA's consolidation as a wind turbine supplier exemplifies this phenomenon.

Contrary to prevailing literature, our study suggests that natural resource-based firms may not be as critical in the technological learning process, particularly during the emergence phase of the cycle. Instead, knowledge-intensive suppliers —those involved in designing, adapting, and manufacturing technology—play a more significant role in the innovation process around the transformation of energy-related natural resources.

Doubts arise regarding the level of specificity of energy-related natural resources and their potential to open windows of opportunity for the emergence of local knowledge networks. Regardless of whether these opportunities exist, or firms seek to capitalize on those resulting from foreign technology diffusion, they must thoroughly understand the sector and develop the necessary technological and commercial capabilities to achieve technological innovation.

These observations are important for the current learning process around green hydrogen production, as there is already an international industry advancing towards its consolidation and the electrolysis technology is maturing. In Argentina, a few local companies with frontier technological capabilities are studying the process of green hydrogen production to become key players in the domestic industry, not so much in the production of electrolysers as in the provision of equipment or services to upgrade production processes. Given the lack of a supportive institutional framework and the neoliberal political context in the country, questions arise regarding the potential opportunities the external demand of green hydrogen and its by-products-this time from developed countries- may bring for technological learning and innovation in this nascent sector.

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Techno-economic assessment of the use of green hydrogen: case study in the ceramic industry

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H2

Resumen

La industria cerámica en Brasil consume volúmenes significativos de gas natural, generalmente para atender procesos que requieren altas temperaturas. Así, el uso de H2 de bajo carbono se convierte en una alternativa potencial para ser introducida en la matriz energética del sector, bajo una modalidad de auto-generación y auto-consumo, con el fin de reemplazar parcialmente el consumo de gas natural en procesos industriales. Se realiza un modelado técnico-económico, utilizando la herramienta H2V-IEPUC, sobre un estudio de caso realizado en colaboración con una empresa de la industria cerámica. La escala de producción y uso de H2 se estimó con base en proyectos internacionales y tomando como referencia los procesos industriales actualmente implementados en una fábrica. La viabilidad del proyecto de hidrógeno verde se demuestra mediante un análisis de sensibilidad con variables técnicas y económicas, además de presentar un escenario determinista de viabilidad. La comprensión del estudio de caso contribuye a los subsectores de la industria al arrojar luz sobre las ventajas y barreras relacionadas con la incorporación de H2 de bajo carbono en las operaciones, contribuyendo a la construcción de proyectos ambiental y económicamente sostenibles.

PALABRAS CLAVE: Palabras clave: hidrógeno, electrólisis, oxígeno, proceso de alta temperatura, cerámica.

Abstract

The ceramic industry in Brazil consumes significant volumes of natural gas, usually for attending to processes that require high temperatures. Thus, the use of low-carbon H2 becomes a potential alternative to be introduced into the sector's energy matrix, under a self-generation and self-consumption modality, in order to partially replace natural gas in industrial processes. Technical-economic modeling is carried out, using the H2V-IEPUC tool, on a case study conducted in partnership with a ceramic industry company. The scale of production and use of H2 were estimated based on international projects and taking as a reference industrial processes currently implemented at a factory. The feasibility of the green hydrogen project is demonstrated by carrying out a sensitivity analysis with technical and economic variables, in addition to presenting a deterministic feasibility scenario. The understanding of the case study contributes to industry subsectors by shedding light on the advantages and barriers related to the incorporation of low-carbon H2 in operations, contributing to the construction of projects that are environmentally and economically sustainable.

KEYWORDS: hydrogen, electrolysis, oxygen, high-temperature process, ceramic

1. INTRODUCTION

The ceramic industry can be divided into two main categories: red ceramics and white ceramics. Red ceramics are typically associated with large-scale structural uses in civil construction (bricks, tiles, etc.), and are produced by using firewood as the predominating energy source in Brazil (EPE, 2018). White ceramics, on the other hand, generally consist of higher-quality products (flooring, tiles, porcelain, etc.) that serve more specific functions and require a higher energy intensity in manufacturing (e.g., in the drying process). In this case, natural gas predominates in Brazil as the main fuel along such a manufacturing chain. Among the emerging uses of H_2, processes involving high-temperature heat (above 400 ºC) can benefit from this resource as a form of decarbonization, presenting as a competitive alternative to electrification (IEA, 2024; ENGIE, 2022). In this way, the energetic use of hydrogen can help preserve existing industrial assets and avoid the need for developing disruptive technologies.

Green H_2, derived from water electrolysis using renewable energy (such as hydric, solar, and wind), is an energy source capable of serving this class of processes as a substitute for fossil fuels. In particular, the Brazilian electricity grid could be suitable for green hydrogen production, since hydropower stands out with a share of almost 60% as one of the main primary energy sources (EPE, 2024). As long as the hydric scenario in the country is favorable, the grid can sustain a low-carbon intensity with reliable provision, for example, facilitating the certification of hydrogen in strict schemes (CCEE, 2024). Overall, the combination of renewable electricity resources in Brazil can allow elevated operational factors, enabling the economic feasibility of electrolysis projects while guaranteeing the environmental attribute of hydrogen.

Notably, international experiences in the ceramics industry have adopted pilot plants to use green hydrogen. For example, a ceramic company in Villareal, Spain, has invested in the GREENH2KER decarbonization project, which aims to replace 50% of natural gas with green H_2 (IBERDROLA, 2021). Another recent experience that endorses the technical feasibility of using a hydrogen-natural gas mixture in the ceramic industry is a project developed in Castellarano, Italy. Success was reported for tests with fuel blends containing 7% H2 to decarbonize the operation of a kiln, and there is an expectation to use mixtures with up to 50% H2 (IRIS, 2024).

Finally, although carbon credits tend to be the main coproduct in economic assessments involving low-carbon H2, the O2 coproduced in electrolysis is usually neglected. Actually, only specific industrial sectors (steel industry, healthcare systems in hospitals, submarine projects) use it at relevant scales (IEA, 2023). Dedicated O_2 production systems tend to be costly for use in enhanced combustion processes, and therefore combustion is conducted commonly with air as comburent. It is noteworthy that some studies are giving purpose to this byproduct. Novaes et al. (2024) evaluated a Power-to-Liquid process sourced with green H2 to produce wax and syncrude as main products. The revenue associated with O2 presented a share of 13% among the outputs, being also almost four times more representative than the selling of carbon credits. Assunção et al. (2025) modeled the use of an electrolysis system in order to supply H2 for fuel cell vehicles (i.e., ambulances) while O2 was stored for attending to the healthcare systems in a hospital. Avoiding the cost of buying O2 allowed a reduction of the levelized cost of Hydrogen (LCOH) from 4.96 to 2.60 USD/kg. Finally, León et al. (2024) studied a bolder model for a cement factory in Spain, in which synfuels are produced by combining CO2 from flue gases and hydrogen from electrolysis; the coproduced O2 was appraised through an oxy-combustion applied to a calcination process. Thus, the possibility of designating a concrete use for O2 can promote the economic feasibility of H2 derived from water electrolysis.

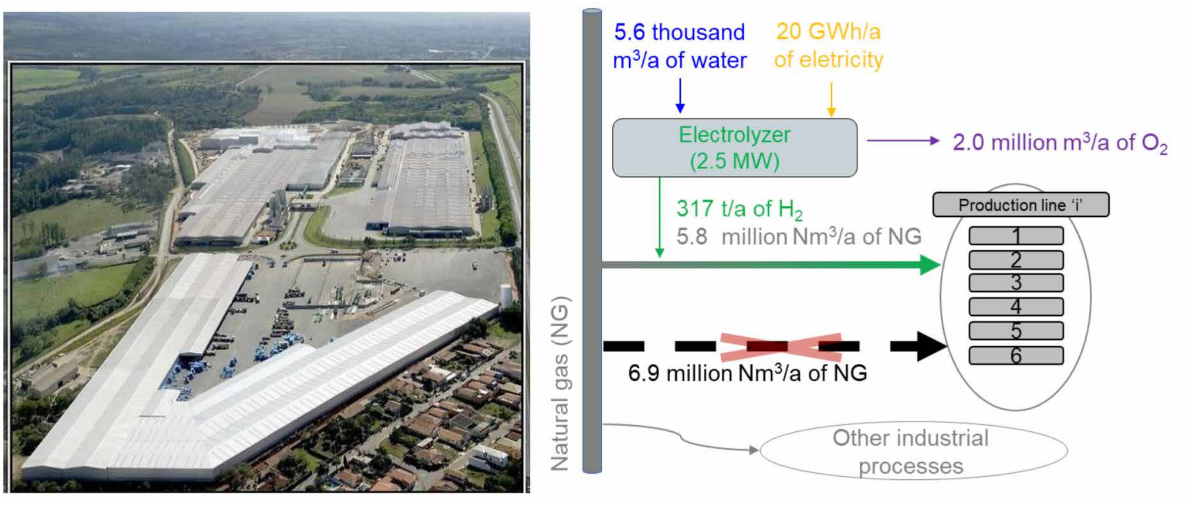
In this context, this study aims to assess the partial substitution of natural gas with green H_2 in the white ceramic sector, focusing on a drying process at a concrete ceramic facility in São Paulo state, Brazil (DELTA, 2024). A feasible substitution level and electrolyzer capacity scale are assumed in the simulation, as exemplified by the presented international projects within the ceramic industry. Variables surrounding this substitution are evaluated with the H2V-IEPUC model (CNI, 2024). The tool enables a sensitivity analysis useful to track deterministic scenarios that are attractive to industry companies, according to technical, economic, and environmental metrics. Therefore, this study aims to track conditioning factors that enable the introduction of low-carbon hydrogen in the ceramic industry, within the framework of a Brazilian company, representing a novelty for the literature.

Within the scope of assessing the feasibility of using hydrogen as a fuel for ceramic processes, the objectives of this paper are to model the incremental cash flow and the net present value (NPV) of the substitution project, within the Brazilian company technic-economic framework; to quantify the main partakes in the cost of green hydrogen in the levelized cost metric (LCOH) as well as revenues associated to coproducts (CO2 credits and O2); and consider a sensitivity analysis on NPV with the CAPEX and electricity cost, identified as key parameters to be combined for the sake of the project's feasibility. The modeling and planning of partial substitution of natural gas in a dedicated branch of the factory allow the industrial player to kick off an initial pilot phase, enabling the introduction of green H_2 in the energy matrix. This means the adoption of a project with a low technical risk, such as intermediate product drying. Depending on the internal experience gained and the technical-operational success in the H_2 usage, the player could expand the system rationally, either by safely increasing the natural gas substitution in existing processes or by extending the H_2 use to other processes within the factory.

2. METHODS

The ceramic-industry player facilities are located in Rio Claro, in São Paulo's interior, Brazil (Figure 1), contributing to the municipality's status as the largest ceramics production center in the Americas and representing a significant production scale globally. This allowed the study case to consider meaningful production scale magnitudes within the ceramics sector. In the factory, there are around 10 production lines established to process raw materials into ceramic products by using natural in kilns and dryers.

Figure 1 – Ceramic factory in São Paulo State, Brazil (left) and evaluated study case (right)



Source: elaborated by the authors with data from Delta (2024).

The factory has a dedicated natural gas line supplying six dryers, each consuming an average of 3,450 Nm^3/d of natural gas. An electrolysis system was sized to replace 15% of the fossil fuel. Given an annual factory operation of 8,000 hours (91.3% operational factor), the current annual consumption of 6.9 million m^3 of natural gas could be reduced to 5.8 million m^3/yr with the use of H_2 (317 tons of H_2 per year) generated by a 2.5 MW electrolyzer (ENZE CUMMINS, 2023). The simulation of physical and cash flows and the economic analysis for the fuel replacement project were conducted using the H2V-IEPUC tool (CNI, 2024).

The input variables are as follows. The technical variables of the electrolyzer were: specific electricity consumption of 61.7 kWh/kg H_2, specific water consumption of 16.92 l/kg, coproduction of 8 kg of O_2/kg H_2, and an annual electrolyzer stack degradation rate of 1% (Khan et al., 2021). The main economic variables are listed in Table 1.

Table 1 – Key input variables for the economical-financial modeling

CAPEXelectrolyzer	7,263 BRL/kW	Other investments	50% of CAPEXelectrolyzer
O&M	5% a.a.	Membrane replacement	20% of CAPEXelectrolyzer
Residual value	30% do CAPEXelectrolyzer	Time horizon	20 years
CAPEX allocation	2 years, with 80% in the 1st year	Electricity cost	300 BRL/MWh
Natural gas cost	4.30 BRL/Nm3	Water cost	0.6 BRL/m3
Carbon credits	250 BRL/t CO2		

Sources: elaborated by the authors with data from Khan et al. (2021) and Delta (2024).

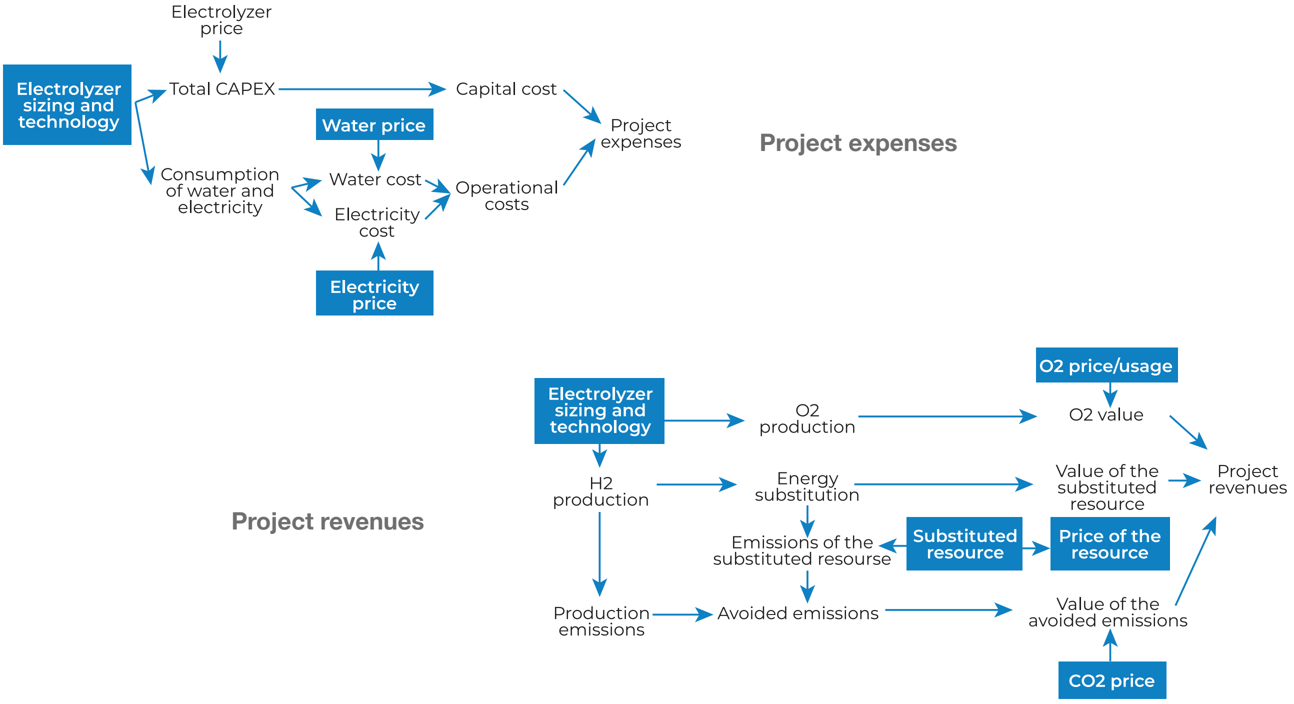
The electrolyzer CAPEX (1,452 USD/kW) and annual OPEX (5% of electrolyzer CAPEX) were adapted from Khan et al. (2021). Besides the electrolyzer CAPEX, 50% of CAPEX was added due to importation, EPC (engineering, procurement, and construction) activities, and contingencies. The electrolyzer project was simulated over 20 years. The total investment (27 million BRL) was allocated in the first two years, with 80% in the first year. Besides the annual OPEX, the need for membrane replacement in the electrolyzer (20% of electrolyzer CAPEX) was considered after 75,000 hours of operation. The cost of water for the electrolysis was assumed to be 0.6 BRL/m^3. The annual water demand of 5,600 m^3 can be sourced from the company's water resources, representing a small volume and low environmental impact within the factory operations (Delta, 2024). The electricity cost of 300 BRL/MWh was considered appropriate to the factory's circumstances. Figure 2 pictures the modeling scheme implemented to build the cash flow.

For the incremental cash flow assessment, the replaced natural gas was considered an avoided cost (revenue), valued at 4.30 BRL/Nm^3. According to the reduction of natural gas consumption (emission factor of 56.15 gCO_2eq/MJ) (IPCC, 2014), revenues from carbon credits were valued at 250 BRL/t CO_2eq.

Given the proximity of hydrogen production to its final use, the O_2 produced from electrolysis was considered for oxygen-enhanced combustion (OEC) purposes (CSN, 2020; Wu et al., 2010). Therefore, through a thermodynamic analysis focused on adiabatic flame temperature (Law, 2010), aiming at enriching the combustion air with O_2 concentrations lower than 30% v/v, a technical potential of saving 0.47 m^3 of natural gas/m^3 of O_2 produced by electrolysis was adopted (Castiñeiras-Filho, et al., 2024). In this way, the appraisal of O_2 aggregates revenues through natural gas savings and the generation of carbon credits.

After entering the input variables, the H2V-IEPUC tool (CNI, 2024) reports many relevant outputs inherent to the simulated incremental cash flow. The main output variables are the net present value (NPV), the internal rate of return (IRR), the levelized cost of hydrogen (LCOH) and its break-down into components, and the competitiveness price of natural gas that equalizes the implementation of the hydrogen project with the business as usual case. Figure 2 pictures a scheme representing how the tools gather the input variables and build up the cash flows. For more details about the modeling of the cash flow, a manual is provided with the tool (CNI, 2024).

Figure 2 – Simplified scheme for estimating revenues and expenses in the modeling



Source: elaborated by the authors.

According to the methodology outlined above, a technical and economic analysis was conducted for two scenarios: a base (conservative) scenario that ignores the potential value of O_2; and a promising scenario that considers O_2 appreciation. It is important to highlight that the latter scenario disregards costs related to O_2 processing and conditioning from electrolysis, as well as other costs associated with equipment and infrastructure adaptations needed for OEC implementation. In addition to the deterministic results for the context presented in this methodology, a sensitivity analysis of the NPV was performed concerning the most impactful variables: natural gas cost, electricity cost, and electrolyzer CAPEX.

3. RESULTS AND DISCUSSION

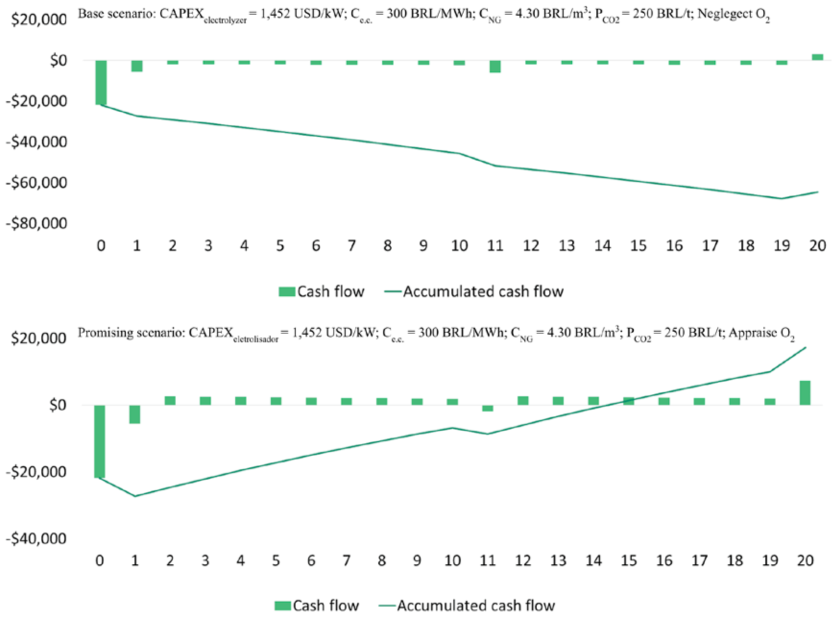
3.1. Analysis of Incremental Cash Flow for the Base and Promising Scenarios

The cash flow and accumulated cash flow of the base and promising scenarios are presented in Figure 3. The base scenario demonstrates the economic unfeasibility of the project, based on the economic assumptions outlined in Table 1. A major issue was that the annual costs (O&M, electricity, etc.) consistently exceeded the revenues (natural gas avoided cost and carbon credits) associated with the partial substitution of natural gas by green H_2. Notably, in year 11, the need to replace the electrolyzer membrane after 75,000 hours of operation showed up as a relevant cost, further impacting the economic viability of the project. Therefore, the base scenario is unfeasible, as it resulted in a negative NPV of -50 million BRL and a strictly decreasing cash flow.

On the other hand, the promising scenario demonstrated that the ability to valorize the O_2 produced from electrolysis enables the project's accumulated cash flow to grow, reflecting the generation of revenues greater than the operational costs. It is noteworthy that the use of O_2 to displace 0.47 m^3 of gas/m^3 of O_2, with a natural gas cost of 4.30 BRL/m^3, generates a value of approximately 2.021 BRL/m^3 of O_2. In addition to this revenue from fuel savings, an additional CO_2 emission reduction of 0.972 $kgCO_2/m^3$ O_2 valued at 250 BRL/t CO_2 results in an extra revenue of 0.243 BRL/m^3 of O_2. This potential valuation highlights the importance of conducting R&D to explore the utilization of O_2 in industrial processes or even to seek its commercialization with third parties.

Finally, although Figure 3 shows that the scenario appraising O_2 seems to have a favorable cash flow, its NPV was equal to -0.822 million BRL and the IRR was 4.7. From an objective perspective, even the valorization of O_2 is not sufficient to approve the implementation of the electrolysis project; however, the feasibility was very close with regard to the discount rate of 5%. This result demonstrates that access to low-interest financing options, crucial for stimulating decarbonization projects, could contribute to the adoption of H_2 in the ceramics sector.

Figure 3 – Cash flow overview for the base scenario (above) and the promising scenario (below)

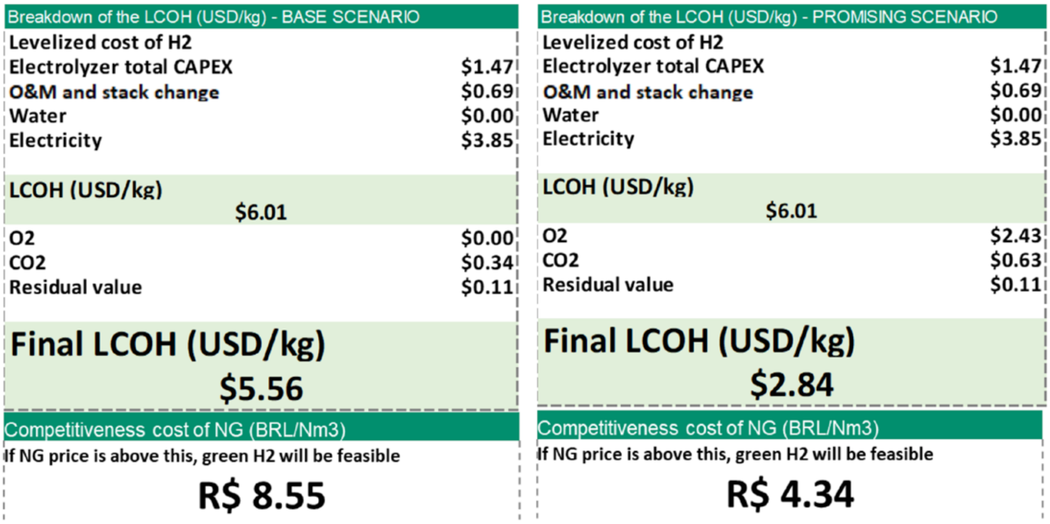


Source: elaborated by the authors.

3.2. Levelized Cost of Hydrogen (LCOH) structure in the scenarios

Figure 4 demonstrates the breakdown of the Levelized Cost of Hydrogen (LCOH) in the evaluated scenarios, as well as the cost of the fossil fuel above which the use of hydrogen becomes competitive. The base scenario resulted in an LCOH of 5.56 USD/kg of H2. The main components were the cost of electricity (3.85 USD/kg, 64% of costs) and the CAPEX of the electrolyzer (1.47 USD/kg, 24.5% of costs). Therefore, reducing these costs is relevant to make the electrolysis projects viable and minimize the cost of the hydrogen produced. Among the cost reducers, the carbon credits contribute to a reduction of 0.34 USD/kg of H2 produced. Additionally, for the sake of the economic competitiveness of H2, natural gas would need to cost 8.55 BRL/m3 in the base scenario, nearly double the cost adopted (4.30 BRL/m3), demonstrating the unfeasibility of the project.

Figure 4 – LCOH for the base scenario (on the left) and promising scenario (right), and competitiveness cost of the fossil source.



Breakdown of the LCOH (USD/kg) - BASE SCENARIO	
Levelized cost of H2	
Electrolyzer total CAPEX	**$1.47**
O&M and stack change	**$0.69**
Water	**$0.00**
Electricity	**$3.85**
LCOH (USD/kg)	**$6.01**
O2	**$0.00**
CO2	**$0.34**
Residual value	**$0.11**
Final LCOH (USD/kg)	**$5.56**
Competitiveness cost of NG (BRL/Nm3)	
If NG price is above this, green H2 will be feasible	**R$ 8.55**

Breakdown of the LCOH (USD/kg) - PROMISING SCENARIO	
Levelized cost of H2	
Electrolyzer total CAPEX	**$1.47**
O&M and stack change	**$0.69**
Water	**$0.00**
Electricity	**$3.85**
LCOH (USD/kg)	**$6.01**
O2	**$2.43**
CO2	**$0.63**
Residual value	**$0.11**
Final LCOH (USD/kg)	**$2.84**
Competitiveness cost of NG (BRL/Nm3)	
If NG price is above this, green H2 will be feasible	**R$ 4.34**

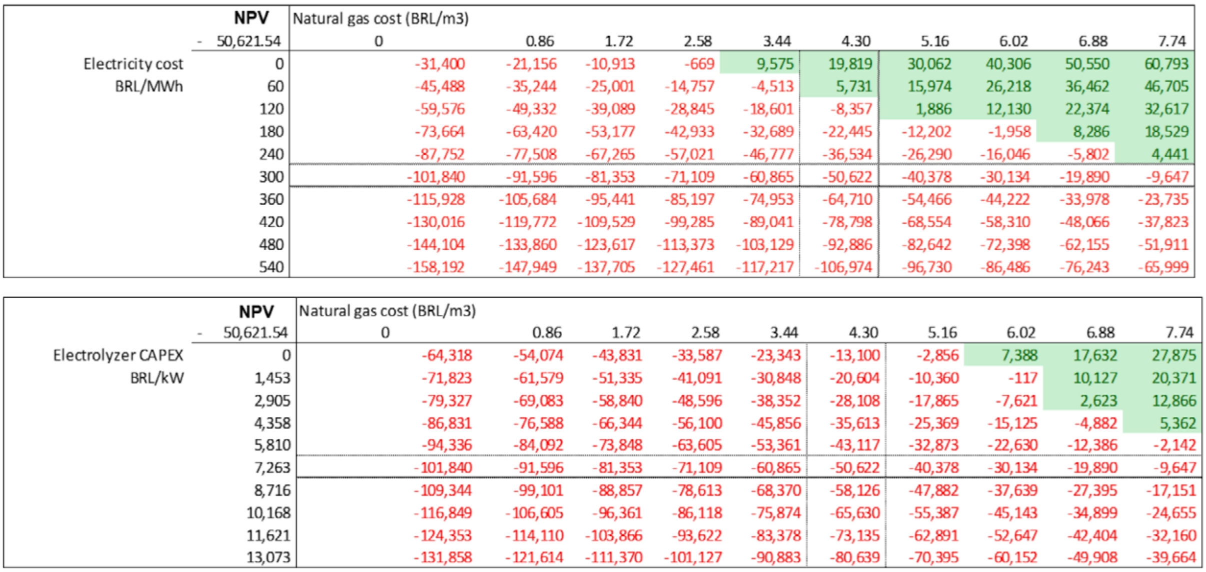
Source: elaborated by the authors with the tool in CNI (2024)

In the promising case, the O2 contributed to a reduction of 2.43 USD/kg in the LCOH, in addition to increasing the carbon credit revenue to a total of 0.63 USD/kg of H2. Thus, the LCOH in the promising case reached 2.84 USD/kg, proposing a competitiveness value for the fossil fuel of 4.34 BRL/m3. As assessed in the previous section, where the natural gas price was established at 4.30 BRL/m3, the substitution project is very close to being viable. Therefore, a structural increase in the price of natural gas over the project's time horizon, for example, can turn the NPV positive, assuming that the other assumptions in Table 1 remain constant.

3.3. Analysis of the sensitivity of the NPV to relevant economic variables

As observed in the LCOH components, the relevant costs are: the cost of the fossil fuel, the electricity cost, and the electrolyzer CAPEX. Figures 5 and 6 show the NPV sensitivity to variations in these parameters for the base and promising scenarios, respectively.

Figure 5 – Sensitivity analysis of NPV in the base scenario (neglecting O2)



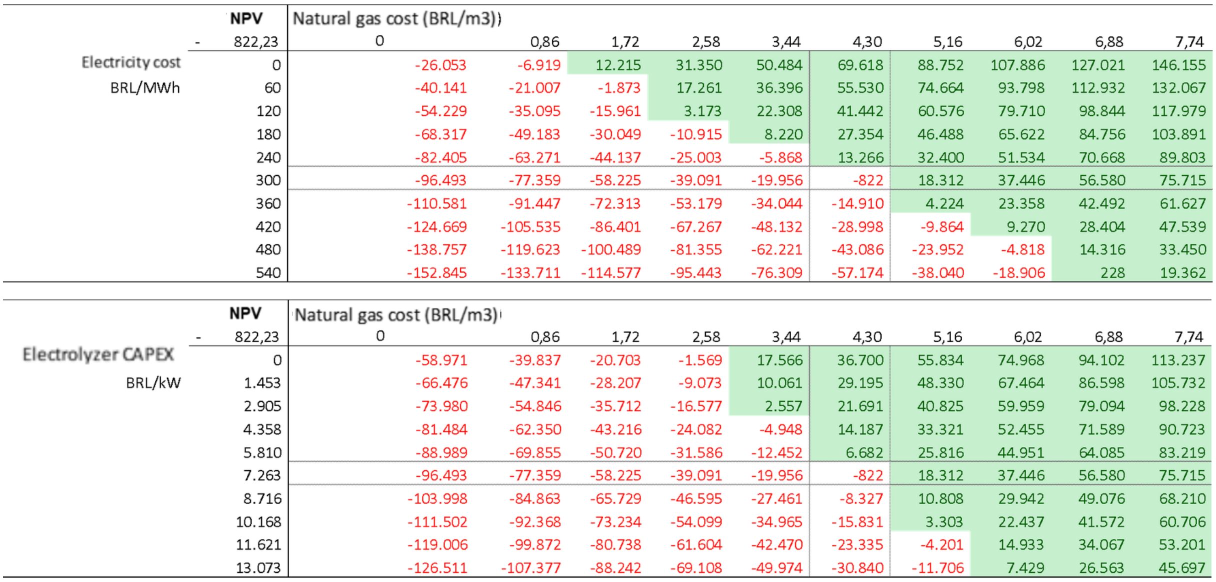
	NPV	Natural gas cost (BRL/m3)									
	- 50,621.54	0	0.86	1.72	2.58	3.44	4.30	5.16	6.02	6.88	7.74
Electricity cost	0	-31,400	-21,156	-10,913	-669	9,575	19,819	30,062	40,306	50,550	60,793
BRL/MWh	60	-45,488	-35,244	-25,001	-14,757	-4,513	5,731	15,974	26,218	36,462	46,705
	120	-59,576	-49,332	-39,089	-28,845	-18,601	-8,357	1,886	12,130	22,374	32,617
	180	-73,664	-63,420	-53,177	-42,933	-32,689	-22,445	-12,202	-1,958	8,286	18,529
	240	-87,752	-77,508	-67,265	-57,021	-46,777	-36,534	-26,290	-16,046	-5,802	4,441
	300	-101,840	-91,596	-81,353	-71,109	-60,865	-50,622	-40,378	-30,134	-19,890	-9,647
	360	-115,928	-105,684	-95,441	-85,197	-74,953	-64,710	-54,466	-44,222	-33,978	-23,735
	420	-130,016	-119,772	-109,529	-99,285	-89,041	-78,798	-68,554	-58,310	-48,066	-37,823
	480	-144,104	-133,860	-123,617	-113,373	-103,129	-92,886	-82,642	-72,398	-62,155	-51,911
	540	-158,192	-147,949	-137,705	-127,461	-117,217	-106,974	-96,730	-86,486	-76,243	-65,999

	NPV	Natural gas cost (BRL/m3)									
	- 50,621.54	0	0.86	1.72	2.58	3.44	4.30	5.16	6.02	6.88	7.74
Electrolyzer CAPEX	0	-64,318	-54,074	-43,831	-33,587	-23,343	-13,100	-2,856	7,388	17,632	27,875
BRL/kW	1,453	-71,823	-61,579	-51,335	-41,091	-30,848	-20,604	-10,360	-117	10,127	20,371
	2,905	-79,327	-69,083	-58,840	-48,596	-38,352	-28,108	-17,865	-7,621	2,623	12,866
	4,358	-86,831	-76,588	-66,344	-56,100	-45,856	-35,613	-25,369	-15,125	-4,882	5,362
	5,810	-94,336	-84,092	-73,848	-63,605	-53,361	-43,117	-32,873	-22,630	-12,386	-2,142
	7,263	-101,840	-91,596	-81,353	-71,109	-60,865	-50,622	-40,378	-30,134	-19,890	-9,647
	8,716	-109,344	-99,101	-88,857	-78,613	-68,370	-58,126	-47,882	-37,639	-27,395	-17,151
	10,168	-116,849	-106,605	-96,361	-86,118	-75,874	-65,630	-55,387	-45,143	-34,899	-24,655
	11,621	-124,353	-114,110	-103,866	-93,622	-83,378	-73,135	-62,891	-52,647	-42,404	-32,160
	13,073	-131,858	-121,614	-111,370	-101,127	-90,883	-80,639	-70,395	-60,152	-49,908	-39,664

Note: Other parameters are constant as in Table 1. Values in green highlight scenarios where the NPV is greater than zero.

Source: elaborated by the authors with the tool in CNI (2024)

Figure 6 – Sensitivity analysis of NPV in the promising scenario (appraising O2)



	NPV	Natural gas cost (BRL/m3))									
	- 822,23	0	0,86	1,72	2,58	3,44	4,30	5,16	6,02	6,88	7,74
Electricity cost	0	-26.053	-6.919	12.215	31.350	50.484	69.618	88.752	107.886	127.021	146.155
BRL/MWh	60	-40.141	-21.007	-1.873	17.261	36.396	55.530	74.664	93.798	112.932	132.067
	120	-54.229	-35.095	-15.961	3.173	22.308	41.442	60.576	79.710	98.844	117.979
	180	-68.317	-49.183	-30.049	-10.915	8.220	27.354	46.488	65.622	84.756	103.891
	240	-82.405	-63.271	-44.137	-25.003	-5.868	13.266	32.400	51.534	70.668	89.803
	300	-96.493	-77.359	-58.225	-39.091	-19.956	-822	18.312	37.446	56.580	75.715
	360	-110.581	-91.447	-72.313	-53.179	-34.044	-14.910	4.224	23.358	42.492	61.627
	420	-124.669	-105.535	-86.401	-67.267	-48.132	-28.998	-9.864	9.270	28.404	47.539
	480	-138.757	-119.623	-100.489	-81.355	-62.221	-43.086	-23.952	-4.818	14.316	33.450
	540	-152.845	-133.711	-114.577	-95.443	-76.309	-57.174	-38.040	-18.906	228	19.362

	NPV	Natural gas cost (BRL/m3)									
	- 822,23	0	0,86	1,72	2,58	3,44	4,30	5,16	6,02	6,88	7,74
Electrolyzer CAPEX	0	-58.971	-39.837	-20.703	-1.569	17.566	36.700	55.834	74.968	94.102	113.237
BRL/kW	1.453	-66.476	-47.341	-28.207	-9.073	10.061	29.195	48.330	67.464	86.598	105.732
	2.905	-73.980	-54.846	-35.712	-16.577	2.557	21.691	40.825	59.959	79.094	98.228
	4.358	-81.484	-62.350	-43.216	-24.082	-4.948	14.187	33.321	52.455	71.589	90.723
	5.810	-88.989	-69.855	-50.720	-31.586	-12.452	6.682	25.816	44.951	64.085	83.219
	7.263	-96.493	-77.359	-58.225	-39.091	-19.956	-822	18.312	37.446	56.580	75.715
	8.716	-103.998	-84.863	-65.729	-46.595	-27.461	-8.327	10.808	29.942	49.076	68.210
	10.168	-111.502	-92.368	-73.234	-54.099	-34.965	-15.831	3.303	22.437	41.572	60.706
	11.621	-119.006	-99.872	-80.738	-61.604	-42.470	-23.335	-4.201	14.933	34.067	53.201
	13.073	-126.511	-107.377	-88.242	-69.108	-49.974	-30.840	-11.706	7.429	26.563	45.697

Note: Other parameters are constant as in Table 1. Values in green highlight scenarios where the NPV is greater than zero.

Source: elaborated by the authors with the tool in CNI (2024)

The base scenario shows that only with an electricity cost between 60 and 120 BRL/MWh would be possible to make the project viable, given the reference price for natural gas of 4.30 BRL/m³. If the cost of natural gas increases by 50%, an electricity cost as low as 120 BRL/MWh would be necessary to achieve economic feasibility, for example. Regarding the electrolyzer CAPEX, a 40% cost reduction (i.e., 4,358 BRL/kW) would only make the project viable for natural gas prices as high as 7.74 BRL/m³.

In the promising scenario, the contexts that make the decarbonization project viable are more diverse. An electricity cost of around 180 BRL/MWh would already make the project viable even if the cost of natural gas was reduced by 20%, to competitive levels as low as 3.44 BRL/m³. Regarding the electrolyzer CAPEX, a 40% reduction of it would also favor the viability of the project.

Thus, the sensitivity analyses highlight that the accessibility of the ceramics industry to low electricity costs is essential for the rational introduction of green H2 into its energy matrix. In the Brazilian context, the industry can invest in distributed or self-generation projects with renewable energy, which may allow access to more competitive electricity costs. This alternative benefits either the electrolysis project or other industrial operations, besides ensuring a renewable energy backing for the H2 produced and the electricity matrix of the factory. In addition to this route, the factory can seek negotiations in the free energy market so as to achieve electricity costs in accordance with the scope of producing H2 for decarbonization purposes.

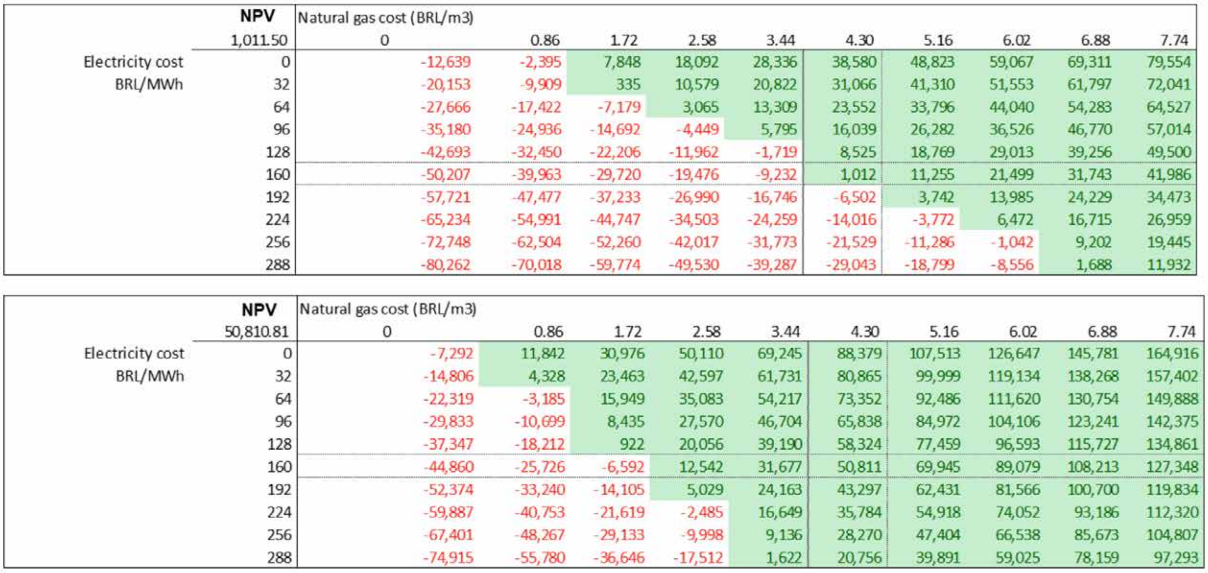
With a lesser impact, the electrolyzer cost is also relevant. Therefore, it is emphasized that the sector can seek financing sources for capital goods to mitigate the CAPEX burden, based on the decarbonization goal pursued by both industrial agents and government bodies. Proper project structuring for electrolysis, with the support of existing credit lines, may be a more appropriate short-term alternative, rather than waiting for the effect of economies of scale over electrolysis technology.

Based on the results above, the sensitivity analysis of the NPV with the costs of natural gas and electricity was reproduced for the base and promising scenarios, considering an electricity cost of 160 BRL/MWh and a 50% reduction in the electrolyzer CAPEX (3,632 BRL/kW) as a new reference level. It is important to note that these references are supported by the perspectives of the excess supply of renewable electricity in Brazil (Brasil Energia, 2024) and current electrolyzer cost levels (BloombergNEF, 2024).

Figure 7 shows the results of this analysis, demonstrating that the reduction in these two variables favors the project's viability. In the new reference case, a positive NPV of 1.0 million BRL was found for the base scenario, without considering the value of O2. In the context of an increase in the cost of natural gas, the project remains viable. In the promising scenario, which takes into account the use of O2, the NPV of the new reference is 50 million BRL. Furthermore, the project remains viable even with highly competitive natural gas prices, as low as R$ 0.86/m3.

Finally, the evaluated scenario supports the result regarding the importance of low electricity costs and electrolyzer CAPEX. In particular, the consideration of the value of O2 presents a relevant potential to mitigate the cost of hydrogen production.

Figure 7 – Sensitivity analysis for the base scenario (top) and promising scenario (bottom) under the new reference



	NPV	Natural gas cost (BRL/m3)									
	1,011.50	0	0.86	1.72	2.58	3.44	4.30	5.16	6.02	6.88	7.74
Electricity cost	0	-12,639	-2,395	7,848	18,092	28,336	38,580	48,823	59,067	69,311	79,554
BRL/MWh	32	-20,153	-9,909	335	10,579	20,822	31,066	41,310	51,553	61,797	72,041
	64	-27,666	-17,422	-7,179	3,065	13,309	23,552	33,796	44,040	54,283	64,527
	96	-35,180	-24,936	-14,692	-4,449	5,795	16,039	26,282	36,526	46,770	57,014
	128	-42,693	-32,450	-22,206	-11,962	-1,719	8,525	18,769	29,013	39,256	49,500
	160	-50,207	-39,963	-29,720	-19,476	-9,232	1,012	11,255	21,499	31,743	41,986
	192	-57,721	-47,477	-37,233	-26,990	-16,746	-6,502	3,742	13,985	24,229	34,473
	224	-65,234	-54,991	-44,747	-34,503	-24,259	-14,016	-3,772	6,472	16,715	26,959
	256	-72,748	-62,504	-52,260	-42,017	-31,773	-21,529	-11,286	-1,042	9,202	19,445
	288	-80,262	-70,018	-59,774	-49,530	-39,287	-29,043	-18,799	-8,556	1,688	11,932

	NPV	Natural gas cost (BRL/m3)									
	50,810.81	0	0.86	1.72	2.58	3.44	4.30	5.16	6.02	6.88	7.74
Electricity cost	0	-7,292	11,842	30,976	50,110	69,245	88,379	107,513	126,647	145,781	164,916
BRL/MWh	32	-14,806	4,328	23,463	42,597	61,731	80,865	99,999	119,134	138,268	157,402
	64	-22,319	-3,185	15,949	35,083	54,217	73,352	92,486	111,620	130,754	149,888
	96	-29,833	-10,699	8,435	27,570	46,704	65,838	84,972	104,106	123,241	142,375
	128	-37,347	-18,212	922	20,056	39,190	58,324	77,459	96,593	115,727	134,861
	160	-44,860	-25,726	-6,592	12,542	31,677	50,811	69,945	89,079	108,213	127,348
	192	-52,374	-33,240	-14,105	5,029	24,163	43,297	62,431	81,566	100,700	119,834
	224	-59,887	-40,753	-21,619	-2,485	16,649	35,784	54,918	74,052	93,186	112,320
	256	-67,401	-48,267	-29,133	-9,998	9,136	28,270	47,404	66,538	85,673	104,807
	288	-74,915	-55,780	-36,646	-17,512	1,622	20,756	39,891	59,025	78,159	97,293

Note: the new references are R\$160/MWh for electricity cost and R\$3,632/kW for the electrolyzer CAPEX. Other parameters are constant as in Table 1. Values in green highlight that the scenario results in a positive NPV.

Source: elaborated by the authors with the tool in CNI (2024)

4. CONCLUSION

The case study conducted with a ceramics industry company demonstrates the potential for hydrogen production at costs between 2.84 and 5.56 USD/kg H2. The modeled incremental cash flows were unattractive and misaligned (NPV lesser than 0) with the technical-economic risk in the current context established with the company. By breaking down the LCOH, the main contributors identified in this metric composition were the CAPEX, electricity cost, and O2 valuation. In sum, the hydrogen production project for partial natural gas replacement is only viable if the potential value of the oxygen (O2) co-produced in electrolysis is fully exploited, which can be achieved through oxygen-enriched combustion (OEC) or commercialization with third parties. Besides, the sector must be able to value avoided emissions at 250 BRL/t CO2. However, since the analysis does not account for O2 processing costs and equipment adaptation, it remains essential to seek electricity contracts at more competitive costs or to pursue well-structured distributed generation or self-production projects with renewable sources to facilitate the feasibility of the project in the long term. As indicated by the sensitivity analysis, combining incentives for the electrolyzer investments (halving the CAPEX) with oxygen appraisal can enable the decarbonization project with electricity prices as high as 288 BRL/MWh. Additionally, access to low-cost credit lines could be provided to the sector as a way to achieve decarbonization goals for the industry. Overall, the ceramic industry company can invest in the green hydrogen project with reasonability and consider it an effective decarbonization strategy if one of the tracked technical-economic contexts in the sensitivity analysis can be fulfilled.

It is further emphasized that the results obtained from the case study with the ceramics industry provide both quantification and an understanding of the potential value for other industrial subsectors regarding the potential for green hydrogen to enter their energy matrices, without overlooking the economic aspects within the energy transition agenda. The critical role of capital costs associated with electrolysis technology and electricity in supporting the process viability is highlighted, as well as the importance of valuing O2 recovery in cases where the hydrogen produced by electrolysis is close to its end-use, as shown in the breakdown of the LCOH. Future studies in this area can be expanded to other industrial sectors and applications involving hydrogen or derivative products, in order to explore technical and economic viability scenarios and guide public policies towards the development of financing programs or tax exemptions for decarbonization projects.

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Assessing Uruguay’s green hydrogen potential: A comprehensive analysis of electricity and hydrogen sector optimization until 2050

Evaluación del potencial de hidrógeno verde en Uruguay: Un análisis integral de la optimización de los sectores de electricidad e hidrógeno hasta el 2050

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H2

Resumen

Uruguay se posiciona como potencial exportador de hidrógeno verde y derivados, según lo descrito en la hoja de ruta. El objetivo principal de este estudio es explorar cómo reacciona el sistema eléctrico del país a los objetivos delineados en la hoja de ruta. Otro objetivo es analizar cómo podría desarrollarse el sector del hidrógeno verde basado en el precio de mercado del hidrógeno. Se propone una metodología para distribuir los costos entre ambos sectores. El análisis revela que cada escenario presenta desarrollos muy diferentes de los sistemas energéticos en Uruguay. Son necesarias expansiones sustanciales en las capacidades de energía renovable, particularmente fotovoltaica y eólica, para apoyar una economía del hidrógeno. Los escenarios impulsados por el mercado, especialmente con precios más altos del hidrógeno, muestran aumentos significativos en las capacidades de los electrolizadores. La viabilidad económica de la producción de hidrógeno a precios más altos sugiere que las exportaciones de hidrógeno podrían convertirse en un negocio rentable para Uruguay.

PALABRAS CLAVE: Hidrógeno, Modelo de sistema energético, Optimización, Coste nivelado de la electricidad, Coste nivelado del hidrógeno, Uruguay.

Abstract

Uruguay is setting out to become a leading exporter of green hydrogen and its derivatives, as described by the hydrogen roadmap. The primary aim of this study is to explore how the country's electricity system reacts to the goals outlined there. Another aim is to analyze how the green hydrogen sector could develop based on the market price for hydrogen. A methodology for distributing the costs among both sectors is proposed. The analysis reveals that very different pictures are painted in each of the scenarios, leading to completely different developments of the energy systems in Uruguay, substantial expansions in renewable energy capacities, particularly photovoltaic and wind power, are necessary to support a hydrogen economy. The market-driven scenarios, especially at higher hydrogen prices, show significant scale-ups in electrolyzer capacities. The economic viability of hydrogen production at higher price points suggests that hydrogen exports could become a profitable venture for Uruguay.

KEYWORDS: Hydrogen, Energy system model, Optimization, Levelized cost of electricity, Levelized cost of hydrogen, Uruguay.

1. INTRODUCTION

The increasing global focus on green hydrogen as an essential energy carrier reflects a widespread commitment to decarbonizing energy systems, particularly in sectors where direct electrification is impractical (IRENA, 2022). To meet the temperature goals set by the Paris Agreement (United Nations, 2015), achieving significant emission reductions across all economic sectors is essential. This requires decarbonizing energy, advancing electrification, increasing the share of renewable energies, and improving energy efficiency. Green hydrogen, produced from renewable sources via water electrolysis, stands out as a clean energy vector (Kumar & Lim, 2022; Stolten & Emonts, 2016) with a high energy-to-weight ratio (Chi & Yu, 2018). Its production process, which relies on solar, wind, or hydroelectric power, positions it as an environmentally friendly and sustainable option (BP, 2022; Kumar & Lim, 2022; Sánchez Delgado, 2019). With zero greenhouse gas emissions, green hydrogen holds significant potential as a substitute for fossil fuels (Kumar & Himabindu, 2019; Laguna-Bercero, 2012), particularly in "hard-to-abate" sectors. For example, Hydrogen can be utilized in fuel cells to regenerate electricity, power cellular radio bases in remote locations, or drive fuel cell electric vehicles, among other applications. It also has the potential to replace natural gas in various heat-dependent processes. Hydrogen can also play a critical role in reducing iron oxide (iron ore) to produce iron (Direct Reduction Iron, or DRI) and steel, eliminating the need for fossil fuels in one of the most challenging industrial processes to decarbonize.

Uruguay, with its advantageous geographic location and robust renewable energy infrastructure, is well-positioned to leverage green hydrogen production for export and to foster the development of new industries (International Energy Agency, 2019, 2022, Appendix A; Ministerio de Industria, Energía y Minería, 2023a). The country has formulated its strategy, embodied by the "Green Hydrogen Roadmap in Uruguay"(Ministerio de Industria, Energía y Minería, 2023b), to cultivate a domestic market for green hydrogen and position itself as a prominent exporter of this renewable energy resource. In the Roadmap it is recognized that Uruguay's potential for renewable energy production far exceeds the future needs of its electricity system. Uruguay's stability, transparent legal framework, and a strong reputation for honoring contracts and commitments make it an appealing destination for large-scale projects in green hydrogen and related fields. Uruguay is uniquely positioned to combine hydrogen with biogenic carbon dioxide (CO2) to produce green methanol. This methanol can be converted into synthetic gasoline, gas, oil, or jet fuel. Uruguay can create new energy sources that fully replace conventional fossil fuels by harnessing renewable resources to produce green hydrogen and utilizing agro-industrial waste. In the short term, Uruguay aims to develop a domestic market for green hydrogen and its derivatives, focusing on heavy and long-distance transportation and green fertilizer production. The national hydrogen roadmap projects that the costs of renewable energy in Uruguay by 2030 would enable green hydrogen production at values between 1.2 and 1.4 USD/kgH2 in the western region and between 1.3 and 1.5 USD/kgH2 in the eastern region. These competitive costs position Uruguay as a strong contender in the export market for hydrogen derivatives. In the long term, Uruguay will explore the potential for offshore green hydrogen production to further enhance its export capabilities (Ministerio de Industria, Energía y Minería, 2023b).

1.1. Literature review

The roadmap is not the first study that investigated Uruguay's hydrogen potential and costs for producing hydrogen in the country.

(Corengia et al., 2020) present a case study where they establish a simulation-based sizing of grid-connected electrolyzer plants for the case of Uruguay. Their limiting factor is the available surplus electricity from the grid; the only service that the electrolyzer would provide to the electricity system is peak shaving. They concluded that the produced hydrogen is too expensive compared to traditional fuels and that the utilization of the electrolyzer plants is too low.

(Corengia & Torres, 2022) propose a design that involves selecting power sources, electrolyzer types and sizes, and energy storage devices for hydrogen production in Uruguay at various scales. The study highlights solid oxide electrolyzers as promising, with alkaline electrolysis preferred over proton exchange membrane electrolysis among current market options. It emphasizes the importance of complementarity in energy sources and challenges the idea of producing hydrogen solely to use energy surplus and avoid curtailment.

(Ibagon et al., 2023) developed a model to optimize the capacity of renewable energy facilities, electrolyzers, storage systems, and hydrogen transport methods to minimize hydrogen costs in Uruguay. It analyzed the impact of hydrogen demand scale and technological maturity (2022 vs. 2030) on production costs and the supply chain. For medium and small demands, conversion, processing, transport, and storage costs are similar to energy costs. For larger demands, the cost of renewable energy represents the most relevant cost and pipelines are the most cost-effective for transporting compressed gas, while trucks are preferred for smaller demands. For medium demand, longer distances favor liquid organic hydrogen carriers by truck, and shorter distances favor trucks for compressed gas. The study predicts that advancements in technology will reduce hydrogen production costs from 3.5 USD/kg in 2022 to 2.3USD/kg by 2030.

The study from (Bouzas et al., 2024) examines hydrogen production costs in Uruguay, focusing on the impact of various techno-economic parameters. It highlights that electricity costs are a major driver of hydrogen production costs, especially when low capacity factors make electrolyzer CAPEX and OPEX more significant. Water costs are found to be negligible. The Weighted Average Cost of Capital (WACC) also has a substantial influence, particularly in scenarios with lower full load hours where electrolyzer investment costs dominate. Overall, WACC significantly impacts investment-based costs.

Previous studies on hydrogen production in Uruguay have focused on identifying optimal renewable locations and estimating production and transportation costs to centers like Montevideo. However, they haven't explored integration with the existing electricity system, interactions with current infrastructure, or the potential synergies of an integrated hydrogen and electricity system. This paper aims to address these gaps by assessing how hydrogen production can be integrated with the electricity system, evaluating infrastructure interactions, and determining incentives for expansion. It also provides the levelized costs of electricity and hydrogen within such integrated systems.

2. METHODOLOGY AND MODEL DESCRIPTION

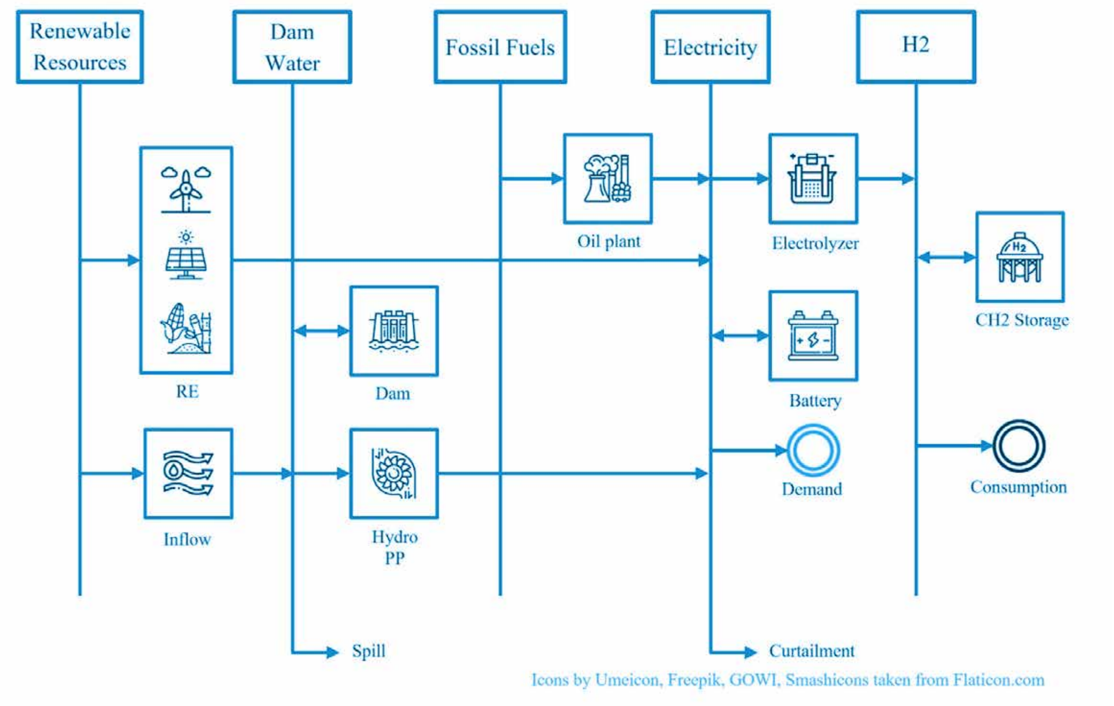
This study employs a linear programming energy system optimization model called urbs (Dorfner, 2016; Dorfner et al., 2019). The software allows the optimization of multi-commodity energy systems. It incorporates inter-temporal planning to analyze development pathways, consisting of a "perfect foresight" model, which means all future variables are defined from the beginning. The model minimizes the total costs of the system, all while fulfilling the given commodity demands. For further information about the mathematical background or the tool in general, check the documentation (Dorfner, 2023). The model in this study encompasses the existing Uruguayan electrical system alongside planned expansions, optimizing the system expansion and operation for electricity generation and hydrogen production. The analysis is an inter-temporal approach that spans multiple reference years, including 2021, 2025, 2030, 2040, and 2050, providing a comprehensive outlook on the evolution of Uruguay's electricity and hydrogen landscape. Uruguay is modeled as a single node in this model, so the costs and respective energy losses of any transmission or distribution lines within the country are not considered. In this section, we will examine the specific assumptions, models, and data utilized throughout the study.

2.1. Reference Energy System

The creation of the energy model requires the creation and definition of different input data and parameters. All the interactions between different technologies and commodities can be visualized and understood through a reference energy system. The reference system for this case can be seen in Figure 1.

In the case of Uruguay, there are different available technologies to generate electricity, from intermittent or non-conventional renewable energies, there are present solar and wind energy, to be more specific, we can find the following technologies: Open field PV, Rooftop PV, Wind onshore Level I, Wind Onshore Level II, and Wind Offshore. For each of them we have a determined potential and generation time series, the specifics are discussed in below section 2.3. All of these have a temporal generation time series as input, and their output is electricity. More traditional renewable energies such as biomass and hydro have the advantage of being flexible when they generate electricity. For biomass, yearly energy potential is the limit. For hydro, the dam can be used to store the water coming from an inflow time-series. This stored water can either be directed to its powerplant to generate electricity or be spilled. The last technology available for electricity production is the Oil plant, which consumes oil for which there is a specific cost associated and generates electricity but also direct CO2 emissions. The domestic demand then consumes electricity; this demand has to be fulfilled every single hour. The electricity could then be stored in batteries, so generation can be shifted in time. Electricity is also an input for hydrogen production using electrolyzers. This produced hydrogen to fulfill the specific demand or to sell hydrogen for a specific price. The produced hydrogen can be stored in a compressed hydrogen storage and then released for use at another time. In addition to storing, there is the possibility of curtailing electricity, which means getting rid of overproduction when this is the cost-optimal solution.

Figure 1 Reference Energy system for urbs model for Uruguay



2.2. Demands

Uruguay, like any other country, assumes an increase in its economic growth and, therefore, its electricity consumption. The Ministry of Energy and Mining has scenarios and projections of the electricity demand of the national interconnected system (SIN) until 2040 (Ministerio de Industria, Energía y Minería, 2018). 'For this study the Baseline scenario ("Tendencial") was used, where there are no significant changes in the demand distribution by sector from 2018 onwards. The growth rate from the last years was then extrapolated to calculate the expected demand for 2050. The respective values can be seen in Table 1.

Table 1. Yearly electricity demand of the National Interconnected System (SIN)

Year	2021	2025	2030	2040	2050
Yearly Electricity Demand [GWh]	11,078	12,190	13,525	16,747	20,608

All these calculations refer to the total yearly electricity demand. The hourly profile is taken from the electricity market operator (ADME, 2024) for the year 2021 is used as a base to disaggregate future yearly demand into hourly values. In the case of hydrogen demand, the roadmap (Ministerio de Industria, Energía y Minería, 2023b) gives information in terms of electrolyzer capacity, market size, and one singular value for the yearly production of 2040 of one million tons H2, corresponding to 9 GW of electrolyzer capacity. With this last value, we can derive that for each GW of electrolyzer, they are assuming 111.111 kg of hydrogen a year, and this ratio is used for all the other years. Since the roadmap goes until 2040, but the time scope of this study is until 2050, some assumptions were required to calculate the 2050 value; we went for a conservative approach of an electrolyzer capacity and demand increase of 20%, which results in 1.2 million tons for 2050. The respective original and calculated electrolyzer capacities and demands can be seen in Table 2.

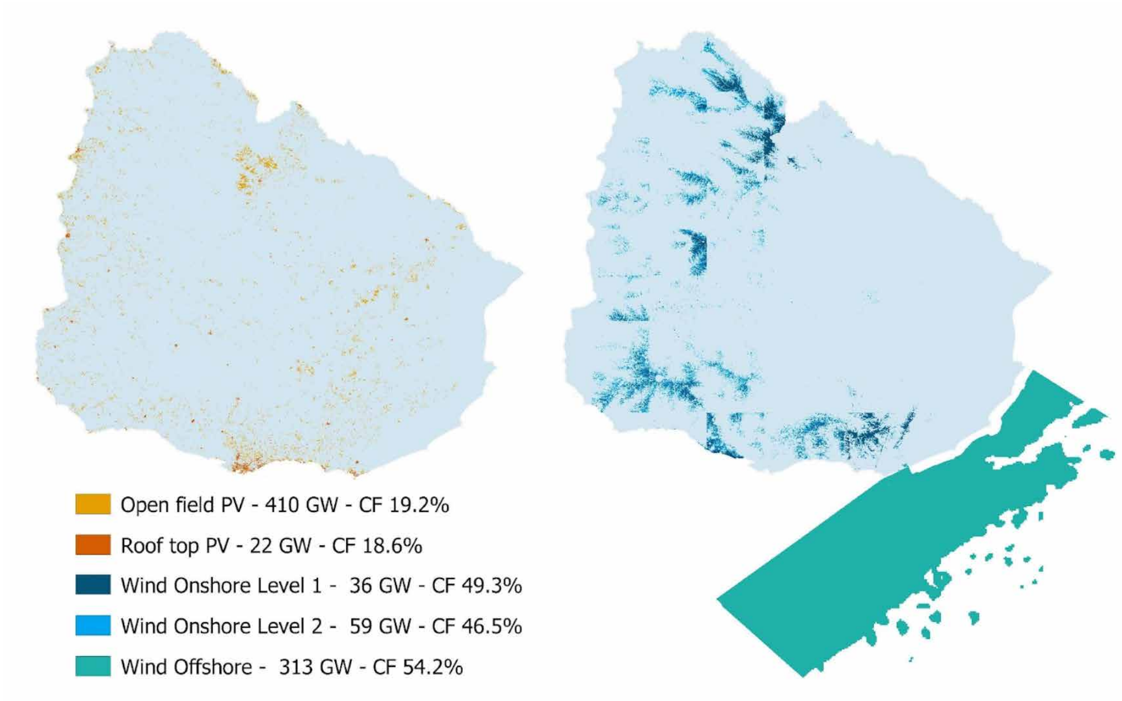
Table 2. Specified electrolyzer capacities and estimated hydrogen demands. Based on: (Ministerio de Industria, Energía y Minería, 2023b)

	2025	**2030**	**2040**	**2050**
Electrolyzer Capacity [GW]	0.1	0.6	9	10.8
Hydrogen demand [kton H2/year]	11.11	66.66	1000	1200

2.3. Renewable Potentials

The renewable potential analysis is carried out using the open-source tool pyGRETA (Kais Siala et al., 2022). The tool performs customizable land use eligibility analysis based on 38 different criteria (Ryberg et al., 2018) at a high spatial resolution of 250m x 250m to estimate the available locations and total potential of solar and onshore wind technologies of a given region. The tool also analyses exclusive economic zones up until a seabed depth of 50m to calculate the fixed offshore wind potential. In addition to potential calculation, the tool also reads historical weather data from MERRA-2 (Global Modeling and Assimilation Office (GMAO), 2015b, 2015a) and Global wind atlas (Global Wind Atlas 3.0, 2022) to calculate the hourly capacity factors of all possible locations. The detailed methodology is described in sources (Kais Siala et al., 2022) and (AUTHOR, 2024). Figure 2 shows the results of this analysis. The map on the left shows the locations of open field and roof top PV potentials and the map on the right shows the locations of onshore and offshore wind potentials considered in the energy model of Uruguay. The capacity factors for solar PV technologies are very similar across Uruguay as it is mostly latitude dependent. So, the total potential of 410 GW for Open field PV and 22 GW of Rooftop PV is considered to have the same hourly capacity factor time series. For wind technologies, the capacity factors are highly dependent on the location's geography and are different across the country. So even though the total onshore wind potential of Uruguay is much higher, only the highest two levels of locations are considered with 49.3% and 46.5% capacity factors, respectively. For simplicity within the model, the capacity factor of 54.2% taken from an average location is assumed for the offshore region. It should be noted that the capacity factors of this magnitude for wind technologies are one of the highest in the whole world, which makes them cost-competitive compared to PV technologies despite drastic cost reductions projected in the future for PV. See below section 2.4.

Figure 2. Renewable Energy Potentials from pyGRETA for Uruguay. Legend: Technology Potential Yearly Capacity Factor



2.4. Technoeconomic Data

The urbs model requires various techno-economic data inputs, including CAPEX and OPEX for all technologies, fuel costs, and broader economic parameters such as the Weighted Average Cost of Capital (WACC) and discount rates for long-term investments. For the technology-specific data, we intentionally minimized the number of different sources used. By relying on a limited set of sources, we ensured that the assumptions and methodologies applied across technologies are consistent, making comparisons between them fairer and uniform. This approach reduces the risk of discrepancies that could arise from using data with varying underlying assumptions, thereby enabling a more balanced evaluation of the different technologies. Investment and operational costs vary significantly across regions, particularly Latin America. To estimate the specific costs for Uruguay, we employed the methodology introduced by the Inter-American Development Bank in their report on optimizing the Latin American electrical system (Inter-American Development Bank & Paredes, 2017).

Table 3. Sources for the Country and Temporal-specific Input Techno-economic data

Technology	Techno-economic Data	Source
Power plants	Investment costs, Operational Costs, Efficiency, Fuel Costs	Brazil Net Zero Emissions by 2050. (International Energy Agency, 2022)
	Lifetime	(NREL (National Renewable Energy Laboratory), 2023)
	Country Cost factor	(Inter-American Development Bank & Paredes, 2017)
Electrolyzers	Investment costs, Operational Costs, Lifetime	≥100MW EPRI Low Range including STACK+ BOP. (EPRI, 2023)
	Efficiency	Efficiency Assumptions based on (IRENA, 2020)
Batteries	Investment costs, Operational Costs, Efficiency, Lifetime	Advanced Scenario. (NREL (National Renewable Energy Laboratory), 2023)
Hydrogen Storage	Compressor (Investment costs, Operational Costs, Efficiency, Lifetime)	(Wang et al., 2012)
	Container (Investment costs, Operational Costs, Efficiency, Lifetime)	(Ibagon et al., 2023)

This approach involves recalculating investment and fuel costs for each country in the region, by using specific factors per technology and fuel. In our case we use Brazil as a baseline and recalculated the factors. For all technologies, we utilized the Net Zero 2050 scenario values, using Brazil as the baseline. The only exception was Rooftop PV, for which we selected techno-economic data from Europe instead of Brazil, due to the significantly lower costs reported for Brazil. According to market reports, such as the recent ones from Wood Mackenzie (Mackenzie, 2023, 2024), the current range for rooftop PV in Brazil is between 1200 to 1500 USD/kW, which aligns more closely with the European starting point of 1120 USD/kW in 2021. The Table 3 summarizes the matching of different data sources used to create the country-specific and year-specific input data.

As previously mentioned, key economic parameters still need to be defined. Studies by (Steinbach & Staniaszek, 2015), (García-Gusano et al., 2016), and the (OECD, 2021), have specifically examined the role of discount rates and the Weighted Average Cost of Capital (WACC) in energy system models, highlighting their influence on long-term investment outcomes. The WACC is crucial for assessing investments, representing the cost of capital in a region and sector, while the social discount rate reflects the time value of money and opportunity cost of capital. Lower discount rates favor renewable energy, while higher rates favor fossil fuels. Due to economic uncertainty in Latin America, adopting a default WACC is inappropriate. Therefore, a region-specific WACC for Uruguay was defined using an approach proposed in the PTX Business Opportunity Analyser tool (Oeko-Institut, 2023), where country-specific Equity Risk Premiums (Damodaran, 2024) are used, resulting in a WACC of 7.38%, compared to the 5% in Uruguay's Hydrogen Roadmap. The WACC will be applied uniformly across all timeframes due to the lack of a reliable projection method. The study also adopted an average social discount rate of 3.894% for South America, based on recommendations for Latin American countries (Moore et al., 2020).

This methodology creates a relevant and adaptable database for the region.

Based on the techno-economic data discussed in this section and the estimated capacity factors for different renewables from above section 2.3, the Levelized cost of Electricity from Open-field PV will decrease considerably from 48 USD/MWh in 2020 to 22 USD/MWh in 2050. For onshore wind, the decrease is from 29-31 USD/MWh in 2020 to only 25-27 USD/MWh in 2050. For offshore wind, LCOE decreases from 101 USD/MWh in 2020 to 41 USD/MWh.

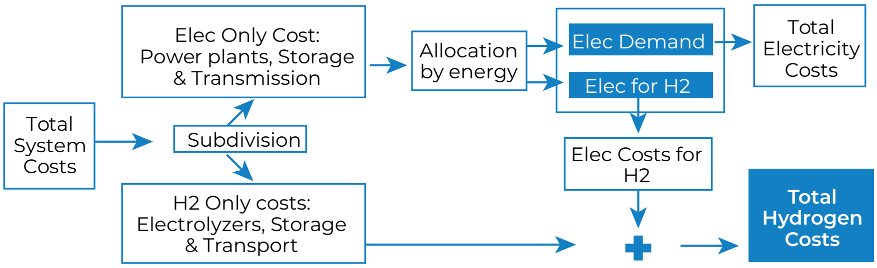
2.5. Levelized cost of Electricity and Hydrogen

To calculate the levelized cost of electricity and hydrogen, we consider their interrelation, as the electrical infrastructure is affected by hydrogen production. Using the urbs framework, our objective is to minimize total global costs for both electricity generation and hydrogen production. To be able to assign the costs between these two products we will use a methodology and approach commonly used in life cycle analysis called subdivision and complemented by allocation, the graphical description of the process can be seen in Figure 3.

Subdivision tries to assign inputs, flows, or, in our case, costs to the singular products. The second approach, allocation, distributes the effects and impacts of a system equitably based on specific characteristics of the co-products. For the subdivision step, the investment, fix, and fuel costs to produce electricity, as well as batteries and their costs, are assigned to electricity generation, and the costs only related to hydrogen such as costs for electrolyzers and H2-Storage are assigned to hydrogen production. For the allocation step, we take into account that the total electricity that gets produced is used as a direct electricity demand and also used in the electrolyzer, so the total electricity generation costs, are allocated between the electricity demand and hydrogen production, this costs of the electricity used for H2 production get summed to the costs which were only related to H2 and this constitutes our total hydrogen costs.

This method ensures a fair distribution of investment and operational costs, recognizing that higher hydrogen demand requires additional investment in the electrical system but may also enable greater integration of low-cost renewable energies. This approach is suitable because our model optimizes the overall system costs, ensuring fair cost and benefit assignment given the interrelated nature of electricity and hydrogen production.

Figure 3. Methodology used for the cost distribution among the products, commodities or sectors



2.6. Scenario definition

To analyze the energy model and system optimization for hydrogen production and electricity generation in Uruguay, which aims to produce and export hydrogen, three distinct scenarios were developed:

Baseline Scenario (Only Electricity): This scenario represents the expected evolution of the energy system without implementing a hydrogen economy. It serves as a reference point, illustrating the system's behavior under current policies and technologies focused solely on electricity supply. The model simulates the current trajectory of the energy system, highlighting potential challenges and limitations in meeting future electricity demands without hydrogen integration.

National Hydrogen Roadmap Implementation (H2 Roadmap): This scenario models the implementation of the country's national hydrogen roadmap. Specific goals for hydrogen production and utilization are set for each year, reflecting the government's strategic plan to integrate hydrogen into the national energy mix. The roadmap includes targets for hydrogen production capacities, and infrastructure development. The model evaluates the roadmap's targets, assessing the required capacities, investments, and resulting costs.

Market-Driven Hydrogen Production (1 to 3 USD/kg H2): In this set of scenarios, a price signal for hydrogen is introduced, allowing the model to determine the optimal production and export quantities based on profitability. The model assesses whether hydrogen production is economically viable and adjusts the production levels accordingly. Various price points are considered, which are kept constant throughout the analysis period to evaluate their impact on the global energy system. The model explores the economic dynamics of hydrogen production, considering various price signals and their influence on production decisions and export potential.

3. RESULTS AND DISCUSSION

The results show notable expansion within the electricity sector, driven by the increased demand necessitated by hydrogen production. The study thoroughly evaluates the generation matrix, Hydrogen production quantities, and their corresponding levelized costs. The information from all figures can also be found in the supplementary material.

Figure 4. Installed Capacities for electricity generation per scenario and year.

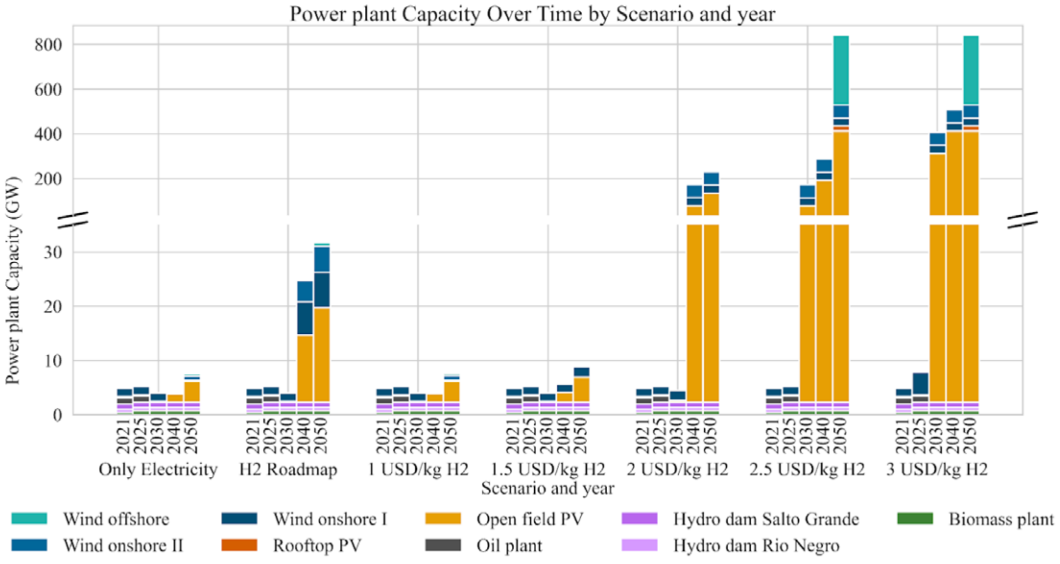
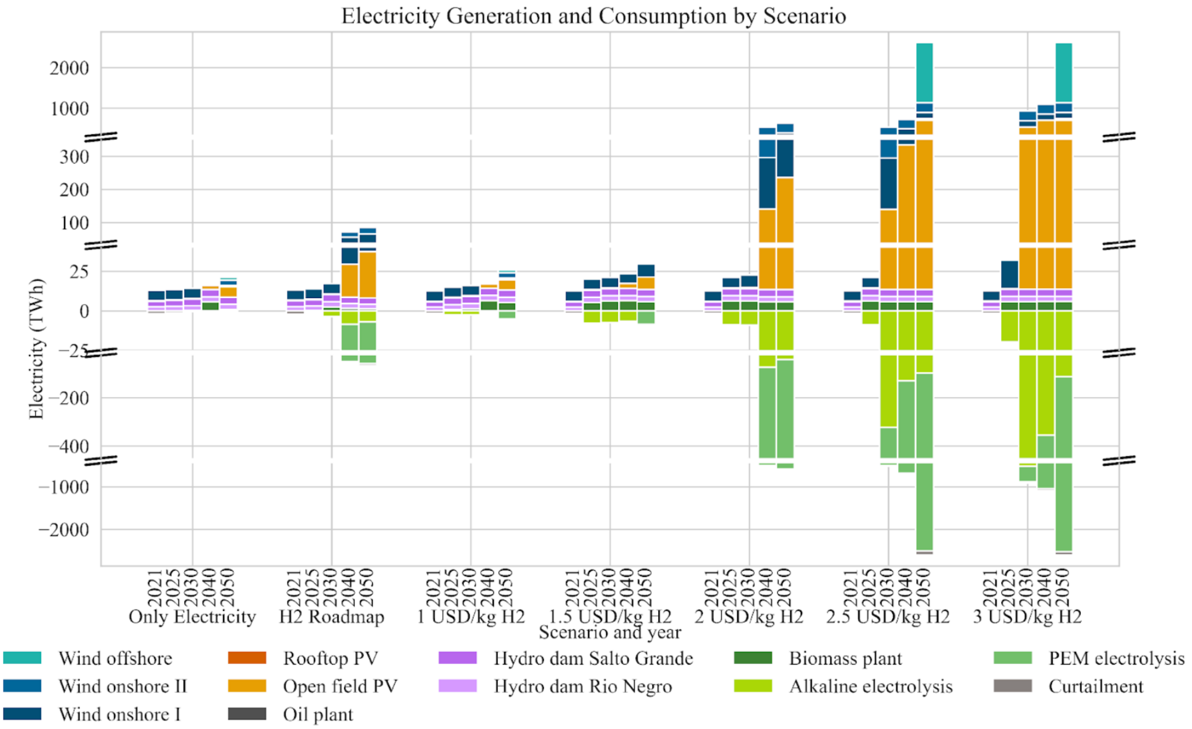


Figure 4 illustrates the installed capacities, and Figure 5 the electricity generation and consumption per scenario and year. In the only electricity scenario, there is minimal expansion up to 2025 and 2030, with the only changes being the addition of an already planned biomass plant and the decommissioning of the oil plant. Hydropower plants provide enough flexibility to meet electricity needs despite lower capacity. By 2040, significant changes occur as existing renewable energy plants end their life. Photovoltaic (PV) capacity increases significantly by 2040 and 2050. On the contrary, onshore wind capacity will decrease, while offshore wind will see new installations by 2050.

Regarding electricity generation and consumption, in all scenarios, the year 2021 shows minimal differences in technology and curtailment, with the electricity mix remaining relatively stable. Approximately 44% of electricity comes from hydropower, 50% from onshore wind, 2.6% from biomass, and the remainder from PV. However, at least 11.8% of generated electricity is curtailed in 2021.

In the electricity-only scenario, there are no significant changes in subsequent years. By 2040, new large-scale renewables are not expected with the decommissioning of existing renewable energy sources, so biomass must provide around 5 TWh of electricity. In 2050, with a larger expansion and diversification of renewables, biomass returns to operating as a peak power plant.

Figure 5. Electricity generation and consumption per scenario and year.

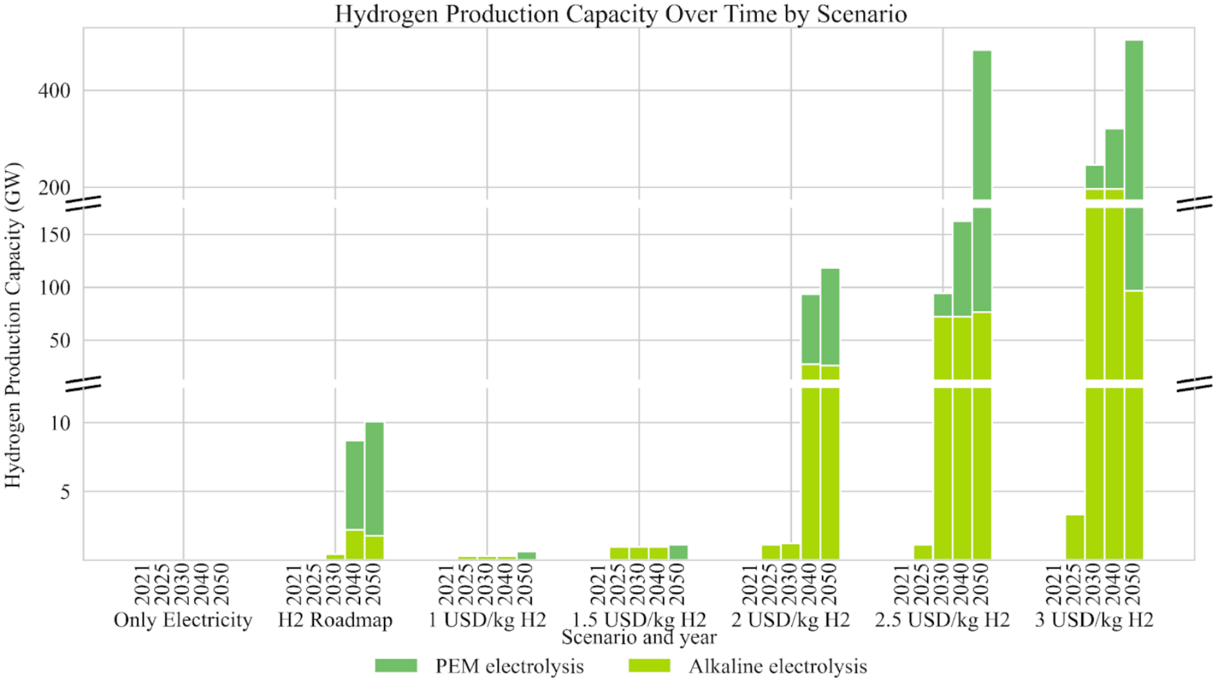


In the hydrogen roadmap implementation scenario, the installed capacity for 2021, 2025, and 2030 mirrors the electricity-only scenario, with existing renewable energies and planned expansions being sufficient for the early stages. By 2040, significant hydrogen demand and depreciated renewables necessitate substantial expansion, with PV, onshore wind, and offshore wind capacities increasing by 2040 and 2050. This scenario requires in total 22.4 GW of renewables by 2040, exceeding the 18 GW new RE target in the official roadmap. The new installations contrast sharply with the existing capacity and expected evolution.

The hydrogen roadmap scenario is quite similar to the electricity-only scenario in 2025 regarding electricity generation and consumption, with some curtailment replaced by hydrogen production. By 2030, curtailment is fully replaced by hydrogen production, and biomass plants operate supply electricity for electrolyzer. In 2040 and 2050, the expansion of renewables, supported by flexibility measures, allows direct operation of electrolyzers. However, 23% of electricity is curtailed in 2040 and 29% in 2050.

For the market-driven hydrogen production scenarios, results vary widely based on the given hydrogen prices. In the initial years (2021 and 2025), installed capacities remain similar to the only electricity scenario, except for the 3 USD/kg H2 scenario, which sees additional onshore wind by 2025. By 2030, higher price scenarios (2.5 and 3 USD/kg H2) show significant PV and onshore wind capacity expansions. From 2040 onwards, scenarios diverge more. The 1 USD/kg H2 remains similar to the electricity scenario, while the 2 USD/kg H2 fully exploits onshore wind potential and adds 75 GW of PV by 2050. Higher price scenarios (2.5 and 3 USD/kg H2) achieve maximum potential for PV and wind offshore by 2050.

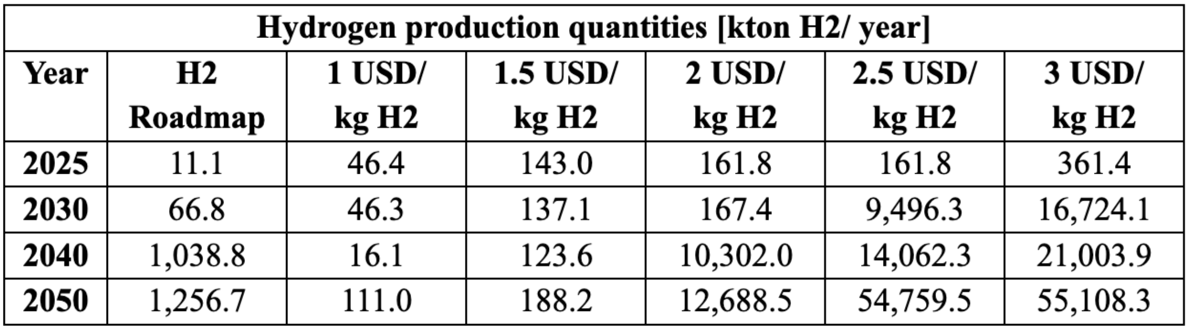
Figure 6. Electrolyzer capacity through the years and scenarios



As a perspective, the Table 4 shows the produced hydrogen per year and scenario. The orders of magnitude among scenarios are not comparable; they show the magnitude of the possible market that Uruguay could have under favorable conditions. In lower price scenarios (1 and 1.5 USD/kg H2), in the first years, hydrogen production is driven by the full utilization of existing power plants, specifically the biomass plant. In 2040, the increase in the electricity demand and the decommissioning of older PV and wind plants will lead to a reduction of available surplus electricity and, therefore, a reduction in hydrogen production in the 1 USD scenario and a slight reduction in the 1.5 USD scenario. In 2050, due to price reductions, it is worthwhile to further expand renewable energies, and hydrogen production will increase again. Electric generation and hydrogen production grow significantly for the higher price scenarios (2, 2.5, and 3 USD/kg H2).

Some curtailment remains, but most electricity produced is used for hydrogen production. This shift means that electricity demand becomes a secondary service, with the primary goal being hydrogen production. According to our model, this would be profitable for the country, but the actual implications for infrastructure, including electricity and hydrogen transport, as well as river transport, maritime, and port infrastructure, are not considered.

Table 4. Hydrogen production quantities in the different scenarios and years.



Hydrogen production quantities [kton H2/ year]						
Year	**H2 Roadmap**	**1 USD/ kg H2**	**1.5 USD/ kg H2**	**2 USD/ kg H2**	**2.5 USD/ kg H2**	**3 USD/ kg H2**
2025	11.1	46.4	143.0	161.8	161.8	361.4
2030	66.8	46.3	137.1	167.4	9,496.3	16,724.1
2040	1,038.8	16.1	123.6	10,302.0	14,062.3	21,003.9
2050	1,256.7	111.0	188.2	12,688.5	54,759.5	55,108.3

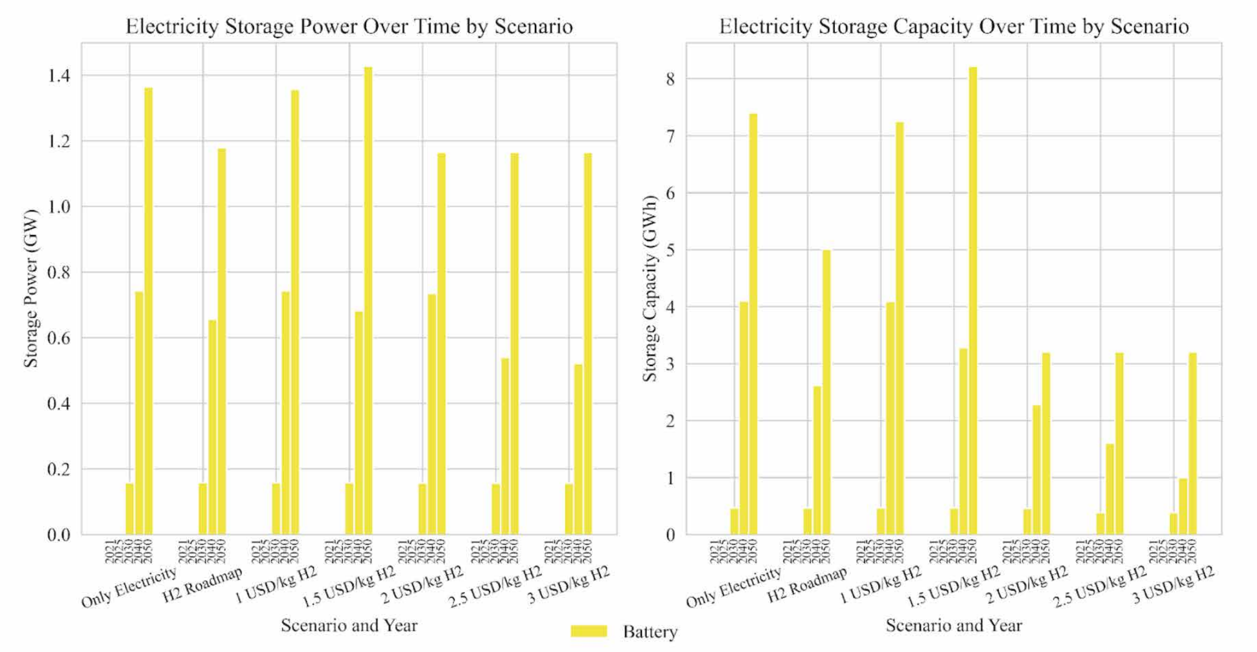
Regarding the hydrogen production system, Figure 6 shows the required electrolyzer capacity expansion across different scenarios. The roadmap scenario differs to the values given in the official hydrogen roadmap, for 2025 approximately 70 MW of electrolyzer are required, in comparison to the 100 MW reported, in 2040 0.43 GW vs 0.6 GW, in 2040 8.69 GW vs 9 GW. These differences can be explained by the difference in the utilization of the electrolyzers; here, they are operated for more hours, so for the same hydrogen demand, you require less electrolyzer capacity. In the Hydrogen roadmap, most projects are assumed as off-grid systems, whether they are fully Wind, PV or PV+Wind operated, and therefore with lower utilization hours.

In market price scenarios, varying hydrogen prices lead to different scales of electrolyzer capacity expansion. The 1 USD/kg H2 scenario maintains modest growth with around 290.6 MW of alkaline electrolyzers until 2040. As prices increase, significant expansions occur. The 2 USD/kg H2 scenario reaches about 27.2 GW by 2040 and 118.5 GW by 2050. The 2.5 USD/kg H2 scenario sees even more growth, with capacities reaching around 113 GW by 2040 and 482.4 GW by 2050. The highest price scenario of 3 USD/kg H2 shows exponential growth, achieving around 320.9 GW by 2040 and 503.8 GW by 2050, illustrating potential massive scale-up under favorable economic conditions.

Technological changes occur over time, with alkaline electrolyzers initially dominant. By 2040, PEM electrolyzers become competitive due to increased efficiency, and by 2050, new installations are about 80% PEM and 20% alkaline for scenarios with capacities above 2 GW.

Regarding the installed battery capacity and power, the Figure 7 shows the results. Battery expansion becomes necessary by 2030 in all scenarios, with hydro dams providing flexibility until then. A synergy between the electrical system and hydrogen production reduces power capacity needs in scenarios with significant hydrogen production. Storage capacity is notably reduced in the H2 roadmap and extreme hydrogen scenarios (2, 2.5, and 3 USD/kg H2), especially by 2050.

Figure 7. Battery capacity and power according to the scenario and year

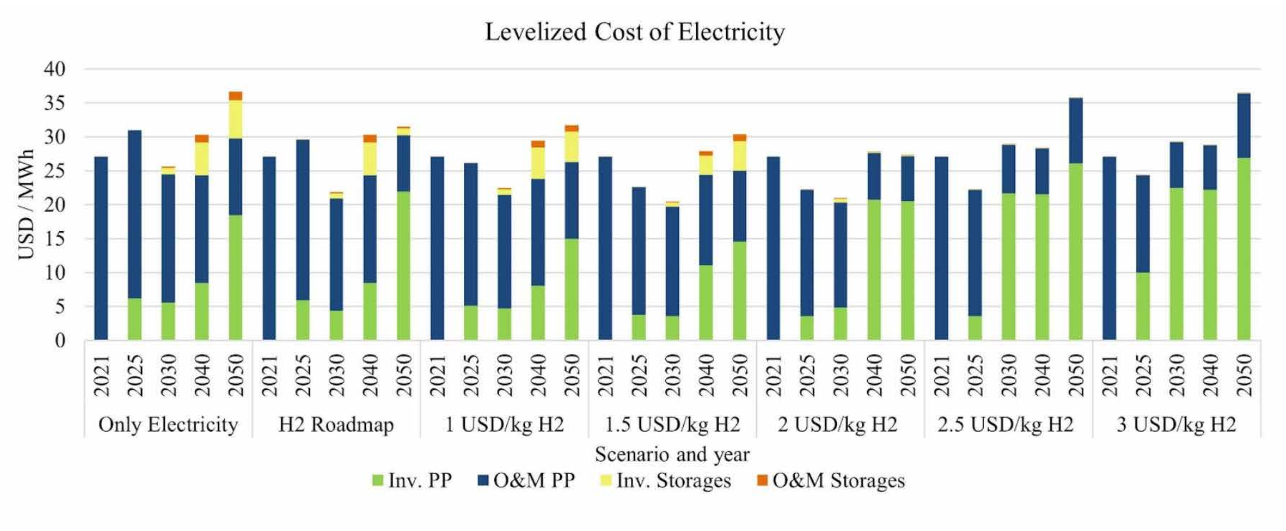


Another technology that delivers flexibility to the system are hydrogen tanks for H2 storage, with significant expansions in the H2 roadmap scenario. By 2050, hydrogen tanks are about 50% of installed electrolyzer capacities but below 7.5% of yearly hydrogen demand. The H2 roadmap scenario requires hydrogen tanks due to constant yearly hydrogen demand, necessitating storage to shift hydrogen delivery to low production hours. In market price scenarios, hydrogen is sold directly once produced, eliminating the need for production shifting.

3.1. LCOE

Figure 8 presents the LCOE for each year and scenario; it shows a shift from operation and maintenance cost-based to investment cost-based systems due to renewable energy expansion. LCOE reacts to investment decisions, which can either increase or decrease it, depending on the utilization of new capacity, as seen in 2025 in the different scenarios. In the "Only electricity" and "H2 Roadmap" scenarios, LCOE increases because the new biomass plant isn't used, while in other scenarios, it reduces overall costs by producing useful electricity. Having huge flexible hydrogen production (scenarios 2, 2.5, and 3 USD/kg H2) decreases the need for battery flexibility. For example, in the "Only electricity" scenario, batteries account for about 6 USD/MWh in LCOE in 2040 and 2050. The LCOE for the "Only electricity" scenario tends to be higher due to the fact there is no other sector or product to share them with, and all capacity expansion costs are solely to electricity. This means that integrating and expanding the system based on hydrogen market prices benefits the country and electricity consumers, promoting renewable energy expansion and lowering LCOE. The only exception is in 2030, where significant capacity expansions in the 2.5 and 3 USD/kg H2 scenarios cause higher LCOEs. Despite different power plant expansions, LCOE remains relatively stable, indicating cost-optimal decisions.

Figure 8. Levelized cost of electricity, by cost categories. Inv: investment. PP: power plants. O&M: Operation and maintenance, including fuel

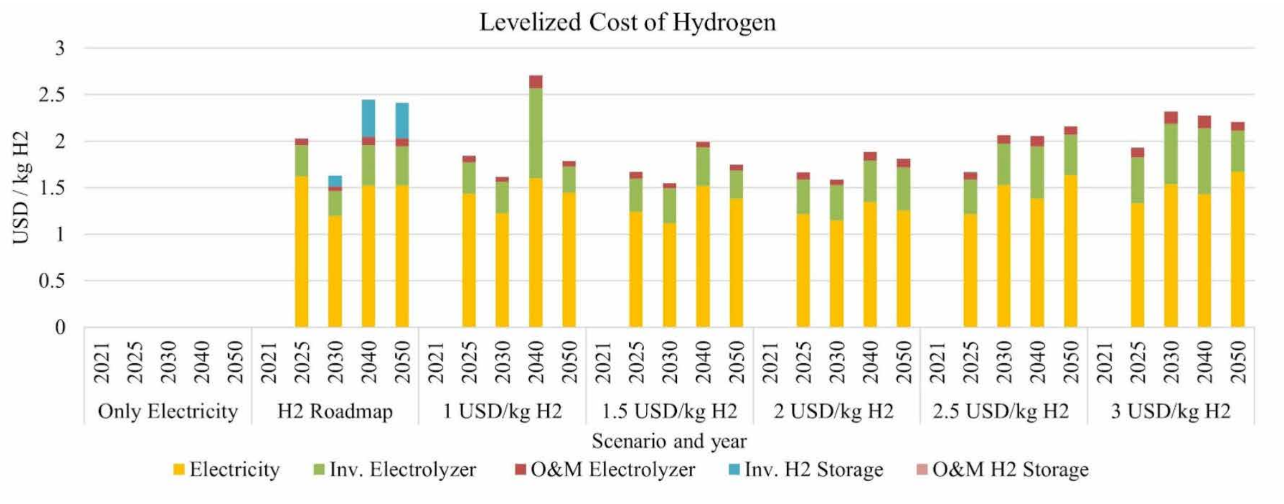


3.2. LCOH

Figure 9 shows the LCOH divided into different cost categories for various scenarios and years. The most significant costs in the LCOH come from the electricity used for hydrogen production, making LCOH closely related to LCOE and reflecting its changes over time. LCOH also depends on the capacity expansion of the hydrogen system, including electrolyzer and hydrogen tank capacities. Due to the modeling assumptions hydrogen storage is only required in the H2 roadmap scenario, adding costs in 2030, 2040, and 2050 in line with storage costs reported in the roadmap (Ministerio de Industria, Energía y Minería, 2023b).

The “H2 Roadmap” scenario indicates that a scale mismatch in the early years (2025 and 2030) can cause higher LCOH due to underutilized electricity systems. In 2040, a significant demand increase leads to a peak in costs driven by storage and electrolyzer investments. In the 1 and 1.5 USD scenarios, LCOHs are above market prices, but the model optimizes total costs by expanding electrolyzers to use otherwise curtailed electricity. This results in higher costs in 2040 due to reduced surplus electricity and limited infrastructure use. For higher price scenarios (2, 2.5, and 3 USD), LCOHs are below market prices, leading to large expansions and high production quantities. Overall, LCOHs tend to decrease over time, with increases during expansion years. Despite different development scenarios for Uruguay’s electricity and hydrogen systems until 2050, LCOH remains relatively homogeneous, following similar trends.

Figure 9. Levelized cost of hydrogen, by cost categories. Inv: investment. O&M: Operation and maintenance, including fuel costs.



4. RESULTS AND DISCUSSION

This work presents a methodology for assigning and distributing costs for a system with co-production of two or more commodities; this methodology can be applied to any energy system that analyzes sector coupling. We also present a comprehensive methodology for deriving all input data, such as demands, year-specific and country-specific CAPEX and OPEX, and economic factors, such as WACC and discount rates. The study presents different scenarios for optimizing Uruguay's electricity and hydrogen systems. Each scenario demonstrates distinct pathways for the evolution of the energy system, highlighting the potential impacts of integrating hydrogen production on installed capacities, electricity generation, and consumption patterns.

The research highlights the strategic role of hydropower and the necessity of battery storage in maintaining grid stability and enhancing system efficiency, particularly to support renewable energy expansions in photovoltaic and wind power.

The research also emphasizes the potential economic benefits of the hydrogen roadmap, including reduced electricity costs for domestic consumers and the promotion of renewable energy sources with costs. The findings suggest that, under favorable market conditions, hydrogen production could significantly contribute to Uruguay's economy, positioning the country as a major hydrogen exporter.

Recommendations for policymakers and stakeholders include investing in renewable energy capacities and hydrogen production, storage, and transportation infrastructure; developing robust market conditions and incentives for integrated renewable energy investments and electrolyzer capacities; exploring the implications for river, maritime, and port infrastructure to handle hydrogen transport and export; and investigating advancements in electrolyzer technologies and flexibility measures to enhance system efficiency and reduce costs.

In conclusion, this study provides valuable insights into optimizing Uruguay's electricity and hydrogen systems, demonstrating the transformative potential of integrating hydrogen production into the national energy mix. The research offers a roadmap for policymakers and stakeholders to navigate the energy transition, emphasizing the importance of strategic planning, infrastructure investment, and supportive policies to realize the full potential of hydrogen as a key component of Uruguay's sustainable energy future.

5. ACKNOWLEDGMENTS

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Solar energy time series analysis via markov chains

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Resumen

Brasil, ante un escenario global de preocupación por el cambio climático, viene incrementando el uso de energías renovables, especialmente la energía solar en los últimos años. Con el crecimiento de su participación, las características de la energía solar, como la intermitencia y las fluctuaciones aleatorias, vienen afectando la planificación de la operación del Sistema Eléctrico Brasileño (SBE). Tales factores pueden ser estudiados con modelos de series de tiempo, auxiliando la planificación de plantas generadoras y SBE. Con el fin de contribuir al análisis factorial, el objetivo de esta investigación es analizar las características de la generación de energía fotovoltaica en las estaciones meteorológicas del año en dos regiones de Brasil con diferentes incidencias solares. Para ello, se aplica una metodología basada en conceptos de Cadenas de Markov para dos series de tiempo estacionarias. El trabajo se destaca por la subdivisión de las series de tiempo entre las estaciones climáticas, por el uso de datos aún no estudiados y por la presentación de la metodología y resultados en detalle. El objetivo de la investigación fue alcanzado con éxito, evidenciando las diferencias entre los modelos de generación de energía solar entre las estaciones meteorológicas y las dos regiones estudiadas.

PALABRAS CLAVE: Fuentes de Energía Renovable, Fuentes de Energía Variables, Energía Solar, Estaciones Climáticas, Cadenas de Markov, K-means

Abstract

Brazil, given a global scenario of concern with climate change, has been increasing the use of renewable energy, especially solar energy in the last years. With the growth in its participation, the characteristics of solar energy, such as intermittence and random fluctuations, have been affecting the operation planning of the Brazilian Electricity System (BES). Such factors can be studied with time series modeling, helping the planning of power plants and BES. In order to contribute to the factor analysis, the objective of this research is to analyze the characteristics of photovoltaic energy generation in the meteorological seasons of the year in two regions of Brazil with different solar incidences. For this, a methodology based on Markov Chain concepts is applied for two stationary time series. The work stands out for the subdivision of the time series between the climatic seasons, for the use of data not yet studied and for the presentation of the methodology and results in detail. The objective of the research was successfully achieved, making evident the differences between the solar energy generation models between the meteorological seasons and the two regions studied.

KEYWORDS: Renewable Energy Sources, Variable Energy Sources, Solar Energy, Climatic Seasons, Markov Chains, K-means

1. INTRODUCTION

Faced with a scenario of concern about climate change, countries are carrying out the energy transition, thus moving away from using fossil energy sources and increasing the use of renewable sources (Malar, 2022). According to the International Renewable Energy Agency (2023), the planet had an increase in renewable energy capacity in 2022 of 13% compared to the previous year. Renewable energies are considered inexhaustible, as they can always be renewed by nature, and generate considerably lower environmental impacts than non-renewable energies (EPE, 2022).

Brazil has been following this transformation in the world's energy matrix. According to the 2023 National Energy Balance, 47.4% of Brazil's domestic energy supply in 2022 came from renewable sources. In 2013, this percentage was 40.6%, that is, in 9 years, there was an increase of approximately 17% (EPE, 2023).

In this context, solar energy is a source that deserves to be highlighted. In 2022, it accounted for 3.6% of the domestic energy supply in Brazil. In addition, between 2021 and 2022, it had an 82.4% growth in installed capacity, being the fastest growing in the country (EPE, 2023). With the increase in its use in Brazil, its characteristics, such as intermittency and random fluctuations, will affect even more the country's energy generation. Solar energy is generated from solar radiation, captured by photovoltaic panels. In addition to being renewable, it has the advantages of being silent, requiring little maintenance and being able to be installed in a short time (Imhoff, 2007). With the increase in its use in Brazil, its characteristics, such as intermittency and random fluctuations, will increasingly affect the country's energy generation. Considering this scenario, the use of time series modeling and simulation methods to study this impact is important for the planning of the plants and the BES.

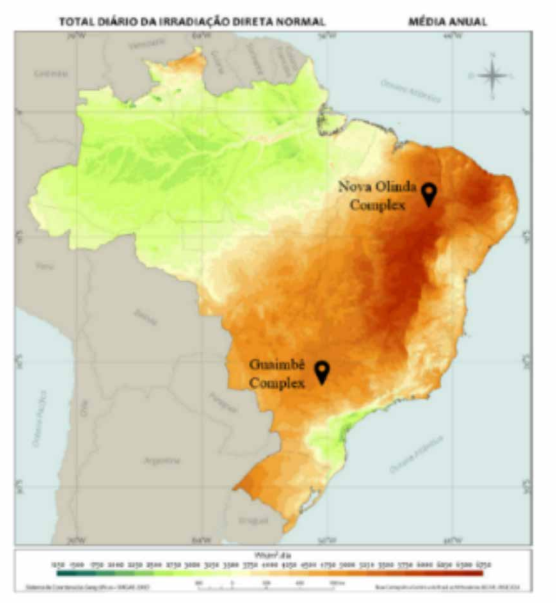
In order to contribute to this theme, the objective of this work is to analyze the characteristics of photovoltaic energy generation in different climatic seasons (summer, autumn, winter and spring) in two regions of Brazil with different solar incidences. For this, the time series discretization approach was used for Markov Chain modeling, a methodology already widely used in the literature for the analysis of electric energy time series. Furthermore, the subdivision by climatic season differs from other studies because it is based on a natural phenomenon, as opposed to monthly subdivisions, which are more frequently used, for example.

It is worth noting that this study presents relevant differentials in the literature. In the first place, to the authors' knowledge, data that have not yet been studied are used. Also, these data are from two plants located in regions with considerably different characteristics and were divided by the climatic seasons of the year, which allowed both geographical and temporal comparisons.

The analysis presented in the study was carried out through two daily photovoltaic energy generation databases from ONS (National Electric System Operator): Nova Olinda Complex, located in Piauí (PI) and founded in 2017 (G1, 2017); and Guaimbê Complex, located in the state of São Paulo (SP) and inaugurated in 2019 (G1, 2019). According to Gadelha de Lima (2020), the state of Piauí has different meteorological characteristics depending on the quarter of the year, which could justify a division into four seasons.

Figure 1 shows the location of the two plants on the brazilian solarimetric map. This map is an adaptation of the one presented in the Brazilian Atlas of Solar Energy (Pereira et al., 2017) and shows the annual average of the total daily normal direct irradiation over Brazil. It is possible to perceive the difference in the averages of direct irradiation between the two locations of the plants, which is greater in the Nova Olinda Complex (Ribeira do Piauí – PI) in relation to the Guaimbê Complex (Guaimbê – SP).

Figure 1 - Brazilian Solarimetric Map - Average annual normal direct irradiation.



Source: Adapted from Pereira et al. (2017).

The applied methodology is exploratory and can be divided into three main phases. The first relates to data pre-processing, including data collection, analysis, and treatment. In the second phase, data processing is performed, involving modeling via Markov Chains and obtaining results such as stationary distribution, recurrence time, and first passage time. In the last phase, data post-processing, the results obtained were analyzed for comparison between the climatic seasons and between the plants.

2. THEORETICAL FRAMEWORK

In the literature, there are several renewable energy modeling studies that apply the concept of Markov Chains in their methodologies. Sigauke and Chikobvu (2017) performed an analysis of daily peaks of electricity demand through Markov Chains, seeking to find the stationary distribution (distribution of states in which the chain will stabilize). To do this, the authors used demand data from South Africa from 2000 to 2011. Models with two states were considered, being the positive or negative variations between the days, and with three states, where the difference between small and large positive variations was considered.

Maçaira et al. (2019), faced with a scenario of increased wind energy use in Brazil, showed that the dispatch model used in the period of their research did not consider the stochastic behavior of this energy source. The model, which sought to optimize long-term energy planning, only evaluated the future aspects of water and thermal sources. In view of this, the work proposed the wind-hydrothermal dispatch model, which incorporated wind power generation using the MCMC (Markov-Chain Monte Carlo) method to simulate energy scenarios.

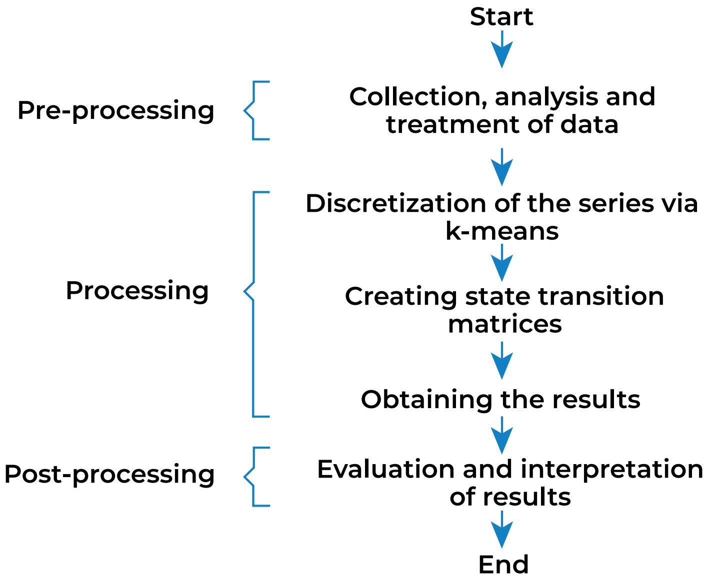
Ma et al. (2020) proposed a methodology for aggregating solar photovoltaic time series data through clustering via k-means, Markov Chains, and Monte Carlo simulation. For the authors, Markovian processes efficiently represent the transitions of photovoltaic power generation time series. Based on the proposed k-means-MCMC methodology, initially, the power generation data should be grouped following the optimal number of clusters, and then the transition matrix should be assembled. Finally, from this matrix, energy scenarios are generated via simulation.

Melo (2022) sought to show the spatial and temporal complementarity between variable renewable energies through the joint stochastic modeling and simulation of solar and wind energy. To this end, it used two methodologies and performs three applications, through databases of mills located in the Northeast of Brazil. Both methodologies use Markov Chain modeling, Monte Carlo simulation to obtain scenarios, and the k-means technique to perform data clustering.

3. METHODOLOGY

A methodology based on Markov Chains was applied to modeling the time series of photovoltaic solar power generation. Figure 2 shows the flowchart with the main stages of the methodology, divided into the data's pre-processing, processing, and post-processing phases.

Figure 2 - Main steps of the methodology.



3.1. Pre-processing

The pre-processing phase consists of obtaining, analyzing, and treating data. The data of the time series of daily photovoltaic energy generation of the Nova Olinda (Piauí) and Guaimbê (São Paulo) complexes were obtained from the National Electric System Operator (ONS, 2022) for a period of four years, from 06/21/2018 to 06/20/2022, with a total of 1,461 observations for each complex. The only two variables used were date and energy generation. According to Ma et al. (2020), due to the characteristics of photovoltaic power generation data, the optimal time scale to fragment scenarios would be daily. The methodology is applied first to the Nova Olinda Complex and then to the Guaimbê Complex, so the two series are worked separately in the modeling.

A preliminary analysis of the data obtained from energy generation during the period was performed. First, to test the stationarity of the time series over the four years, Augmented Dickey-Fuller (ADF) unit root tests were carried out. The null hypothesis of the ADF test is that there are unit roots in the time series and, therefore, it would not be stationary (Dickey, D.; Fuller, 1979). The stationarity test is essential for the application of the Markov Chain concepts, because a non-stationary series depends on time, and in Markovian processes, the probabilities of transition to the next state depend only on the current state (Norris, 1998). Furthermore, non-stationarity would mean a change in the installed capacity of the plants.

To complete the pre-processing phase, a treatment of the databases is carried out so that the time series can be modeled as Markov Chains. First, the null or missing values were replaced by the averages of the month in the corresponding year, as it is an adequate estimate for the value of generation in the period, given seasonality. Then, so that the time series could be analyzed by climatic season, they were subdivided into four subsets: Summer, Autumn, Winter, and Spring.

3.2. Processing

3.2.1 Series discretization via k-means

In order to group the observations with greater similarities, the subsets of the solar energy generation time series, divided by climatic season, were discretized into markovian states independently. The clustering method used was k-means (MacQueen, 1967), as it is easily programmable and computationally economical. In the k-means method, a number k of clusters is pre-specified, and initial k centroids (average value of clusters) are defined based on a random variable. Then, the following steps are performed: Observations are assigned to the nearest centroid cluster by calculating the distance from each observation to each centroid; New k centroids are calculated from the average of intra-cluster observations; Iterations of steps 1 and 2 are performed until the centroid values do not change further The method can be summarized by the objective function (1).

$$J = \sum_{j=1}^{k} \sum_{i=1}^{n} \|x_i^{(j)} - c_j\|^2 \qquad (1)$$

However, to apply the k-means method, it is necessary to pre-define the number k of clusters. According to Fritz et al. (2020), choosing the wrong values for k can lead to poor results, and to choose the ideal number of clusters, it is common to use the elbow method, first discussed by Thorndike (1953). As the number of clusters increases, the sum of the squared error of the distance between the observations and the centroids tends to decrease (Thorndike, 1953). Hence, the elbow method helps to limit the choice of very high values for k, in which there are no relevant benefits with the addition of a new cluster. The elbow method can be used in conjunction with the k-means method to find the optimal number of clusters (Fritz et al., 2020).

To apply the elbow method using k-means, it is first necessary to perform the k-means steps for each k-value up to a chosen maximum number. Then, the sum of the intra-cluster squared error, or Within-Cluster-Sum of Squared Errors (WSS), is calculated for each clustering obtained by the k-means result. The WSS consists of the sum of the square of the euclidean distances from each observation to the centroid of the cluster to which it belongs.

Consequently, a graph can be created that presents the WSS for each value of k. So it is possible to observe the point k at which the curve presents a “fold”, like an elbow, and it can be inferred that the difference between the WSS of k and k+1 would not provide substantial gains to clustering.

3.2.2 Creating State Transition Matrices

The next step is to create the daily transition matrices of states, P. Transition matrices are composed of the transition probabilities pi,j between a state i and a state j between a period n and n+1 (Chung, 1960). The transition probabilities and transition matrices are represented by (2) and (3), respectively.

$$P\{x_n(\omega) = j \mid x_{n-1}(\omega) = i\} = p_{i,\,j} \quad (2)$$

$$P = \begin{pmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,k-1} & p_{1,k} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,k-1} & p_{2,k} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ p_{k-1,1} & p_{k-1,2} & \cdots & p_{k-1,k-1} & p_{k-1,k} \\ p_{k,1} & p_{k,2} & \cdots & p_{k,k-1} & p_{k,k} \end{pmatrix} \quad (3)$$

In this step, based on Melo (2022) and Ma et al. (2020), the transition probabilities are calculated by the ratio between the number of occurrences of transitions from state i to state j and the total occurrences of transitions from state I, as represented by (4).

$$p_{i,j} = \frac{n_{i,j}}{\sum_{a=1}^{k} n_{i,a}} \qquad (4)$$

3.2.3 Obtaining the results

To analyze the properties of the transition matrices, three measures of interest were calculated: Stationary distribution (π) - represents the distribution of states in which the chain will stabilize, satisfying the equations (5) and (6); Recurrence time (mii) - the expected number of periods for a system in state i to return to that state again, as in the equation (7); First passage time (mij) - The number of periods expected for a system in state i to first passage through state j, as in the equation (8) (Chung, 1960).

$$\pi_j = \sum_{i=0}^{M} \pi_i p_{ij} \; \forall \, j = 0, 1, \ldots, M \tag{5}$$

$$\sum_{i=0}^{M} \pi_j = 1 \tag{6}$$

$$m_{ii} = \frac{1}{\pi_i} \; \forall \, i = 0, 1, \ldots, M \tag{7}$$

$$m_{ij} = 1 + \sum_{k \neq j} p_{ik} m_{kj} \tag{8}$$

Interpreting the above concepts, the measures presented are important to assist in analyzing the behavior of the Markov Chains model when the process stabilizes. With a stationary distribution, it is possible to identify the most frequent states of the system, where the process is most likely to be in the future. The recurrence time allows us to understand, for example, the average time to return to a state of maximum or minimum energy generation, while the first passage time would indicate the average transition time between these two states.

3.3. Post-processing

Finally, in the post-processing phase, the analysis and evaluation of the results obtained in the previous phase were carried out, with the objective of analyzing the characteristics of the generation of the two plants in the four climatic seasons and in regions of Brazil with different solar incidences. In this phase, the main purposes were: to identify the most frequent states of each season; to compare the recurrence times of the most extreme power generation states; and to compare the first passage times between the states of highest and lowest power generation of each climatic season.

4. DISCUSSION AND PRESENTATION OF RESULTS

In this chapter, the results of the methodology's application are presented for the two plants individually, starting with the Nova Olinda Complex (PI) and, later, addressing the Guaimbê Complex (SP). Finally, the results of the two plants are compared. All the computational steps in this chapter were performed in the R® programming language (R Development Core Team, 2009).

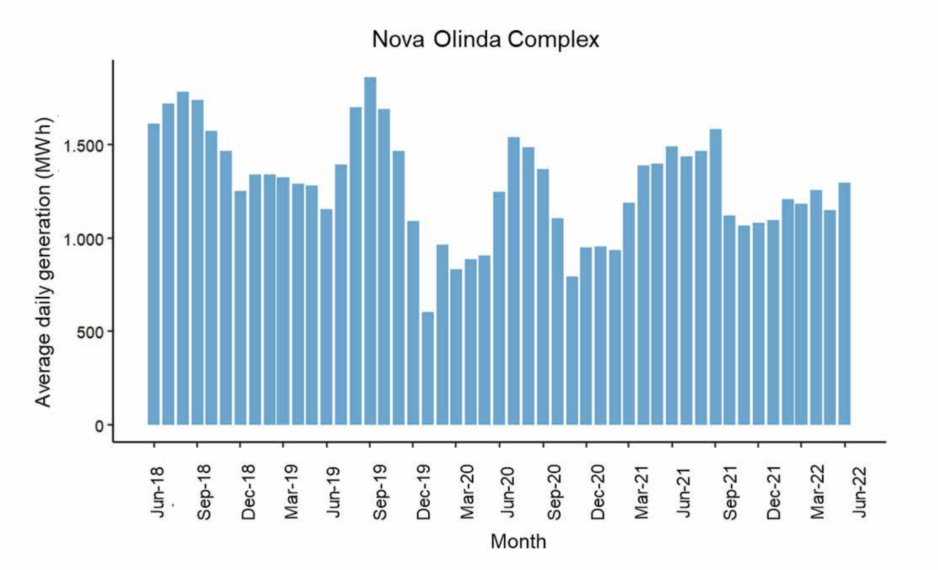
4.1. Nova Olinda Complex (Piauí)

4.1.1 Pre-processing

4.1.1.1 Collection, analysis and treatment of data

When testing the stationarity of the time series of the Nova Olinda Complex in the analyzed period, the result obtained was a p-value lower than 0.01, i.e., the null hypothesis that the time series would not be stationary is rejected. Thus, it is concluded that the time series is stationary and, therefore, the installed capacity is constant, which is fundamental for the Markov Chain modeling performed in this work. The stationarity of the time series in the period can be seen in Figure 3, which represents the average daily generation per month. In addition, the series presents considerable volatility and annual seasonality, with higher energy generation in the months of July, August, and September and lower generation in the months of December, January, February, and March, while the other months assume intermediate energy generation values. It is possible to notice greater similarities in the data in the months of the same climatic season. Due to this observation, an opportunity is identified to model the time series by subdividing it into four subsets, one for each climatic season, for a better representation of the data in each period.

Figure 3 - Average daily generation - Nova Olinda Complex.



Source: Based on data from ONS (2022).

Table 1 shows that winter has the highest daily average of energy generation in the Nova Olinda Complex in Piauí, with 1,572.87 MWh/day. Meanwhile, the summer has a daily average of 32% lower than that of winter, with 1,066.39 MWh/day, probably due to a higher number of cloudy days in this period of the year, which reduces the average daily solar radiation in the region of the plant. Furthermore, it is also possible to note that winter has the lowest standard deviation, while spring, the second season with the highest average energy generation, has the highest standard deviation, therefore, a greater dispersion of data.

Table 1: Measures of daily energy generation - Nova Olinda Complex.

	General	Summer	Autumn	Winter	Spring
Average (MWh)	1,282.78	1,066.39	1,208.70	1,572.87	1,271.72
Median (MWh)	1,323.02	1,067.53	1,246.82	1,605.86	1,285.52
Standard deviation (MWh)	394.55	357.41	325.43	269.34	427.05

4.1.2 Processing

4.1.2.1 Discretization of the series via k-means

The discretization of the photovoltaic time series was performed individually for each climatic season, so that the number of clusters and the values for the centroids were better suited specifically to each of the subsets.

The first step in the execution was to create a function that would calculate the k-means for values of k from 1 to 20. The maximum number of 20 clusters was chosen because it was verified that this is a sufficient amount to represent the data. The second step was to create a function that returned WSS for each of the 20 clusters. The third step was to apply the previously created functions to each of the subsets created. The fourth step was the application of the elbow method. With the results of the WSS calculation, a list was created that contained the ratio between the WSS of a number k and k+1 of clusters for k=1 to k=19. Then, for each of the subsets, the k-value of clusters in which the calculated ratio was greater than 0.90 was identified, i.e., the number of clusters necessary for the reduction of the sum of the intra-cluster squared error, when including a new cluster, to be less than 10%, which would not justify the addition.

Thus, the k-means result for each of the subsets found the ideal number of clusters (Table 2) and centroid values (Table 3).

Table 2: Ideal number of clusters - Nova Olinda Complex.

	Summer	Autumn	Winter	Spring
Number of clusters	11	12	8	8

Table 3: Centroids of the states - Nova Olinda Complex.

Centroids (MWh)		**States**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Seasons	**Summer**	289	545	740	874	1,018	1,137	1,239	1,350	1,453	1,557	1,819	-
	Autumn	307	624	799	916	990	1,075	1,182	1,279	1,372	1,469	1,582	1,709
	Winter	875	1,209	1,407	1,508	1,604	1,720	1,825	1,945	-	-	-	-
	Spring	309	741	980	1,187	1,407	1,634	1,814	1,969	-	-	-	-

4.1.2.2 Creating State Transition Matrices

In this step, the transition matrices of the Nova Olinda Complex (Figure 4) were constructed from the transition frequencies between the states for each subset.

Figure 4 - Transition matrices - Nova Olinda Complex.

Summer

$$\begin{array}{c|ccccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 \\
\hline
1 & 0,29 & 0,43 & 0,07 & 0,14 & 0,07 & 0,00 & 0,00 & 0,00 & 0,00 & 0,00 & 0,00 \\
2 & 0,13 & 0,17 & 0,17 & 0,17 & 0,13 & 0,10 & 0,10 & 0,00 & 0,03 & 0,00 & 0,00 \\
3 & 0,10 & 0,12 & 0,24 & 0,15 & 0,15 & 0,10 & 0,05 & 0,07 & 0,02 & 0,00 & 0,00 \\
4 & 0,02 & 0,13 & 0,27 & 0,13 & 0,16 & 0,13 & 0,00 & 0,11 & 0,04 & 0,00 & 0,00 \\
5 & 0,00 & 0,06 & 0,14 & 0,22 & 0,16 & 0,12 & 0,10 & 0,06 & 0,06 & 0,04 & 0,02 \\
6 & 0,00 & 0,03 & 0,05 & 0,16 & 0,26 & 0,18 & 0,16 & 0,03 & 0,08 & 0,05 & 0,00 \\
7 & 0,00 & 0,06 & 0,00 & 0,15 & 0,09 & 0,21 & 0,06 & 0,18 & 0,12 & 0,09 & 0,03 \\
8 & 0,03 & 0,00 & 0,08 & 0,06 & 0,19 & 0,08 & 0,17 & 0,06 & 0,14 & 0,14 & 0,06 \\
9 & 0,00 & 0,03 & 0,07 & 0,00 & 0,07 & 0,03 & 0,20 & 0,30 & 0,13 & 0,13 & 0,03 \\
10 & 0,00 & 0,04 & 0,00 & 0,00 & 0,00 & 0,04 & 0,08 & 0,29 & 0,21 & 0,29 & 0,04 \\
11 & 0,00 & 0,00 & 0,00 & 0,08 & 0,08 & 0,00 & 0,00 & 0,08 & 0,08 & 0,17 & 0,50
\end{array}$$

Autumn

$$\begin{array}{c|cccccccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\
\hline
1 & 0,00 & 0,00 & 0,30 & 0,10 & 0,20 & 0,00 & 0,10 & 0,00 & 0,30 & 0,00 & 0,00 & 0,00 \\
2 & 0,06 & 0,18 & 0,24 & 0,18 & 0,00 & 0,06 & 0,06 & 0,06 & 0,00 & 0,06 & 0,12 & 0,00 \\
3 & 0,04 & 0,15 & 0,19 & 0,15 & 0,11 & 0,04 & 0,11 & 0,07 & 0,11 & 0,04 & 0,00 & 0,00 \\
4 & 0,09 & 0,04 & 0,09 & 0,13 & 0,13 & 0,22 & 0,04 & 0,13 & 0,09 & 0,00 & 0,00 & 0,04 \\
5 & 0,04 & 0,04 & 0,12 & 0,08 & 0,23 & 0,12 & 0,12 & 0,12 & 0,04 & 0,08 & 0,04 & 0,00 \\
6 & 0,00 & 0,10 & 0,03 & 0,08 & 0,10 & 0,21 & 0,21 & 0,08 & 0,00 & 0,05 & 0,10 & 0,05 \\
7 & 0,03 & 0,03 & 0,06 & 0,06 & 0,08 & 0,17 & 0,11 & 0,14 & 0,11 & 0,06 & 0,17 & 0,00 \\
8 & 0,02 & 0,00 & 0,00 & 0,02 & 0,02 & 0,15 & 0,20 & 0,22 & 0,17 & 0,10 & 0,05 & 0,05 \\
9 & 0,04 & 0,02 & 0,06 & 0,02 & 0,04 & 0,04 & 0,06 & 0,21 & 0,23 & 0,06 & 0,19 & 0,00 \\
10 & 0,00 & 0,03 & 0,06 & 0,00 & 0,03 & 0,06 & 0,11 & 0,06 & 0,19 & 0,31 & 0,14 & 0,03 \\
11 & 0,00 & 0,03 & 0,03 & 0,05 & 0,00 & 0,13 & 0,03 & 0,08 & 0,13 & 0,18 & 0,15 & 0,21 \\
12 & 0,04 & 0,00 & 0,00 & 0,04 & 0,00 & 0,00 & 0,00 & 0,00 & 0,12 & 0,08 & 0,27 & 0,46
\end{array}$$

Winter

$$\begin{array}{c|cccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\hline
1 & 0,26 & 0,37 & 0,00 & 0,00 & 0,21 & 0,16 & 0,00 & 0,00 \\
2 & 0,09 & 0,25 & 0,14 & 0,25 & 0,14 & 0,07 & 0,05 & 0,02 \\
3 & 0,03 & 0,26 & 0,21 & 0,18 & 0,16 & 0,11 & 0,05 & 0,00 \\
4 & 0,06 & 0,10 & 0,25 & 0,17 & 0,19 & 0,15 & 0,04 & 0,04 \\
5 & 0,04 & 0,04 & 0,07 & 0,18 & 0,38 & 0,19 & 0,07 & 0,01 \\
6 & 0,03 & 0,07 & 0,07 & 0,08 & 0,22 & 0,32 & 0,17 & 0,03 \\
7 & 0,02 & 0,03 & 0,05 & 0,03 & 0,05 & 0,16 & 0,56 & 0,10 \\
8 & 0,00 & 0,00 & 0,00 & 0,06 & 0,03 & 0,06 & 0,22 & 0,63
\end{array}$$

Spring

$$\begin{array}{c|cccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\hline
1 & 0,21 & 0,32 & 0,16 & 0,21 & 0,11 & 0,00 & 0,00 & 0,00 \\
2 & 0,17 & 0,41 & 0,22 & 0,15 & 0,05 & 0,00 & 0,00 & 0,00 \\
3 & 0,07 & 0,14 & 0,48 & 0,24 & 0,02 & 0,03 & 0,02 & 0,00 \\
4 & 0,00 & 0,13 & 0,24 & 0,34 & 0,23 & 0,06 & 0,00 & 0,00 \\
5 & 0,05 & 0,00 & 0,06 & 0,15 & 0,45 & 0,20 & 0,08 & 0,02 \\
6 & 0,02 & 0,02 & 0,02 & 0,09 & 0,28 & 0,28 & 0,22 & 0,07 \\
7 & 0,00 & 0,03 & 0,00 & 0,05 & 0,05 & 0,43 & 0,30 & 0,14 \\
8 & 0,00 & 0,00 & 0,00 & 0,00 & 0,00 & 0,15 & 0,35 & 0,50
\end{array}$$

4.1.2.3 Obtaining the results

All the transition matrices created were classified as irreducible and ergodic, important properties for the Markov Chain to have a stationary distribution. Then, stationary distributions (Table 4), recurrence times (Table 5), and first passage times (Figure 5) were calculated.

Table 4: Stationary distribution - Nova Olinda Complex.

a) Summer	**States**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Centroid (MWh)	289	545	740	874	1,018	1,137	1,239	1,350	1,453	1,557	1,819
Stationary distribution	0.0401	0.0851	0.1191	0.1246	0.1390	0.1073	0.0910	0.1049	0.0827	0.0719	0.0343

b) Autumn	**States**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Centroid (MWh)	307	624	799	916	990	1,075	1,182	1,279	1,372	1,469	1,582	1,709
Stationary distribution	0.0269	0.0456	0.0693	0.0622	0.0665	0.1068	0.0997	0.1110	0.1253	0.0962	0.1162	0.0745

c) Winter	**States**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Centroid (MWh)	875	1,209	1,407	1,508	1,604	1,720	1,825	1,945
Stationary distribution	0.0503	0.1108	0.1007	0.1246	0.1829	0.1668	0.1757	0.0882

(d) Spring	**States**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Centroid (MWh)	309	741	980	1,187	1,407	1,634	1,814	1,969
Stationary distribution	0.0553	0.1199	0.1777	0.1784	0.1798	0.1419	0.0949	0.0522

Table 5: Recurrence time - Nova Olinda Complex.

a) Summer	**States**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Centroid (MWh)	289	545	740	874	1,018	1,137	1,239	1,350	1,453	1,557	1,819
Recurrence time (days)	25	12	8	8	7	9	11	10	12	14	29

b) Autumn	**States**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Centroid (MWh)	307	624	799	916	990	1,075	1,182	1,279	1,372	1,469	1,582	1,709
Recurrence time (days)	37	22	14	16	15	9	10	9	8	10	9	13

c) Winter	**States**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Centroid (MWh)	875	1,209	1,407	1,508	1,604	1,720	1,825	1,945
Recurrence time (days)	20	9	10	8	5	6	6	11

(d) Spring	**States**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Centroid (MWh)	309	741	980	1,187	1,407	1,634	1,814	1,969
Recurrence time (days)	18	8	6	6	6	7	11	19

Figure 5 - First passage time - Nova Olinda Complex.

Summer

$$\begin{array}{c|ccccccccccc|}
 & \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} & \mathbf{8} & \mathbf{9} & \mathbf{10} & \mathbf{11} \\
\mathbf{1} & 0 & 7 & 9 & 7 & 8 & 12 & 13 & 13 & 17 & 24 & 62 \\
\mathbf{2} & 32 & 0 & 9 & 8 & 7 & 10 & 12 & 12 & 15 & 23 & 61 \\
\mathbf{3} & 33 & 13 & 0 & 8 & 7 & 10 & 12 & 11 & 15 & 23 & 60 \\
\mathbf{4} & 36 & 13 & 8 & 0 & 7 & 10 & 12 & 11 & 15 & 22 & 60 \\
\mathbf{5} & 38 & 15 & 10 & 8 & 0 & 10 & 11 & 10 & 14 & 21 & 58 \\
\mathbf{6} & 39 & 15 & 11 & 8 & 6 & 0 & 10 & 10 & 14 & 21 & 59 \\
\mathbf{7} & 39 & 15 & 12 & 9 & 8 & 9 & 0 & 9 & 13 & 19 & 57 \\
\mathbf{8} & 38 & 16 & 11 & 9 & 7 & 11 & 10 & 0 & 12 & 18 & 55 \\
\mathbf{9} & 39 & 16 & 12 & 10 & 8 & 11 & 9 & 7 & 0 & 17 & 55 \\
\mathbf{10} & 40 & 17 & 13 & 11 & 9 & 12 & 10 & 6 & 11 & 0 & 54 \\
\mathbf{11} & 40 & 18 & 13 & 10 & 9 & 13 & 13 & 9 & 12 & 15 & 0
\end{array}$$

Autumn

$$\begin{array}{c|cccccccccccc|}
 & \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} & \mathbf{8} & \mathbf{9} & \mathbf{10} & \mathbf{11} & \mathbf{12} \\
\mathbf{1} & 0 & 26 & 13 & 16 & 15 & 12 & 10 & 11 & 8 & 15 & 11 & 27 \\
\mathbf{2} & 35 & 0 & 14 & 15 & 19 & 11 & 11 & 11 & 11 & 15 & 11 & 27 \\
\mathbf{3} & 36 & 23 & 0 & 15 & 17 & 11 & 10 & 11 & 10 & 15 & 12 & 27 \\
\mathbf{4} & 34 & 26 & 17 & 0 & 17 & 9 & 11 & 10 & 10 & 15 & 11 & 26 \\
\mathbf{5} & 36 & 26 & 16 & 17 & 0 & 10 & 10 & 10 & 10 & 14 & 11 & 27 \\
\mathbf{6} & 38 & 25 & 18 & 17 & 18 & 0 & 9 & 11 & 11 & 14 & 10 & 25 \\
\mathbf{7} & 37 & 27 & 18 & 18 & 18 & 10 & 0 & 10 & 9 & 14 & 9 & 26 \\
\mathbf{8} & 37 & 28 & 19 & 19 & 20 & 10 & 9 & 0 & 9 & 13 & 10 & 25 \\
\mathbf{9} & 37 & 27 & 18 & 19 & 19 & 11 & 11 & 9 & 0 & 14 & 9 & 26 \\
\mathbf{10} & 39 & 27 & 18 & 19 & 20 & 11 & 10 & 11 & 8 & 0 & 9 & 25 \\
\mathbf{11} & 38 & 27 & 19 & 19 & 21 & 11 & 12 & 11 & 9 & 12 & 0 & 20 \\
\mathbf{12} & 37 & 29 & 20 & 19 & 21 & 13 & 13 & 12 & 9 & 13 & 7 & 0
\end{array}$$

Winter

$$\begin{array}{c|cccccccc|}
 & \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} & \mathbf{8} \\
\mathbf{1} & 0 & 7 & 13 & 9 & 6 & 7 & 14 & 32 \\
\mathbf{2} & 25 & 0 & 11 & 7 & 7 & 8 & 13 & 31 \\
\mathbf{3} & 26 & 9 & 0 & 8 & 7 & 8 & 13 & 31 \\
\mathbf{4} & 26 & 11 & 10 & 0 & 7 & 7 & 13 & 30 \\
\mathbf{5} & 26 & 12 & 12 & 8 & 0 & 7 & 12 & 31 \\
\mathbf{6} & 27 & 12 & 13 & 9 & 7 & 0 & 11 & 30 \\
\mathbf{7} & 29 & 14 & 14 & 11 & 9 & 7 & 0 & 26 \\
\mathbf{8} & 30 & 15 & 15 & 11 & 10 & 9 & 8 & 0
\end{array}$$

Spring

$$\begin{array}{c|cccccccc|}
 & \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} & \mathbf{8} \\
\mathbf{1} & 0 & 10 & 8 & 6 & 10 & 15 & 24 & 51 \\
\mathbf{2} & 18 & 0 & 7 & 6 & 11 & 16 & 25 & 52 \\
\mathbf{3} & 22 & 12 & 0 & 6 & 11 & 15 & 24 & 51 \\
\mathbf{4} & 25 & 14 & 9 & 0 & 8 & 13 & 22 & 49 \\
\mathbf{5} & 26 & 18 & 13 & 8 & 0 & 9 & 18 & 45 \\
\mathbf{6} & 27 & 19 & 14 & 9 & 7 & 0 & 14 & 40 \\
\mathbf{7} & 29 & 20 & 15 & 10 & 9 & 5 & 0 & 35 \\
\mathbf{8} & 30 & 22 & 17 & 12 & 10 & 5 & 6 & 0
\end{array}$$

4.1.3 Post-processing

4.1.3.1 Evaluation and interpretation of results

After obtaining the model's results, it becomes possible to analyze and interpret the generated values and better understand the behavior of the daily photovoltaic power generation time series, mainly from the stationary distributions, recurrence times and first passage times.

From the stationary distribution, in Table 4, it is observed that the system presents higher probabilities for the states of intermediate generation values in the summer and spring seasons. Also, the probabilities decay little by little and in a similar way for the lower and higher extreme states. Another way to analyze it is by the time of recurrence of the states in Table 5. In both seasons, the recurrence times of the extreme states are significantly higher compared to the central states and very close to each other. Analyzing the extreme states, in the summer, states 1 (289 MWh) and 11 (1,819 MWh) have a recurrence of 25 and 29 days, respectively, while states 1 (309 MWh) and 8 (1,969 MWh) in spring have a recurrence of 18 and 19 days, respectively. Consequently, the tendency is for the system to remain in medium-generation states and the extremes to be rarer, with lower expectations of low or high generation in a day, especially in the summer, whose recurrence times of extreme states are even longer.

Autumn, on the other hand, has a higher probability of being in the central and upper states, with lower probabilities in states of lower energy generation, comparatively. At this season, the two states with the highest power generation, states 11 (1,582 MWh) and 12 (1,709 MWh), have recurrence times of 9 and 13 days, respectively. Meanwhile, the recurrence times of the two lowest-generation states, states 1 (307 MWh) and 2 (624 MWh), are 37 and 22 days, respectively. In addition, the recurrence time of state 1 of autumn is the longest among all states of all seasons, i.e., autumn presents the longest average period for the system to return to low levels of power generation. Hence, it appears that the system has a tendency towards higher states with a lower risk of low generation.
Furthermore, by investigating the first passage times of summer and spring, it is possible to analyze that the time to leave the state of lowest energy generation and reach the state of highest generation for the first time is longer than the reverse. For example, the first passage time from state 1 (309 MWh) to state 8 (1,969 MWh) in the spring is 51 days, while the time from state 8 to state 1 is 30 days, approximately 40% shorter. Therefore, although the probabilities of the system being at each extreme are close, once the system is in a low-generation state, it will take longer to reach the higher-generation states in both seasons.

Meanwhile, when looking at winter, the first passage times between the two most extreme states, lower and upper, are close — 32 days from state 1 (875 MWh) to state 8 (1,945 MWh) and 30 days from state 8 to state 1— although their recurrence times are quite different (20 days for state 1 and 11 days for state 8). It is interesting to note that the first passage times between states with more distant generation levels may be shorter than among others with closer generations. For example, the first passage time from state 2 (1,209 MWh) to state 3 (1,407 MWh) is 11 days, while the time from state 2 to state 6 (1,720 MWh) is 8 days.

4.2. Guaimbê Complex (São Paulo)

4.2.1 Pre-processing

4.2.1.1 Collection, analysis and treatment of data

By testing the stationarity of the time series of the Guaimbê Complex in the analyzed period, it was concluded that the time series is stationary and, therefore, the installed capacity is constant. The stationarity of the time series in the period can be seen in Figure 6, which represents the average daily generation per month. In addition, the series has considerably lower volatility than that of the Nova Olinda Complex, with low variations in energy generation over the months.

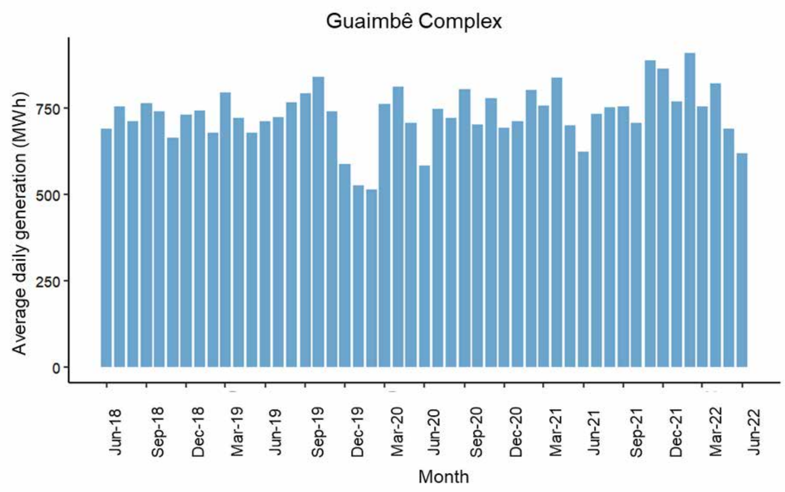


Table 6 shows that spring has the highest daily average of energy generation in the Guaimbê Complex, with 752.92 MWh/day. Meanwhile, the summer has a daily average of 5% lower than that of spring, with 717.33 MWh/day, being the lowest average for the plant. Consequently, the low variability of energy generation between the seasons of the year is evident, with all values being considerably close to the general average. Also, the standard deviation of the seasons also assumes close values.

Table 6: Measurements of daily energy generation - Guaimbê Complex.

	General	Summer	Autumn	Winter	Spring
Average (MWh)	733.22	717.33	727.17	735.38	752.92
Median (MWh)	774.37	733.33	774.09	777.22	796.82
Standard deviation (MWh)	196.43	201.25	188.33	181.12	213.40

4.2.2 Processing

4.2.2.1 Discretization of the series via k-means

The discretization of the photovoltaic energy time series for the Guaimbê Complex was performed with the same method as the Nova Olinda Complex, but in a totally independent way, using the k-means technique and the elbow method. The ideal number of clusters and centroid values are shown in Tables 7 and 8, respectively.

Table 7: Ideal number of clusters - Guaimbê Complex.

	Summer	**Autumn**	**Winter**	**Spring**
Number of clusters	8	9	11	8

Table 8: Centroids of the states - Guaimbê Complex.

Centroids (MWh)		**States**										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Seasons	**Summer**	234	386	499	610	715	810	909	1,018	-	-	-
	Autumn	244	459	619	699	760	810	867	924	992	-	-
	Winter	182	324	448	545	615	679	741	791	840	900	983
	Spring	269	457	593	688	780	863	949	1,033	-	-	-

4.2.2.2 Creating State Transition Matrices

Thus, the transition matrices of states of the Guaimbê Complex were created, represented in Figure 7.

Figure 7 - Transition matrices - Guaimbê Complex.

Summer

$$\begin{array}{c|cccccccc|}
 & \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} & \mathbf{8} \\
\mathbf{1} & 0,00 & 0,38 & 0,13 & 0,25 & 0,13 & 0,00 & 0,13 & 0,00 \\
\mathbf{2} & 0,00 & 0,39 & 0,43 & 0,11 & 0,07 & 0,00 & 0,00 & 0,00 \\
\mathbf{3} & 0,12 & 0,09 & 0,12 & 0,30 & 0,14 & 0,12 & 0,07 & 0,05 \\
\mathbf{4} & 0,02 & 0,09 & 0,25 & 0,26 & 0,18 & 0,09 & 0,11 & 0,02 \\
\mathbf{5} & 0,02 & 0,02 & 0,07 & 0,18 & 0,29 & 0,24 & 0,15 & 0,04 \\
\mathbf{6} & 0,02 & 0,02 & 0,05 & 0,14 & 0,24 & 0,26 & 0,22 & 0,05 \\
\mathbf{7} & 0,00 & 0,03 & 0,06 & 0,06 & 0,06 & 0,24 & 0,40 & 0,16 \\
\mathbf{8} & 0,00 & 0,00 & 0,03 & 0,03 & 0,06 & 0,11 & 0,31 & 0,46
\end{array}$$

Autumn

$$\begin{array}{c|ccccccccc}
 & \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} & \mathbf{8} & \mathbf{9} \\
\mathbf{1} & 0,25 & 0,13 & 0,29 & 0,08 & 0,08 & 0,13 & 0,04 & 0,00 & 0,00 \\
\mathbf{2} & 0,08 & 0,14 & 0,22 & 0,14 & 0,06 & 0,22 & 0,11 & 0,03 & 0,00 \\
\mathbf{3} & 0,19 & 0,17 & 0,14 & 0,14 & 0,14 & 0,11 & 0,06 & 0,00 & 0,06 \\
\mathbf{4} & 0,05 & 0,16 & 0,13 & 0,16 & 0,21 & 0,11 & 0,11 & 0,08 & 0,00 \\
\mathbf{5} & 0,06 & 0,06 & 0,08 & 0,19 & 0,31 & 0,15 & 0,05 & 0,06 & 0,03 \\
\mathbf{6} & 0,02 & 0,06 & 0,06 & 0,05 & 0,29 & 0,35 & 0,08 & 0,06 & 0,03 \\
\mathbf{7} & 0,02 & 0,13 & 0,06 & 0,06 & 0,06 & 0,17 & 0,37 & 0,13 & 0,00 \\
\mathbf{8} & 0,00 & 0,00 & 0,00 & 0,05 & 0,11 & 0,03 & 0,34 & 0,37 & 0,11 \\
\mathbf{9} & 0,00 & 0,00 & 0,00 & 0,00 & 0,13 & 0,13 & 0,06 & 0,31 & 0,38
\end{array}$$

Winter

$$\begin{array}{c|ccccccccccc|}
 & \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} & \mathbf{8} & \mathbf{9} & \mathbf{10} & \mathbf{11} \\
\mathbf{1} & 0,21 & 0,00 & 0,14 & 0,14 & 0,21 & 0,14 & 0,00 & 0,00 & 0,07 & 0,07 & 0,00 \\
\mathbf{2} & 0,20 & 0,00 & 0,30 & 0,20 & 0,00 & 0,00 & 0,10 & 0,10 & 0,10 & 0,00 & 0,00 \\
\mathbf{3} & 0,07 & 0,07 & 0,07 & 0,07 & 0,07 & 0,14 & 0,14 & 0,07 & 0,00 & 0,14 & 0,14 \\
\mathbf{4} & 0,06 & 0,11 & 0,17 & 0,00 & 0,11 & 0,11 & 0,06 & 0,17 & 0,17 & 0,06 & 0,00 \\
\mathbf{5} & 0,09 & 0,04 & 0,04 & 0,13 & 0,17 & 0,09 & 0,22 & 0,17 & 0,04 & 0,00 & 0,00 \\
\mathbf{6} & 0,08 & 0,03 & 0,03 & 0,14 & 0,05 & 0,27 & 0,11 & 0,19 & 0,08 & 0,00 & 0,03 \\
\mathbf{7} & 0,00 & 0,05 & 0,05 & 0,04 & 0,04 & 0,16 & 0,39 & 0,16 & 0,07 & 0,04 & 0,02 \\
\mathbf{8} & 0,03 & 0,00 & 0,00 & 0,03 & 0,06 & 0,12 & 0,22 & 0,34 & 0,12 & 0,06 & 0,02 \\
\mathbf{9} & 0,00 & 0,02 & 0,00 & 0,02 & 0,07 & 0,02 & 0,07 & 0,24 & 0,40 & 0,16 & 0,02 \\
\mathbf{10} & 0,00 & 0,02 & 0,02 & 0,00 & 0,02 & 0,02 & 0,04 & 0,06 & 0,27 & 0,47 & 0,08 \\
\mathbf{11} & 0,00 & 0,00 & 0,00 & 0,00 & 0,00 & 0,00 & 0,00 & 0,00 & 0,00 & 0,39 & 0,61
\end{array}$$

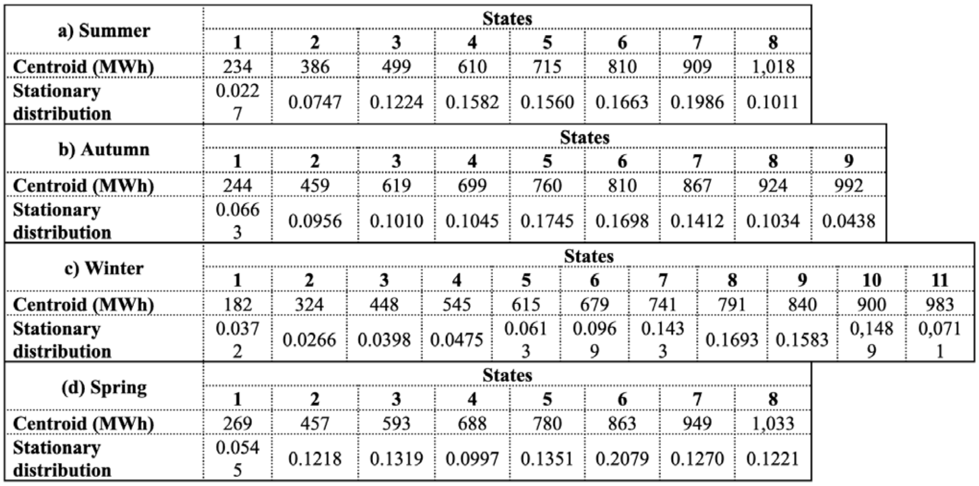
Spring

$$\begin{array}{c|cccccccc|}
 & \mathbf{1} & \mathbf{2} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{6} & \mathbf{7} & \mathbf{8} \\
\mathbf{1} & 0,05 & 0,21 & 0,16 & 0,21 & 0,16 & 0,05 & 0,11 & 0,05 \\
\mathbf{2} & 0,15 & 0,12 & 0,37 & 0,17 & 0,05 & 0,07 & 0,05 & 0,02 \\
\mathbf{3} & 0,02 & 0,34 & 0,11 & 0,11 & 0,17 & 0,15 & 0,09 & 0,02 \\
\mathbf{4} & 0,03 & 0,06 & 0,17 & 0,17 & 0,06 & 0,29 & 0,09 & 0,14 \\
\mathbf{5} & 0,10 & 0,15 & 0,10 & 0,10 & 0,10 & 0,21 & 0,17 & 0,06 \\
\mathbf{6} & 0,03 & 0,05 & 0,08 & 0,09 & 0,27 & 0,39 & 0,05 & 0,03 \\
\mathbf{7} & 0,07 & 0,09 & 0,11 & 0,00 & 0,13 & 0,20 & 0,20 & 0,20 \\
\mathbf{8} & 0,00 & 0,02 & 0,02 & 0,02 & 0,04 & 0,11 & 0,30 & 0,49
\end{array}$$

4.2.2.3 Obtaining the results

Then, stationary distributions (Table 9), recurrence times (Table 10), and first passage times (Figure 8) were calculated.

Table 9: Stationary distribution - Guaimbê Complex.



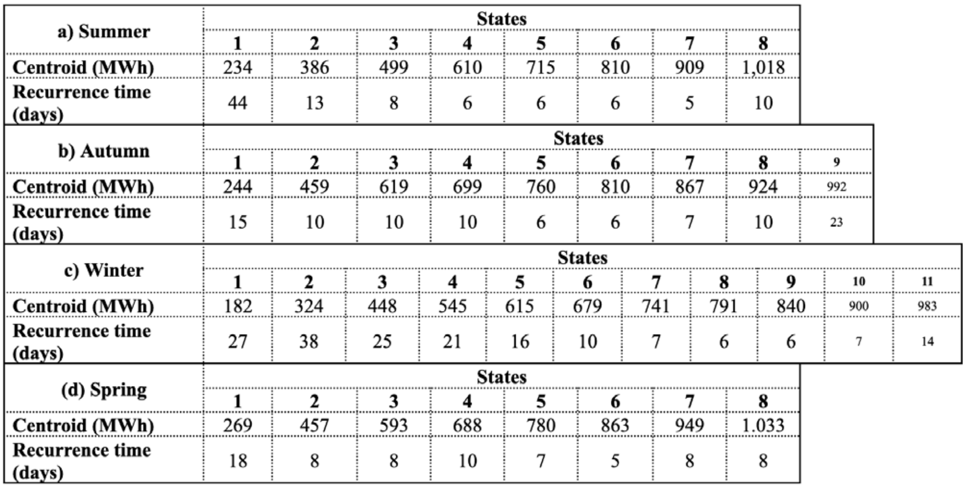
a) Summer	States							
	1	2	3	4	5	6	7	8
Centroid (MWh)	234	386	499	610	715	810	909	1,018
Stationary distribution	0.0227	0.0747	0.1224	0.1582	0.1560	0.1663	0.1986	0.1011

b) Autumn	States								
	1	2	3	4	5	6	7	8	9
Centroid (MWh)	244	459	619	699	760	810	867	924	992
Stationary distribution	0.0663	0.0956	0.1010	0.1045	0.1745	0.1698	0.1412	0.1034	0.0438

c) Winter	States										
	1	2	3	4	5	6	7	8	9	10	11
Centroid (MWh)	182	324	448	545	615	679	741	791	840	900	983
Stationary distribution	0.0372	0.0266	0.0398	0.0475	0.0613	0.0969	0.1433	0.1693	0.1583	0,1489	0,0711

(d) Spring	States							
	1	2	3	4	5	6	7	8
Centroid (MWh)	269	457	593	688	780	863	949	1,033
Stationary distribution	0.0545	0.1218	0.1319	0.0997	0.1351	0.2079	0.1270	0.1221

Table 10: Recurrence time - Guaimbê Complex.



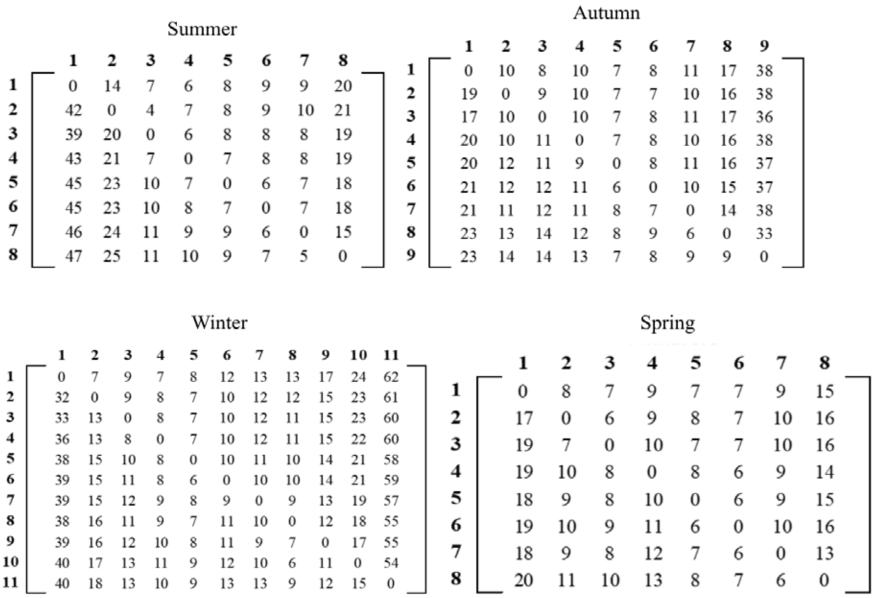
a) Summer	States							
	1	2	3	4	5	6	7	8
Centroid (MWh)	234	386	499	610	715	810	909	1,018
Recurrence time (days)	44	13	8	6	6	6	5	10

b) Autumn	States								
	1	2	3	4	5	6	7	8	9
Centroid (MWh)	244	459	619	699	760	810	867	924	992
Recurrence time (days)	15	10	10	10	6	6	7	10	23

c) Winter	States										
	1	2	3	4	5	6	7	8	9	10	11
Centroid (MWh)	182	324	448	545	615	679	741	791	840	900	983
Recurrence time (days)	27	38	25	21	16	10	7	6	6	7	14

(d) Spring	States							
	1	2	3	4	5	6	7	8
Centroid (MWh)	269	457	593	688	780	863	949	1.033
Recurrence time (days)	18	8	8	10	7	5	8	8

Figure 8 - First passage time - Guaimbê Complex.



Summer

	1	2	3	4	5	6	7	8
1	0	14	7	6	8	9	9	20
2	42	0	4	7	8	9	10	21
3	39	20	0	6	8	8	8	19
4	43	21	7	0	7	8	8	19
5	45	23	10	7	0	6	7	18
6	45	23	10	8	7	0	7	18
7	46	24	11	9	9	6	0	15
8	47	25	11	10	9	7	5	0

Autumn

	1	2	3	4	5	6	7	8	9
1	0	10	8	10	7	8	11	17	38
2	19	0	9	10	7	7	10	16	38
3	17	10	0	10	7	8	11	17	36
4	20	10	11	0	7	8	10	16	38
5	20	12	11	9	0	8	11	16	37
6	21	12	12	11	6	0	10	15	37
7	21	11	12	11	8	7	0	14	38
8	23	13	14	12	8	9	6	0	33
9	23	14	14	13	7	8	9	9	0

Winter

	1	2	3	4	5	6	7	8	9	10	11
1	0	7	9	7	8	12	13	13	17	24	62
2	32	0	9	8	7	10	12	12	15	23	61
3	33	13	0	8	7	10	12	11	15	23	60
4	36	13	8	0	7	10	12	11	15	22	60
5	38	15	10	8	0	10	11	10	14	21	58
6	39	15	11	8	6	0	10	10	14	21	59
7	39	15	12	9	8	9	0	9	13	19	57
8	38	16	11	9	7	11	10	0	12	18	55
9	39	16	12	10	8	11	9	7	0	17	55
10	40	17	13	11	9	12	10	6	11	0	54
11	40	18	13	10	9	13	13	9	12	15	0

Spring

	1	2	3	4	5	6	7	8
1	0	8	7	9	7	7	9	15
2	17	0	6	9	8	7	10	16
3	19	7	0	10	7	7	10	16
4	19	10	8	0	8	6	9	14
5	18	9	8	10	0	6	9	15
6	19	10	9	11	6	0	10	16
7	18	9	8	12	7	6	0	13
8	20	11	10	13	8	7	6	0

4.2.3 Post-processing

4.2.3.1 Evaluation and interpretation of results

With the measurements of interest obtained for the Guaimbê Complex, the next step is to analyze the model's characteristics for each of the seasons.

In summer, the stationary probability of the system being in the state of lower power generation is the lowest (2.27%), resulting in a recurrence time of 44 days, that is, the occurrence of a state of low generation is extremely rare, and, once in this state, many transitions are expected for the return. Furthermore, state 2 (386 MWh) has the second-lowest stationary probability at 7.47%, followed by state 8 (1,018 MWh) at 10.11%. The states with the highest probabilities are the higher power plants, and the state with the highest stationary probability is state 7 (909 MWh), with 19.86%.

Looking at autumn, the system has a higher probability of being stationary in the upper central states of power generation values in the seasons, with the probabilities gradually decreasing to the lower and upper extreme states. The two states with the longest recurrence times are the extremes, states 1 (244 MWh) and 9 (992 MWh), with 15 and 23 days, respectively. Winter, on the other hand, in the Guaimbê Complex, has higher stationary probabilities for the upper states and very low probabilities for the four states with lower energy generation. An interesting case is that the recurrence time of state 2 (324 MWh) is 38 days, which is approximately 40% longer than the time of state 1 (182 MWh) 27 days. In this way, the risk of the system being in low-generation states is lower, and there is an expectation of higher energy generations, comparatively.

Spring has more balanced stationary probabilities among its eight states, with the exception of state 1 (269 MWh), which has lower power generation and a probability of only 5%.

Analyzing the times of the first passage, it can be seen that, in the summer of the Guaimbê Complex, the time to leave the state of the highest generation to the state of the lowest generation is more than double the reverse. The first passage time from state 8 (1,018 MWh) to state 1 (234 MWh) is 47 days, while from state 1 to state 8 is 20 days. Hence, this characteristic is favorable to generation because the average time to have a low generation from a high generation is high. However, autumn and winter have first passage times with the reverse logic, it takes longer to move from a state of lower generation to one of greater generation. This analysis is important because, in low-generation situations, the expected time to return to high-generation is longer. In the autumn, the first passage time from state 1 (244 MWh) to state 9 (992 MWh) is 38 days, and the reverse is 23 days. Meanwhile, in winter, the time from state 1 (182 MWh) to state 11 (983 MWh) is 62 days, and the reverse is 30 days.

4.3 Comparison of results

Analyzing the time series of the Nova Olinda and Guaimbê complexes, the differences in the variability of the average photovoltaic energy generation throughout the year are evident since Nova Olinda presents seasonality with higher average generation in winter and lower in summer, which is the wet period, while the averages of Guaimbê are closer in all climatic seasons. In the case of Nova Olinda, the reason for subdividing the series by the climatic seasons to perform the modeling is more evident, however, although the Guaimbê Complex presents more homogeneous monthly averages, the results for the stationary distributions and recurrence and first passage times were significantly different in each season, as previously analyzed. Thus, the subdivision by climatic season proved to be relevant for both plants.

Another interesting fact is that the climatic seasons affect each region differently as well, with similarities between different seasons in the two regions. For example, the highest concentration of stationary probabilities in upper central states is a case present in summer and spring in the Nova Olinda Complex, but it also happens in the autumn in the Guaimbê Complex. On the other hand, the autumn of Nova Olinda is similar to the winter of Guaimbê because the states of lower generations have significantly lower stationary probabilities than the others and higher probabilities in the higher states. Meanwhile, Nova Olinda's winter and Guaimbê's spring are the seasons with the most balanced stationary probabilities between the states.

In addition, analyzing the first passage times, other similarities were found. The cases in which the first passage time from the state with the highest generation to the lowest was longer than the inverse were the autumn in Nova Olinda and the summer in Guaimbê. The opposite happened in the summer and spring in Nova Olinda and in the autumn and winter in Guaimbê. On the other hand, the winter of Nova Olinda and the spring of Guaimbê had the closest first passage times when comparing the most extreme states.

Finally, BES can use this analysis to assist in the country's energy planning by calculating the probability of possible scenarios of low or high photovoltaic generation by region and climatic season. The detailed study of the characteristics of renewable sources brings greater security to the supply of energy demand in the country.

5. CONCLUSION

Brazil has been going through a process of changing its energy matrix and increasing the use of renewable energies non-dispatchable. In this context, photovoltaic solar energy has stood out due to the significant growth of its share in the country. Hence, its characteristics of intermittency and random fluctuations have a greater impact on the national energy supply scenario. Therefore, the study of photovoltaic generation through modeling methods is relevant, and an opportunity to contribute to the literature was found through the present work.

This work studies the generation characteristics of two photovoltaic solar power plants located in regions with solar incidences of different magnitudes and seasonalities. The methodology used was based on Markov Chains. The time series were subdivided among the climatic seasons of the year. Then, the state transition matrices were created, and the results of the measures of interest, such as stationary distribution, recurrence time, and first passage time, were investigated. Consequently, it was possible to analyze the differences between the photovoltaic energy generation in the different seasons and regions. In this way, the objective of the work was achieved in a pertinent way.

Confirming the initial hypothesis, the results showed significant differences in solar energy generation between the regions and between the climatic seasons, which evidenced the relevance of the comparative study carried out. By analyzing and better understanding the specificities of each location and season, power plants and the Brazilian Electric System can plan more efficiently about energy generation, analyzing the probabilities of the occurrence of states of different generation values.

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China and the global expansion of green energy technologies: EVs, batteries and lithium investments in Latin America.

China y la expansión global de las tecnologías de energía verde: vehículos eléctricos, baterías e inversiones en litio en América Latina

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POWER
CONNECT
CHARGING
FAULT
59%

Resumen

China se ha convertido en un líder mundial en baterías de litio y ha utilizado estas capacidades para desarrollar un importante ecosistema de innovación en vehículos eléctricos, cuyas empresas se están expandiendo al mundo. El factor clave para la promoción exitosa de los vehículos eléctricos en China ha sido la política industrial. Las tecnologías verdes pueden verse como la nueva frontera para la expansión global de las empresas chinas debido a sus capacidades tecnológicas y de innovación y América Latina es uno de los principales destinos de la inversión extranjera directa (IED) en vehículos eléctricos, litio y baterías. El presente artículo examina el panorama y las tendencias de la IED realizada por empresas chinas en la región, con el objetivo de analizar la posibilidad de que los países latinoamericanos integren la cadena de valor liderada por China en energía verde como parte de sus procesos de desarrollo y políticas industriales. Los resultados son preliminares, pero inferimos que hay una nueva fase de participación China en América Latina post-Covid, con un cambio en el perfil de la IED: 1) las inversiones relevantes ahora se realizan no solo a través de empresas estatales, sino cada vez más realizadas por empresas privadas; 2) los sectores de destino están cambiando lentamente del petróleo, el gas y la agricultura hacia fuentes de energía renovables, vehículos eléctricos y minería de minerales estratégicos; 3) los flujos de inversiones son menores en la cantidad total, pero hay un mayor número de proyectos en la región en general; 4) los proyectos de IED se dirigen cada vez más a sectores intensivos en conocimiento/tecnología, en lugar de sectores intensivos en capital, con un aumento gradual de la IED totalmente nueva como modo de entrada.

PALABRAS CLAVE: China; vehículos eléctricos; upgrading; inversiones extranjeras directas; América Latina.

Abstract

China has become a global leader in ion-lithium batteries and has used these capabilities to develop an important innovation ecosystem in electric vehicles, which are now expanding to the world. The key driver to China's successful promotion of electric vehicles has been industrial policy. Green technologies can be seen as the new frontier for the global expansion of Chinese firms due to their innovation and technological capabilities and Latin America is one of the main destinations for foreign direct investments (FDI). The present article examines the landscape and trends of FDI conducted by Chinese firms in the region, analyzing the possibility for Latin-American countries to integrate Chinese-led value chain in green energy as part of their developmental processes and industrial policies. The key findings are preliminary,: 1) relevant investments are now conducted not only through state owned enterprises, but increasingly made by private firms,; 2) sectors of destination are slowly changing from oil, gas and agriculture towards renewable energy sources, electric vehicles and mining of strategic minerals; 3) the flows of investments are smaller in the total quantity, but there is a higher number of projects in the region overall; 4) the FDI projects are increasingly directed in knowledge/technologically intensive sectors, instead of capital intensive ones with a gradual increase in greenfield FDI as the mode of entry.

KEYWORDS: China; electric vehicles; upgrading; foreign direct investment; Latin America.

1. INTRODUCTION

China has become a global leader in ion-lithium batteries and has used these capabilities to develop an important innovation ecosystem in electric vehicles, which are now expanding globally. CATL is the most well-known successful case in battery production, followed by BYD, which produces both batteries and cars, in a business model of vertical integration. Another important Chinese player in EVs market is Great Wall Motors. Taken together these firms have invested significant funding in foreign direct investment projects for manufacturing and assembly, mainly in Argentina, Brazil and Chile. Other important Chinese actors in this landscape include mining firms such as Tianqi Lithium, Jixing Mining and Ganfeng Jixin (Sanderson, 2022; AEI, 2024).

Green technologies and efforts towards decarbonization can be seen as a new frontier for the global expansion of Chinese firms due to their innovation and technological capabilities in these areas, and Latin America has been a region of growing interest in this regard. Considering these points, the present article examines the landscape and trends of FDI conducted by Chinese firms in the region, aiming to analyze the possibility for Latin-American countries to integrate Chinese FDI in green energy as part of their developmental path and industrial policies.

Ford's popularization of combustion vehicles led the way for the creation of immense wealth for oil companies in the XX century. The popularization of electric cars could create wealth for the mining companies that access the minerals needed for producing the batteries for these vehicles, something that will bear a cost for the environment. The lithium-ion battery is a game changer due to its capacity for powering digital devices, the fact of being small-sized, safe, and offering a long time of use (autonomy) before needing to be recharged. These batteries have made possible the extensive production and use of electric vehicles. Investments in R&D capacity for ion-lithium batteries and governmental subsidies for the purchase of electric vehicles are the main policy drivers leading the development of these sectors. In 2021 China sold half of the world's EVs. However, this development has not been without costs. From 2009-2019, the total cost for the government stood at just under 100 billion USD. Almost half of the total corresponded to EV purchase subsidies (Dezan & Shira associates, 2020).

As the industry's capabilities grew, subsidies have been lowered and R&D investments have risen. Between 2018-2020, each year's R&D spending was almost six times the spending on R&D for the 2009-2017 period, showing a growing concern with innovation and upgrading, which fuel the global expansion of its firms. The research will include a theoretical framing regarding the importance of technology and upgrading and has a focus on qualitative analysis using the case study method mentioning the main investments in the countries in the region, semi-structured interviews were conducted with specialists in related fields in order to ascertain the nature and trends of China's FDI in Latin America.

The article will be structured as follows: the first section will analyze the importance of technology for economic growth while reviewing concepts such as upgrading. It is an important topic as technological capabilities are the reason that explain why China is able to invest abroad and compete with established developed countries in key strategic sectors. The second section will analyze the development of ion-lithium batteries in China; the third section oversees the upgrading in the EVs sector. And the fourth section verses on the general trends of Chinese investments in Latin America's energy sector, with a focus on specific projects, located mainly in Argentina, Brazil and Chile. The conclusions analyze all these facts and present the preliminary results of the research summarized in four key points.

2. ANALYTICAL FRAMEWORK: THE IMPORTANCE OF TECHNOLOGY AND UPGRADING

Technology is a fundamental input of economic growth, as it engenders productivity gains across different sectors. In this sense, technological upgrading provides stimulus and supports the process of economic development. From the perspective of late industrializers or emerging countries, it is a necessary input in order to promote catching up with global markets. Domination of the leading technologies of each historical period allows nations to capture the higher value-added activities and the resulting rents in order to foster economic growth.

Solow (1994) was perhaps one of the first to point out the importance of technical advances for sustained economic growth, by separating this factor from the inputs of capital and labor which were prominently featured in classical economic models. Romer (1990) follows on this thread, but presents an endogenous model of economic growth, highlighting the importance of human capital for technological change. However, in a sense, this tradition dates back to Joseph Schumpeter's "Capitalism, Socialism, and Democracy" (1942), which analyzes economic change and the role of innovation and technology in increasing productivity. One main subject that remains across these studies is the prevalence of state-led policies or market institutions as propellers of technological change.

Market-led growth often focuses on the role of firms as actors in the process of technological development, while also recognizing the importance of institutions. Institutions are the rules of the game which help to organize the economy and the market (North, 1990). Examples include securing property rights, an adequate system of intellectual property, opportunity for high quality education, among others (Acemoglu and Robinson, 2012). The State-led growth perspective relies on public policy and the agency of the state, through industrial policy and other mechanisms, to foster growth and innovation. The concept of the developmental state was coined by Chalmers Johnson (1984) to explain the development of Japan in the post-War period and later has been applied to other cases in Southeast Asia, such as South Korea, Taiwan, Singapore, Hong Kong, among others (Haggard, 2018).

Technology policy is a tool by which the State acts to foster the development of specific economic sectors that are deemed strategic for a country. It can be seen differently from the perspective of a developed country and another who is still trying to catch up to the international technological frontier. However, the perception that technology is central for economic growth is one key aspect. Technology policy aims to bridge the gap between investments in basic science and research on one hand; and the activities of firms and industry on the other (Lundvall and Borras, 2005).

These policies are based on the notion that market failures need some form of intervention in order to be solved and that markets may not be the most efficient allocators of resources for invention and innovation. Arrow (1962) affirms that markets tend to underinvest in new technologies due to the unpredictability of the resources and the time that needs to be invested in order to produce profitable results from R&D. The author reaffirms the importance of the public sector in this process, in order to maximize spillover effects as well as promoting invention and innovation as public goods.

Even if investments in innovation do not generate immediate gains through commercially viable products, they can spillover to other activities over time. Mazzucatto (2014), for example, shows the importance of the investment in military research in the United States (conducted mainly by the government agency DARPA) that ended up creating many technologies, such as infrared waves, the GPS, the internet, touch screen technology and even computers. These technologies were then scaled to civilian and commercial use, engendering new whole industries and high profitability in subsequent decades.

Furthermore, in recent years technology is not only linked with actual products but is intertwined with the ability to produce knowledge. Knowledge and information can be seen as commodities or be characterized as intangible assets, such as patents, trademarks, industrial designs, marketing; in addition to other forms of knowledge, such as business strategies, organizational capacity, management tools, among others is an important fact that contributes to prosperity and development (Stiglitz, Greenwald, 2018).

The national systems of innovation approach, on the other hand, looks at the interaction between the state, national firms and research institutions aiming at a broader paradigm for analyzing innovation. Knowledge is assumed to be the central element for the economy, consequently, learning and innovation are the central processes through which knowledge is reproduced and applied into the generation of value through goods and services. Learning occurs in a socially embedded context and in a dynamic process that cannot be dissociated from the modern state (Lundvall, 2010).

In this sense, the systems of innovation approach present and encompassing view on the subject, by affirming that countries that would be best positioned to stimulate innovation would foster a combination of three elements working together: 1) the national economy and public policy; 2) institutions such as universities and research centers, and 3) private firms. The mutual interaction between these different actors with their respective goals and perspectives would be the best scenario conducive to innovation (Lundvall and Borras, 2005). None of the three elements of an Innovation System is more important than the other. Depending on the historical period and the technology in question, one of these three elements might have a greater role in generating either radical or incremental innovations in a given sector.

According to a Schumpeterian view, there are breaking points of technological change which bring about new economic paradigms. These radical innovations alter the structure of different national economies which later expand these to a set of incremental innovations across many industries (Perez and Soete, 1988; Perez, 2001). In each of these stages, different possibilities arise for late-industrializers and their firms, depending on the responses, catch-up strategies, and the global geopolitical context. These moments of rupture and change in technical paradigms would be the best window of opportunity for latecomers to try to leapfrog into new products and sectors that surpass the international technological frontier (Lee, 2019).

According to Lee (2019) catching-up means trying to close the gap between lower and higher-income countries and although the process involves a certain aspect of emulating the technologies from the leading nations, this is not enough. Catching up involves taking different paths, adapting technologies into new usages or new scales and it can also involve leapfrogging. By leapfrogging one understands a process in which a less advanced nations manages to produce a technology that transcends the international frontier, going even beyond that which is being produced in the leading nations.

Upgrading can occur within economic sectors, in the case that a country becomes more sophisticated, more efficient and/or adds more value to a product that is already being made. Upgrading can also occur between economic sectors, in the case that a country or firm ceases to produce lower value-added goods and moves into other economic sectors. Henry Yeung (2016) cites the example of Samsung, which started as a trading company focused on food and textiles and eventually upgraded into high value-added activities such as the production of smartphones and computers, for example.

Overall, these perspectives emphasize different aspects regarding the importance of technology for economic growth and prosperity. There are different ways to promote innovation and upgrading if these matters are analyzed through a predominantly market-led or state-led lenses. Some perspectives emphasize the importance of institutional factors such as property rights while others see the importance of technology policy in order to address market failures. Pundits studying cases of late-development point that industrial policy might be one of the most valuable tools in order to foster catching-up processes. Among other factors, (neo) Schumpeterian perspectives point to the importance of specific windows of opportunity, during which latecomers can approach the international technological frontier. Finally, the national systems of innovation approach aim to bring a holistic perspective for studying innovation, growth and technology, presenting a framework that considers the importance of firms, universities and national institutions.

3. THE STRATEGIC IMPORTANCE OF ION-LITHIUM BATTERIES: THE CASE OF CATL

The ion-lithium battery has been a game changer due to its capacity for powering digital devices, the fact of being small-sized, safe, and offering a long time of use (autonomy) before needing to be recharged. These batteries have made possible the extensive production and use of electric vehicles. Although first invented in the 1970's in the context of growing environmental concerns about climate change and the high dependence of oil in economic systems, it wasn't until the mid-1980's that these batterie became effective to be used in vehicles. ExxonMobil and BP, two of the biggest energy companies in the world, were among the first entities to fund research in the search for alternative energies, predicting that combustion vehicles would soon become obsolete.

However, in the 1980's the tide turned with falling oil prices fueling yet another round of global expansion of combustion vehicles. According to Sanderson (2022), companies investing in ion-lithium batteries at the time realized that it would take too long to see returns remotely similar to those that could be rapidly achieved by investing in oil and betting on internal combustion vehicles, due to the fact that at that point, the investment in ion-lithium batteries was basically still working in the basic science stage of innovation. It wasn't until 1985, with the innovations made by Oxford-based chemist John Goodenough that ion-lithium batteries would become suitable to be used in vehicles.

His invention would pave the way for Japan-based scientists to conduct secondary innovations enhancing the batteries capacity, operational system, and weight, which would ultimately lead to the rise of electronic consumer products in the 1990's and beyond, initially led by companies such as Sony, Toshiba, among others. The basic science in lithium-ion batteries, which is a crucial step for any innovation, was developed by researchers in the United States and the United Kingdom. But Japanese researchers and firms did the second crucial step: upgrading the technology for mass production with cost-efficiency. This is the key step that allows for the expansion of firms, new business models and innovative products. If Sony was the mass producer for the batteries that would be used in consumer goods, China would occupy this place in regard to ion-lithium batteries used in electric vehicles (Sanderson, 2022).

According to He et. Al. the Tenth Five Year plan (2001-2005) marks the beginning of an official policy for the development of electrical vehicles in China through growing R&D investments, denominated the "Three Verticals and Three Horizontals". The Three Horizontals refer to developing technologies for engines, batteries, and vehicle controllers, corresponding to the parts and components used to build the Three Verticals, which corresponds to the finished goods such as battery electric vehicle, hybrid electric vehicle and fuel cell electric vehicle (FCEV) (He et. Al., 2022).

In 2009 Beijing expanded its previous industrial policy for the EV industry. Wan Gang, Minister of Science and Technology and automotive expert, was a central figure in this process. China also launched a program to subsidize electric buses in 2009 covering ten cities, which later expanded to include financing for private electric car covering six cities as the first efforts to try to stimulate that segment. Between 2009 and 2017 subsidies reached a staggering US$ 60 billion. Government procurement was a strong policy tool with local governments purchasing vehicles from local companies (Sanderson, 2022).

China accounted for more than 60% of global sales of electric vehicles in 2022, showing the success of these policies over time. The country has focused especially on battery-powered vehicles due to its strong capabilities in battery production. This has resulted in the growing importance of the minerals used to fuel these industries. In fact, lithium, cobalt, nickel, and copper, as well as aluminum and steel are some of the most important minerals in the value chain. The battery is one of the most expensive parts of an electric vehicle and this is especially important considering that more than 60% of EVs in China and Europe are SUVs and larger cars, which require batteries that can be two to three times larger than those used in smaller models (IEA, 2023).

The extraction of the minerals needed to build electric vehicles are subject to geopolitics and distribution conflicts between countries, not to mention the fact that they have an environmental impact. The structure of ion-lithium batteries supply chain has shown China's greater dominance, with China-based CATL (Contemporary Amperex Technology), founded in 2011, reaching more than 37% of the global market share by 2022. Furthermore, the company has managed to strike a deal in 2019 to produce ion-lithium batteries in Germany, supplying companies such as Audi, BMW and Mercedes-Benz in their attempt to advance in the EVs market. It also supplies goods to Daimler's electric buses (Kim, 2023).

ATL was originally founded in Hong Kong in 1999 as a company manufacturing batteries for mobile phones. In the 2000's with the boom of mobile phones and later MP3 players, ATL bought a patent from Bell labs in the US to produce polymer batteries. ATL managed to produce batteries at a much lower cost than their Korean and Japanese counterparts and became a supplier to major telecommunications and electronics companies. This period coincided with China's entry into the WTO and foreign direct investment was abundant. ATL received funding from the US-based Carlyle Group and integrated Apple's GVC, supplying batteries for the Ipod in 2004. The company was on a path of modernization and in 2005 it was bought by the Japanese company TDK (Sanderson, 2022).

CATL separated from ATL in 2011 in the context of the boom of the governmental policies fostering the expansion of electric vehicles in China. The company hired foreign talent who had worked on the joint ventures between Chinese firms and multinational companies in the automotive sector in order to structure its research and development sector. CATL built a battery that lasts for 16 years, meaning it could be reutilized, outlasting the original car. It also continued to work on reducing the size and weight of the batteries as well as improving durability and safety. The reduction of costs is a fundamental step in popularizing EVs for mass consumption.

In 2013 CATL was contracted by BMW Brilliance, a joint venture with a Chinese firm. The rigorous supervision and standards of BMW helped CATL to upgrade its processes and product quality. According to Sanderson:

> "Between 2014 and 2017 CATL's sales increased at a compound annual growth rate of 263 percent. (...) In 2017 CATL filed for an initial public offering (IPO) on the Shenzhen Stock Exchange, with the help of Goldman Sachs. The company raised $853 million and became the world's largest producer of electric car batteries with a fifty percent share of the Chinese market. It would maintain that position consistently for the next four years." (Sanderson, 2022, p. 44).

Furthermore, the use of robotics rapidly enhanced China's electric batteries scale, reducing its costs and raising its competitive capabilities (Wang, 2023). The fact that the Chinese Government determined that Chinese electric vehicles had to use locally produced batteries was a powerful incentive to the industry's expansion. In 2020 Tesla created a factory in Shanghai using CATL as their supplier (Kane, 2020).

3. THE STRATEGIC IMPORTANCE OF ION-LITHIUM BATTERIES: THE CASE OF CATL

The key driver to China's successful promotion of electric vehicles has been subsidies for purchasing EVs (given to the automakers for each car sold), which were first introduced in 2009. Although they were supposed to be phased out several times including this year, there is renewed discussion about extending them.[1] Over time, the subsidies have been adjusted in large part due to widespread scale fraud by automakers who sold cars to themselves and passed government certification tests with larger batteries than were used in the cars sold on the market in order to qualify for larger subsidies (subsidies were based on battery size). Tax rebates for EVs have also played a role and will loom larger as China eventually phases out subsidies. The government also introduced a credit system in 2018. Automakers received credits for each EV sold with the aim to force automakers to sell more and more EVs as a percentage of total cars sold (Yang et. al. 2021; Dezan Shira and Associates 2022).

The cost of building this industry has been substantial for the government. From 2009-2019, the total cost was just under 100 billion USD. Almost half the total were the EV purchase subsidies. As subsidies have been ratcheted down, the state has increased R&D spending. For both 2018 and 2019, each year's R&D spending was almost six times the spending on R&D for the 2009-2017 period (Dezan Shira and Associates 2022). While many have hailed the government's investment in the infrastructure of EVs, it has not been costly relative to the other types of expenditure. Four of the top ten recipients of subsidies in China are automotive manufacturers and most of those subsidies are for EVs: SAIC, BYD, Great Wall and JAC. Contemporary Amperex Technology Co. Limited (CATL) was the eleventh largest recipient, and two other automakers were in the top twenty (Kawase 2022).

The goal established by the Central Government for 2020 was for new energy and electric vehicles to account for 70 percent of the domestic market. Moreover, China aimed to produce two firms ranking in the top 10 players worldwide. Electric batteries, motors, and other components should have reached an international level of quality and represent 80 percent of China's market. By 2025, Chinese EVs firms should represent 80 percent of the domestic market, and two homegrown companies should be in the ranks of the 10 leading firms with 10 percent of their total sales (State Strategic Advisory Committee 2015). The electric vehicle industry presents an interesting example of China's growing proficiency in the production of electric batteries (ion-lithium batteries), with CATL being the most well-known success case. Founded in 2011, the company has advanced

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[1] .- Provincial governments have stepped in to make up for the shortfall in central government subsidies (https://www.bloomberg.com/news/articles/2023-03-07/china-s-provinces-offer-ev-sweeteners-as-national-subsidies-fade#xj4y7vzkg).

quickly in global markets and in 2021 it accounted for more than 32% of the global market share of ion-lithium batteries, making it the biggest producer in the world (Sanderson 2022).

China's domination of lithium batteries for EVs has also been a direct product of government policy. The government operated a "whitelist" of approved domestic battery manufacturers which were the only producers that EV manufacturers could use if they wished to receive the government subsidies for EVs. This policy led directly to the rise of CATL and helped BYD transition from phone batteries to auto batteries. With Guoxuan, these three are the second, fifth and ninth largest EV battery makers in the world. From 2014-2017, CATL's sales increased at a compound annual growth rate of 263 percent (Sanderson 2022).

The case of BYD Auto is important and needs to be mentioned, considering it overtook Tesla's position as the biggest market share in electric vehicles, producing cars, trucks, buses, electric bikes, among other products. BYD has been founded in 1995, the company expanded upon the acquisition of Qinchuan Automobile Company in 2002 and after that it has raised HKD$ 1.6 billion in the Hong Kong Stock Market. The firm's electric batteries division, called Fin Dreams, currently holds third place among the biggest battery makers in the world, with a 13% market share.

The firm grew very rapidly in the last two decades, supported by the expansion of China's consumer market, while also being aided by the intensive industrial policies conducted by the Chinese state, currently holding more than 30 industrial parks across six continents. Although most of its sales are focused on Mainland China, the firm has been expanding into global markets, with special focus on Europe. According to the firm's official website it had sold more than 2.68 million vehicles (BYD, 2023) by September 2022.

By 2019, local firms, including JVs, already dominated China's EV market with 85 percent market share.[2] As of now SAIC, Geely and BYD have had a certain degree of success in their internationalization strategy, especially exporting to European markets. Other firms such as BAIC and Chery continue to be suppliers mainly to the domestic market. There are also smaller brands such as Nio Inc. and Xpeng which are trying to expand internationally. In fact, SAIC-GM-Wuling (a joint venture with General Motors) and BYD ranked third and fourth in the largest sales of EVs in 2021, with market shares of 10.5% and 9.1% respectively (Kane 2022), which means China has reached the goal of producing two major international players in the sector.

In 2021, China accounted for more than half of the world's global sales of EVs. However, the structure of the EV market in China is still fragmented with more than 200 firms producing parts, components and the other steps in the EV value chain. Trends suggest that there will be growing competition in the domestic market between the established firms, SAIC-GM-Wuling, BYD, Geely, and newcomers such as Nio and Xpeng (Daxue Consulting 2022). Sanderson (2022) points out that government funding and subsidies that have been directed to the industry since 2009 have directly contributed to the rise of new firms in the sector.

While the building of large-scale battery makers has been successful, subsidies have encouraged both lots of firm entry into the EV market and allowed too many of them to continue to survive. There were 119 producers of EVs in 2020. With a market of approximately 1.5 million EVs, each producer on average produced 12,600 vehicles, far below the necessary scale economies (Kennedy 2020). The other issue is that quality of Chinese EVs still lags behind. They tend to export only to developing countries. While BYD sells more units than Tesla, Chinese EV firms generally sell to the low and middle tiers of auto buyers. The Chinese makers comprise 80 percent of the domestic market, which at 3.3 million cars sold in 2021 comprised 53 percent of global sales in units. In the same year China accounted for 35% of exported electric cars, compared with 25% in 2021. Europe

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[2] .- McKinsey "Winning the Chinese BEV Market," May 4, 2021.

remains China’s largest trade partner for both EVs and batteries. In 2022, the share of EVs made in China and sold in the European market increased to 16%, up from about 11% in 2021 (IEA 2022; IEA, 2023).

4. AN OVERVIEW ABOUT CHINESE INVESTMENTS IN LATIN AMERICA

Between 2005 and 2012 is estimated that China’s total FDI toward South America plus Mexico totaled around $63 billion, while between 2005-2023 the total FDI of Chinese firms in the same countries reached $212 billion. Brazil represented just over one-third of the total, with $73.3 billion worth of Chinese investment in 264 projects (AEI, 2024). Chinese FDI in Latin America continued to grow until it was interrupted by the social and economic challenges of the pandemic, aggravated by China’s strict lockdown and zero COVID policies. In 2020 and 2021, Latin America saw a downfall of the total amount invested by China in the region.

However, the investment flows grew in 2022 and 2023 – only this time, the funds were directed toward new sectors such as solar, wind, and hydropower as well as electric vehicles (EVs). Mining in strategic materials such as lithium and rare earth minerals, which are crucial as supplies for the value chain of many advanced technologies involved in decarbonization is also a priority. Prominent Chinese firms acting in these new subsectors are privately owned and/or mixed capital companies, such as BYD and Great Wall Motors, for example (Rhodium Group, 2024).

In Latin America in 2022-2023 the general trend of Chinese investment has been of a higher number of smaller projects. This means a shift from the previous trend of big infrastructure projects under the Belt and Road Initiative (BRI), such as State Grid’s and China Three Gorges’ multi-billion investments in Brazil and Argentina, for example, toward more nimble, numerous, and technologically intensive projects (Kotz and Haro-Sly, 2023). Albeit smaller in size, these new projects are directed toward strategic areas.

Analysts have noted that the term “New Infrastructure,” which has appeared in Chinese media and policy documents, as the lexicon designating the sectors China wants to develop at home while also becoming a competitive global player (Myers, Melguizo and Wang, 2024). Information technologies linked to data centers, semiconductors, and artificial intelligence are important focuses of policymakers in Beijing, but so are renewable energy generation and electric vehicles. Technology is a key aspect in China’s efforts to revive its domestic economy and competing with the United States.

The shift in foreign investment policy reflects the changing priorities and characteristics of the Chinese economy. Concepts such as new “quality productive forces,” “small but beautiful,” “indigenous innovation,” and self-reliance have emerged as priorities for the Chinese state. The government is trying to reignite economic growth amid the difficulties and slowdown caused by an aging population, high youth unemployment, the property crisis in the real estate sector, and a recovery in consumption post-COVID that was not as exuberant as Beijing had expected. All of these reflect in Chinese firms investing abroad, which are trying to find new markets and trade partners, focusing on technology and innovation, while also exporting overcapacity in industries where domestic demand is falling, as the case of EVs (Myers, Melguizo and Wang, 2024).

The following cases of FDI in different countries illustrate the broader trends mentioned in the previous paragraphs. For example, in 2022, there were two FDI acquisitions in the lithium sector in Argentina, made by Ganfeng Lithium and Zijin Mining Group, with a total value of $1.7 billion.

Greenfield investments in battery factories and mining by Chinese automobile manufacturer Chery and a lithium carbonate factory from Liex, a subsidiary of Zijin Mining Group, were both announced in Argentina in 2023 (AEI, 2024).

In Chile, the Chinese EV manufacturer BYD announced a $290 million investment to exploit lithium. In addition to that, automobile manufacturer Geely acquired seven plants globally, including one in Cordoba, Argentina, by forming a joint venture with Renault. The plants make aluminum parts for gearboxes that will be used in its subsidiary Horse, which produces gearboxes at other plants in Chile and Brazil and supplies companies like Renault, Dacia, Nissan, and Mitsubishi (China Daily, 2024). Chile produces circa 32% of the world's lithium and represented 89% of China's imports of lithium carbonate in 2022, reinforcing the country's strategic position vis-à-vis the Asian partner. Moreover, much of the lithium that is produced in Argentina goes through Chile to be exported to China, reinforcing its competitive profile due to logistics.

Chile has developed a national strategy to try to move up the lithium value chain, adding value to the sector instead of just extracting and exporting the mineral. Although in its initial stages, Boric's industrial policy will focus on public-private partnerships to try to maintain stages of the adding value inside the country's territory. It will also establish the creation of a public company focused on research and development and technology projects linked to mineral sectors. Moreover, Chile also detains expressive reserves of copper, which is also used in technologies linked to decarbonization and just general-purpose electronics (Chile National Lithium Strategy, 2024). As of this moment in the North American firm Albermale and Chilean private firm SQM are the main firms acting in Chile's lithium sector. The firm Tianqi Mining acquired a 22% stake at SQM and if BYD's project does go through, it would promote a greater presence of Chinese firms in Chile.

In Brazil, there was continued investment by Great Wall Motors, which in 2021 bought a Mercedes-Benz factory in São Paulo state aiming to produce electric vehicles and batteries. The company continues building production capacity with an investment plan of 4 billion Brazilian real ($776 million) between 2022-2025. The automaker will manufacture electric cars and hybrids, in addition to developing research and development projects. Volvo, a Swedish automaker whose main shareholder position has been acquired by the Chinese firm Geely, made an investment of 881 million real in its factory in Paraná state, Brazil. These funds will be used for the development of products and services focusing on electromobility and decarbonization and are part of a greater investment cycle that is projected to reach 1.5 billion yuan between 2022-2025 (Reuters, 2024).

BYD is investing 1.1 billion reals in the Brazilian state of Bahia to produce chassis for electric buses and trucks, manufacture electric and hybrid passenger vehicles (with an initial projected capacity of 150,000 units annually), as well as processing lithium and iron phosphate in Brazil, that will later be exported to global markets. In July 2023, the project was confirmed. BYD will take over three factories formerly owned by U.S.-based Ford Motors in the Bahia state, which left the country in 2021 after more than 50 years of operations in Brazil. BYD expects to start production in Brazil in the second half of 2024 and has already partnered with local energy firm Raizen to build charging network stations in eight large metropolises in the country (Reuters, 2024).

The only Chinese battery manufacturing plant in South America is owned by BYD and it's located in the Northen region of Brazil called Manaus. The production started in 2020 and there are still many improvements that could be made possible by industrial policies and local suppliers' upgrading, seeing that the Manaus plant acts mostly in the assembly of batteries, a lower value-added activity if compared to the actual manufacturing of key parts and components. As BYD's plants in Bahia start their production in 2025, there will possibly be a greater demand for batteries and possibly greater investments in that sector within Brazil. However, since the country's consumer market is very expressive, with a population exceeding 215 million people, and sales of automobiles reaching 2.3 million in 2023 (CSIS, 2024), it is still uncertain whether or not BYD's battery factories will serve simply to supply for the local market and/or if they will also be used for exports to other countries, potentially the MERCOSUR partners with whom Brazil has a preferential agreement on common tariffs based on the amount of local added value in the end-product, for example.

In Peru, Zijin Mining has just announced a US$ 250 million investment project for metal extraction, which is still at the planning stage. Regarding the case of Bolivia, the country lost possible funding opportunities due to political and institutional instability. Only very recently, in June and July of 2023 Chinese companies began to invest there again, with two projects focused on the extraction of lithium. The first amounting to US$ 1.38 billion, to exploit the salt flats of Uyuni and Copasa in partnership with local firm Yacimientos de Litio Boliviano (YLB), and led by China's CATL, the battery firm previously mentioned. CATL has 66% of the shares in this project. The second one was conducted by China International Trust and Investment (CITIC) amounting to US$ 400 million, which is still underway (Benchmark Minerals, 2024; CSIS, 2024).

Regarding its position in Latin America, in summary, China's state-owned enterprises were the firstcomers to the region in the 2000's, building the basis in oil and gas and agriculture investments, aiming to access natural resources needed for maintaining the growth of China's economy, through mergers and acquisitions. After 2012, came a different phase of FDI, in which state-owned firms such as State Grid and China Three Gorges made multibillion dollar investments in generation, transmission and distribution of electricity, which were then considered as being part of China's foreign policy of economic integration known as the Belt and Road Initiative. In this period there was greater presence of China's banks in this process, such as the China Export Import Bank (EXIMBANK) and the China Development Bank, trends that have been going down since 2019 and, since then, firms have taken the lead through greenfield and brownfield FDI. These processes allowed for Chinese firms to learn about the local realities as well as the institutional, regulatory and labor standards in different countries.

5. CONCLUDING REMARKS

Regarding the development of technology and domestic manufacturing capabilities in China, industrial policy was essential for the growth of the EVs market since 2009, when the Government started acting more directly in the industry through two different measures: on the demand side, government procurement for taxis, buses and public transportation helped to boost up the market and subsidies for buyers were also offered. On the other hand, in the supply side, protectionism was used to ensure that national companies would be the main beneficiaries of government funds. Subsidies were given to companies that produced cars domestically, but even foreign firms were obliged to use components made by Chinese firms such as the batteries made by CATL and BYD if they wanted to sell to Chinese customers.

After Covid, private companies in the EVs and green energy sector have been investing abroad in sectors that allow for greater profits, and which are more intensive in technology. As was mentioned before, these changes in the profile of FDI are connected to the domestic challenges and the qualitative transformation of China's domestic economy, which is inextricably linked to the processes of upgrading, innovation and technological development. In this sense, as China's economy transitions towards different sectors such as A.I, biotechnology, pharmaceuticals, solar and wind power generation and equipment, electric vehicles, among others, so changes the profile and strategy of Chinese firms abroad. The recent changes in the profile of FDI in Latin America is part of the new chapter of Chinese firms going global. It may yet be too soon to affirm, but evidence point to the articulation of a regional value chain in green technologies led by Chinese firms, with Chile and Argentina producing strategic minerals and batteries, for example, while manufacturing capacity for EVs and solar panels is located in Brazil, which could serve as a hub for exports to the region as a whole.

The key findings are preliminary, but we infer that there is a new phase of Chinese engagement in Latin America post-Covid, with a change in the profile of FDI: 1) relevant investments are now conducted not only through state owned enterprises, but increasingly made by private firms, especially when seeing outside of legacy sectors; 2) sectors of destination are slowly changing from oil, gas and agriculture towards renewable energy sources, electric vehicles and mining of strategic minerals such as lithium and rare earth minerals; 3) the flows of investments are smaller in the total quantity, but there is a higher number of projects in the region overall; 4) the FDI projects are increasingly directed in knowledge/technologically intensive sectors, instead of capital intensive ones, as was the case in traditional (legacy) sectors (such as electricity generation and oil) of the pre 2019 phase, which was the year of transition with the first EV projects being rolled out and the post-Covid period being the consolidation of this new phase, which is also seeing a gradual increase of greenfield investments as a mode of entry, vis-a-vis a predominance of mergers and acquisitions in the early to mid-2010's.

In conclusion, in a context of higher tariffs and protectionism being imposed on Chinese products in developed country markets such as Europe and the US, China will continue to focus on the international expansion of its companies in the Global South, and Latin America is gaining relevance. Faced with this situation, Latin American countries must develop their own plans, industrial policies and strategies for technological upgrading, innovation and production of higher value-added goods. Chinese capital can be seen as a positive factor for the region's development processes, as long as the respective countries take control of their own macroeconomic and institutional environments.

Trends indicate that there is a window of possibilities and opportunities open in this regard, especially in sectors linked to decarbonization, renewable energy, electromobility and green technologies. However, the countries in the region must focus on developing their industrial policies and innovation strategies, as well as maybe requiring technology transfer agreements linked to some of these FDI projects. In addition to that, investments in education and integration of local labor into these initiatives could potentialize spillover effects for upgrading. Conversely, the risk remains that Latin America could go down on a path of dependency and continuing to export natural resources and commodities, in exchange for industrial goods, a historical pattern that has deleterious effects on local societies in terms of sustainable development.

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Uma análise sobre a influência geopolítica da transição energética na cadeia de valor global de materiais críticos

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Resumen

A medida que el mundo avanza hacia la transición energética, la demanda por materiales críticos aumenta significativamente debido a la necesidad de nuevas tecnologías con baja huella de carbono. Así, la producción y el procesamiento de minerales y metales altamente concentrados geográficamente, considerados críticos, representan una dinámica geopolítica compleja de escasez y abastecimiento. En este sentido, el presente artículo discute la relación entre producción y procesamiento de materiales considerados críticos con el fin de analizar la concentración del mercado de estos materiales en todo el mundo. Para ello, se utiliza el Índice de Herfindahl-Hirschman (IHH) para evaluar el grado de concentración de los materiales y, en consecuencia, la producción de nuevas dependencias económicas y geopolíticas. Este análisis busca identificar riesgos asociados con la productividad y la concentración de estos recursos, esenciales para la transición energética.

PALABRAS CLAVE: Transición energética, Minerales críticos, Índice de concentración

Abstract

As the world moves towards renewable energy sources, the demand for critical materials increases significantly due to the need for new low-carbon technologies. In this context, this article discusses the association between production and processing of materials considered critical in order to analyze their market concentration around the world. For this purpose, the Herfindahl-Hirschman Index (HHI) is used to assess the degree of concentration of these materials and, consequently, the production of new economic and geopolitical dependencies. This analysis aims to identify the challenges associated with the lack and concentration of these resources, which are essential for the energy transition.

KEYWORDS: Energy transition, Critical minerals, Concentration index

1. INTRODUÇÃO

Para alcançar as metas climáticas estabelecidas no Acordo de Paris, a descarbonização de diversos setores como transporte, energia e a economia global, como um todo, tornou-se uma prioridade para os governos (Hache, Gondia Seck & Guedes, 2023). À medida que o mundo avança para o uso de energias renováveis e de tecnologias com menor pegada de carbono, surgem novos desafios associados ao aumento da demanda por materiais essenciais para a transição energética (IRENA, 2021). Nesse contexto, há um objetivo em comum: a reestruturação de sistemas energéticos, visando a produção de energia limpa, com o uso e desenvolvimento, por exemplo, de painéis solares e baterias para veículos elétricos (Greim et al., 2020).

Ao longo da história, o cenário geopolítico mundial esteve associado à concentração de reservas de petróleo, onde os maiores produtores possuíam vantagens estratégicas sobre a cadeia de suprimentos (Månberger & Johansson, 2019). A partir da ascensão das energias renováveis, a produção e o processamento de minerais e metais altamente concentrados geograficamente, considerados críticos, representam uma dinâmica geopolítica complexa de escassez e abastecimento (Månberger & Johansson, 2019). Essa mudança sugere que países com grandes reservas e com grande capacidade no refino desses minerais críticos podem emergir enquanto atores estratégicos na geopolítica global, influenciando não apenas o mercado, mas também as cadeias de valor associadas à transição energética.

Nesse sentido, o objetivo deste estudo é analisar como a transição energética afeta o mercado de materiais críticos, considerando a distribuição de reservas desses materiais, assim como seu processamento ao redor do mundo. Isto é, avaliar se a distribuição global desses materiais representa uma relação de dependência que pode ser utilizada com objetivos geopolíticos, visto que são considerados materiais críticos. Para tanto, utiliza-se o Índice de Herfindahl-Hirschman (IHH) a fim de avaliar o grau de concentração tanto das reservas quanto do processamento desses materiais.

Na primeira seção deste estudo, apresenta-se a breve discussão em torno do conceito de reserva e recurso de materiais críticos diante da transição energética, assim como discutir a demanda por esses materiais. Em seguida, descreve-se a abordagem metodológica utilizada para atingir os objetivos descritos anteriormente. O IHH foi aplicado aos seguintes produtos: níquel, lítio, cobalto e cobre. Por fim, apresenta-se uma discussão em torno dos resultados obtidos para cada um dos materiais críticos avaliados, baseando-se no índice IHH. Essa análise discute a relação da concentração da produção dos materiais selecionados e o seu processamento, a fim de identificar quais países se destacam na cadeia de valor e, consequentemente, sua influência geopolítica sobre o setor.

2. MATERIAIS CRÍTICOS PARA TRANSIÇÃO ENERGÉTICA: UMA DISCUSSÃO SOBRE RECURSOS E RESERVAS

Ao longo da história, a transição para outras fontes de energia esteve associada à demanda por materiais (Zotin, Rochedo & Szklo, 2023). À medida que a exploração dos minerais avançou, tornou-se possível desenvolver novas aplicações e melhorar o desempenho técnico de diversos produtos (National Research Council, 2008). Desde a transição do carvão para o petróleo, a expansão das indústrias e o surgimento de novas tecnologias possibilitaram o surgimento de sistemas energéticos (Fouquet, 2009).

Durante a Revolução Industrial, a máquina vapor e a expansão das ferrovias aumentaram a demanda por aço, cobre e outros minerais (Yang et al. 2021). O acesso às reservas de carvão e às tecnologias embutidas nesse processo também contribuíram para que a Inglaterra obtivesse uma posição de prestígio ao longo do século XIX, consolidando-se como uma potência industrial e econômica (Barak 2015). Da mesma forma, motores a combustão interna, automóveis e petroquímicos impulsionaram a expansão da indústria do petróleo (Groß et al., 2022). O acesso a combustíveis fósseis conduziu grande parte da riqueza de países como Estados Unidos e a antiga União Soviética durante o século XX (Criekemans, 2023).

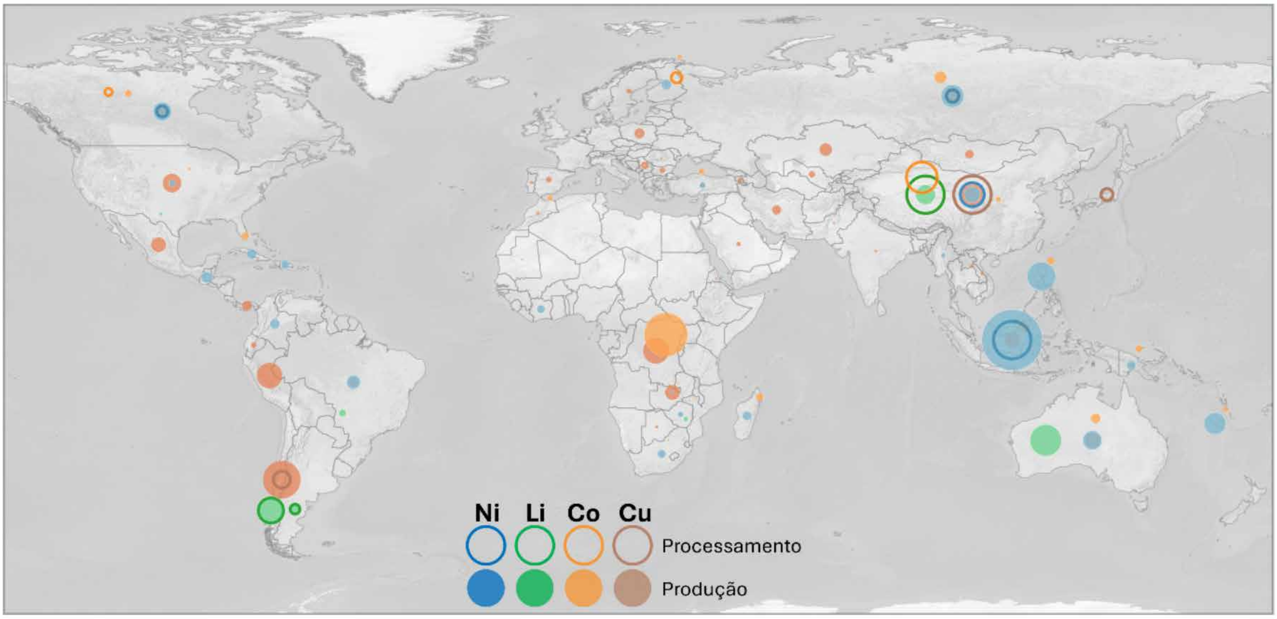
Diante desse cenário, a ascensão de energias renováveis na atual transição energética reitera o debate sobre a relevância da inovação e dos avanços tecnológicos no mercado de energia e suas dinâmicas geopolíticas (Su et al., 2021). Novas rotas comerciais e uma maior demanda por matérias-primas consideradas relevantes para fabricação de tecnologias de energia renovável intensificam a concorrência para controlar determinados materiais, considerados estratégicos para garantir a transição (Hatipoglu, Al Muhanna & Efird 2020). Ao mesmo tempo, as áreas de produção de materiais e minerais críticos também exercem sua influência no mercado de energia de modo que países produtores e consumidores enfrentam riscos geopolíticos associados à dependência de materiais (Månberger & Johansson 2019).

A disponibilidade desses minerais e materiais na natureza para futura extração pode ser classificada como recursos ou reservas, dependendo do grau de conhecimento geológico, maturidade tecnológica e nível de certeza sobre a viabilidade comercial para explorá-los (Lundaev et al., 2023). A jazida de minerais cuja extração é econômica e tecnologicamente viável é denominada como reserva (Roonwal, 2019). Esses aspectos fundamentais diferenciam as reservas dos recursos, que consistem na disposição de minerais ou materiais alocados na natureza que são inacessíveis devido a questões econômicas, tecnológicas e ambientais (National Research Council. 2008). É necessário destacar que esses conceitos não consistem em uma categorização fixa, visto que sua classificação enquanto recursos ou reservas podem variar de acordo com revisões técnicas, avanços tecnológicos ou a viabilidade econômica de sua exploração (Lundaev et al., 2023).

Da mesma forma, a compreensão sobre o nível de criticidade de materiais também pode modificar-se ao longo do tempo. Na literatura, o termo de criticidade é amplo, pois sua definição é reavaliada à medida que a preocupação em torno do acesso à oferta desses materiais é crescente, devido ao aumento da demanda (Greim et al., 2020). A segurança do abastecimento de materiais críticos está associada à sua abundância e, consequentemente, à sua escassez. Isso ocorre porque a concentração da oferta desses materiais, em determinadas regiões, classifica-os como críticos devido à importância que possuem para a produção de tecnologias limpas, principalmente em um contexto de transição energética (Lundaev et al., 2023).

Países dependentes da importação de materiais se esforçam para garantir o fornecimento de energia e outros recursos necessários para suas economias. Para tanto, adotam estratégias que garantam seu acesso aos materiais no mercado internacional a fim de adquirir matéria-prima para produção de tecnologias essenciais para a transição energética (Su et al., 2021). Por outro lado, os países que controlam o processamento também utilizam seus recursos para aumentar sua influência política tanto a um nível regional quanto global (Månberger & Johansson 2019). Nesse sentido, a alta concentração da ocorrência de depósitos minerais e produção de materiais e minerais críticos em poucos países pode implicar na dependência de tais importações para países que consomem esses materiais (Korinek & Kim 2011). A figura 1 abaixo ilustra objetivamente essa questão:

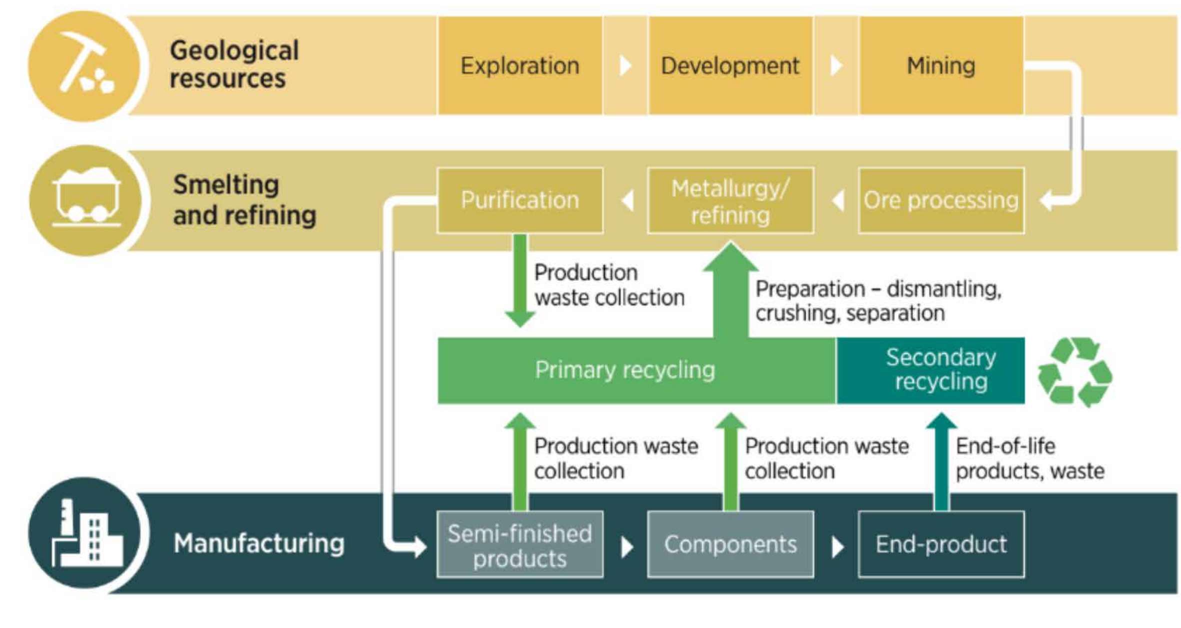
Figura 1 - Produção e processamento de suprimentos para materiais críticos selecionados em 2022 (Ni-Níquel, Li-Lítio, Co-Cobalto e Cu-Cobre)



Fonte: Elaboração própria, com dados da WMD -World Mining Data (2024)

O desenvolvimento de baterias de lítio desempenha um papel relevante na descarbonização de certos setores (Hache, Sokhna Seck & Guedes 2023). Outros minerais críticos como cobalto, níquel e cobre também são relevantes para o desenvolvimento de redes elétricas, armazenamento de energia, tecnologias de geração fotovoltaicas e eólicas, assim como sua aplicação em outras tecnologias de baixo carbono, como na produção de hidrogênio (Grandell et al., 2016). Como um dos setores demandantes, tem-se o mercado de baterias recarregáveis de íon lítio (IEA, 2018). Em 2022, por exemplo, a venda de carros elétricos ultrapassou 10 milhões de unidades, enquanto a capacidade dos sistemas de armazenamento dobrou no mesmo período. Entre 2017 e 2022, o setor de energia foi o principal fator que provocou um aumento de 70% na demanda por cobalto, 40% por níquel e a uma triplicação na procura por lítio (IEA, 2023).

A **figura 2** abaixo ilustra a cadeia de abastecimento de materiais críticos, considerando suas etapas principais, que envolvem desde a prospecção mineral, extração das minas até o produto final.



Fonte: IRENA (2023)

O diagrama ilustra a interconexão entre essas diferentes etapas. Primeiramente inicia-se com a exploração, caracterização e classificação enquanto reserva até culminar na etapa de lavra mineral. Após a extração, os materiais são transportados para plantas de processamento mineral, onde são convertidos em minério concentrado, que variam dependendo da matéria-prima. O refino inclui as fases de purificação e ultra-processamento dos minerais, crucial para retirar as impurezas dos metais, preparando-os para usos industriais. Cada vez mais, há uma discussão sobre a reciclagem desses produtos, incluindo determinados resíduos gerados ao longo de seu ciclo de vida. A figura 2 também demonstra a dinâmica de interdependência na cadeia de abastecimento de materiais críticos (IRENA, 2023).

Nesse contexto, os países buscam garantir não apenas o abastecimento, mas posicionar-se como players relevantes nesse mercado. O Departamento de Defesa norte-americano, por exemplo, concedeu $20,6 milhões em 2023 para avançar na exploração de níquel em Minnesota. Além disso, o país investiu $90 milhões para apoiar a reabertura de uma mina de lítio na Carolina do Norte para retomar as operações até 2035 (U.S. Geological Survey 2023). Nos últimos anos, a China também demonstrou sua preocupação com materiais críticos. O país investiu em inovações tecnológicas para descarbonização, tornando-se um dos atores mais relevantes no registro de patentes na área de engenharia, química e transportes, de acordo com o relatório Global Innovation Index (WIPO, 2023). Apesar de ser desafiador prever a demanda futura por materiais críticos, especialmente a longo prazo, estima-se que as transformações necessárias para a transição energética produzam novas rotas comerciais e outras dinâmicas geopolíticas (Hache, Sokhna Seck & Guedes 2023).

3. MÉTODO

Nesta seção, descreve-se a abordagem utilizada para analisar como a transição energética afeta o mercado de materiais críticos. Para tanto, considera-se a concentração da produção e do processamento de minerais críticos a fim de avaliar se sua distribuição geográfica representa uma relação de dependência entre países, associada ao uso desses materiais. Optou-se por analisar os seguintes produtos: cobre, lítio, níquel e cobalto. Essa escolha deve-se ao uso desses materiais na produção de tecnologias necessárias para a transição energética, como turbinas, painéis solares e baterias para veículos elétricos. Para avaliar o grau de dependência, utilizou-se o Índice de Herfindahl-Hirschman (IHH) para medir a concentração desses mercados.

Ao longo deste estudo, analisou-se a produção e o processamento dos materiais críticos selecionados a fim de delimitar o foco da investigação, que se propõe a avaliar o mercado atual de materiais – desconsiderando as possibilidades de extração futura em sua análise. Essa escolha metodológica pretende facilitar a análise da capacidade de produção atual do mercado de materiais críticos, visto que o conceito de reservas considera o total estimado que poderá ser extraído no futuro. Portanto, focou-se na análise da atividade de extração, em vez de considerar as reservas, assumindo que a extração de materiais implica na disponibilidade de reservas para tal atividade.

Nesse sentido, a primeira seção deste trabalho consiste na discussão sobre o uso do conceito de recursos e reservas, assim como discutir a demanda por esses materiais. Essa etapa baseia-se na revisão da literatura sobre o tema, abordando o funcionamento do mercado de materiais críticos. Em seguida, calcula-se o Índice de Herfindahl-Hirschman (IHH) para cada produto mencionado anteriormente desde 2020 até 2023 para acompanhar o comportamento do IHH ao longo do tempo. Isto é, compreender a dinâmica do mercado de materiais críticos tanto na extração quanto no processamento. Os valores considerados para análise foram retirados do relatório Critical Minerals Market Review 2023 produzido pela International Energy Agency – IEA, publicado em 2023. Por fim, discute-se os resultados obtidos ao longo da realização deste estudo.

3.1. Índice de Concentração

Índices de concentração pretendem indicar o grau de concorrência em determinado mercado. Quanto maior o valor do índice de concentração, menor é o grau de concorrência e mais concentrado estará o poder de mercado virtual da indústria (Resende, p. 55, 2013). Nesse sentido, uma maior concentração industrial significa que há desigualdades nesse mercado, o que poderá implicar em maior grau de concentração.

Diferentes métricas podem ser utilizadas para medir o grau de concentração de mercado. Dentre as mais comuns, destacam-se as razões de concentração (CR), que pode ser definida pela Fórmula 3.1:

$$CR(k) = \sum_{i=1}^{k} s_i \qquad (3.1)$$

O CR(k) indica a parcela que as firmas possuem em determinado mercado. Por exemplo, CR (5) trata-se das 5 maiores firmas atuantes (Naldi & Flamini, 2014). Outra ferramenta analítica é o Índice de Herfindahl–Hirschman (IHH), que busca mensurar a dimensão das firmas em relação à indústria que atuam. O IHH, portanto, permite avaliar o grau de concentração do mercado de determinado setor (Resende, 2013).

Tal expressão pode ser definida pela Fórmula 3.2:

$$HH = \sum_{i=1}^{n} s_i^2 . \qquad (3.2)$$

Elevar o market share de cada empresa ao quadrado permite atribuir um peso maior às empresas relativamente maiores. Assim, quanto mais elevado for o IHH, maior será a concentração em determinado mercado. Isto é, haverá menor concorrência entre os produtores (Resende, 2013). Como o IHH trata-se das parcelas de mercado, há três faixas para avaliar o IHH considerando processos de fusões, assim como os valores potenciais do índice após a fusão entre dois atores. Dessa forma, compreende-se que:

Tabela 1: Níveis de concentração de mercado.

Nível de concentração	IHH
Baixo	$0 \leq HH < 1.000$
Moderado	$1.000 \leq HH \leq 1.800$
Alto	$HH > 1.800$

Fonte: Oliveira (2023)

3.2. Dados utilizados

Diante das informações apresentadas até aqui, esta seção explora os dados obtidos sobre a concentração de materiais críticos, considerando a produção e o processamento de cobre, lítio, níquel e cobalto

3.2.1. Cobre

A concorrência de grandes depósitos minerais de cobre concentra-se no Chile, Peru, República Democrática do Congo (RDC) e na China, respectivamente. A China desempenha um papel dominante no processamento de cobre, atuando como principal país neste mercado. De modo geral, a extração manteve-se estável nos últimos anos, com o aumento da participação de outros países tanto na extração quanto no processamento.

Em seguida, o Chile e o Japão também se destacam em relação ao processamento. Nota-se que, ao longo dos anos, a extração de cobre nos países selecionados mostrou-se relativamente constante. O mesmo ocorre no processamento, com um crescimento menos acelerado em 2023. A China está aumentando sua capacidade de processamento de forma consistente, o que pode indicar um maior domínio no mercado global de cobre processado. A expansão da produção no Peru e RDC sugere um aumento na importância desses países na cadeia de suprimento de cobre. A tabela 2 e 3 abaixo resumem os dados de produção e processamento de cobre de alguns países.

Tabela 2: Produção de cobre

Extração de Cobre em Mt	2020	2021	2022	2023
Chile	5.7	5.6	5.4	5.6
Peru	2.1	2.3	2.5	2.58
RDC	1.6	1.8	2.1	2.42
China	1.9	1.5	1.2	1.9
Outros	9.7	9.8	10.8	10.2

Fonte: IEA (2023)

Tabela 3: Processamento de cobre

Processamento de Cobre em Mt	2020	2021	2022	2023
China	9.9	10.4	10.5	11.2
Chile	2.3	2.3	2.2	2.2
Japão	1.8	1.4	1.6	1.6
Outros	10.1	10.4	11	11.4

Fonte: IEA (2023)

3.2.2. Lítio

Os principais países que possuem depósitos minerais de lítio são Austrália, Chile, China e Argentina. A Austrália destaca-se na extração, enquanto a China domina o processamento. Desde 2020, a capacidade de processamento da China aumentou de 265 kt para 604 kt em 2023, ou seja, expandiu-se significativamente. A participação de outros países cresceu nos últimos anos, o que pode indicar uma maior diversificação na capacidade do processamento global de lítio, embora ainda seja pouco expressiva.

A tabela 3 e 4 abaixo resumem os dados de produção e processamento de lítio de alguns países.

Tabela 4: Produção de lítio

Extração de Lítio em kt LCE	2020	2021	2022	2023
Austrália	200	264	363	506
Chile	113	154	202	234
China	55	74	131	126
Argentina	32	36	36	54
Outros	9.7	9.8	10.8	10.2

Fonte: IEA (2023)

Tabela 5: Processamento de lítio

Processamento de Lítio em kt LCE	2020	2021	2022	2023
China	265	340	457	604
Chile	109	143	206	234
Argentina	33	34	31	60
Outros	4	7	9	42

Fonte: IEA (2023)

3.2.3. Níquel

A Indonésia concentra os principais depósitos minerais de níquel e está emergindo como principal líder no processamento, aumentando sua capacidade de 0.64 Mt em 2020 para 1.67 Mt em 2023. Rússia e Canadá também se destacam no processamento de níquel, mantendo-se relativamente estável nos últimos anos. Embora a China seja relevante neste mercado, o país apresentou um declínio na sua participação no processamento de níquel, de 0.67 Mt em 2020 para 0.43 Mt em 2023. Essa mudança pode significar um maior protagonismo da Indonésia neste mercado. A tabela 5 e 6 abaixo resumem os dados de produção e processamento de níquel de alguns países.

Tabela 6: Produção de níquel

Extração de Níquel em Mt	2020	2021	2022	2023
Indonésia	0.77	1.03	1.58	1.81
Filipinas	0.33	0.39	0.31	0.41
Rússia	0.23	0.202	0.19	0.23
NC	0.207	0.188	0.21	0.21
Outros	0.863	0.89	0.91	0.99

Fonte: IEA (2023)

Tabela 7: Processamento de níquel

Processamento de Níquel em Mt	2020	2021	2022	2023
Indonésia	0.64	0.89	1.377	1.67
China	0.67	0.7	0.563	0.43
Rússia	0.15	0.07	0.15	0.15
Canadá	0.13	0.11	0.12	0.13
Outros	0.95	0.92	0.96	0.94

Fonte: IEA (2023)

3.2.4. Cobalto

A República Democrática do Congo (DRC) lidera a produção de cobalto, apresentando um crescimento de 103 kt em 2020 para 168 kt em 2023, consolidando-se como o principal produtor mundial. A Indonésia, embora tenha permanecido relativamente estável, segue como um dos produtores mais relevantes. A categoria que inclui outros países mostrou-se mais expressiva nos últimos anos, contribuindo para a oferta global. A China destaca-se no processamento de cobalto, crescendo de 95 kt em 2020 para 140 kt em 2023. A tabela 7 e 8 abaixo resumem os dados de produção e processamento de cobalto de alguns países.

Tabela 8: Produção de cobalto

Extração de Cobalto em kt	2020	2021	2022	2023
DRC	103	121	147	168
Indonésia	6	5	6	7
Filipinas	5	6	6	5
Cuba	4	5	6	6
Outros	26	25	35	47

Fonte: IEA (2023)

Tabela 9: Processamento de cobalto

Processamento de Cobalto em kt	2020	2021	2022	2023
China	95	114	126	140
Finlândia	13	15	15	14
Canadá	6	5	7	9
Outros	19	18	16	22

Fonte: IEA (2023)

4. RESULTADOS

Diante das informações apresentadas até aqui, esta seção explora os resultados obtidos sobre a concentração de materiais críticos, considerando a produção e o processamento de cobre, lítio, níquel e cobalto

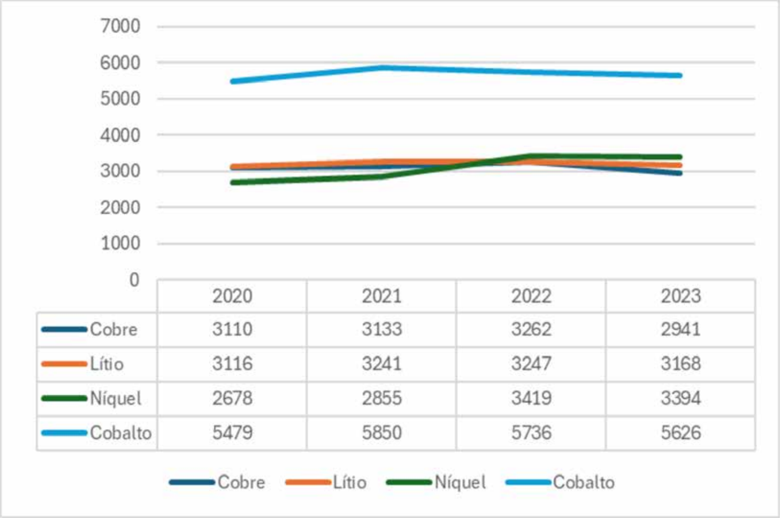
4.1. Índice de Concentração

As figuras abaixo representam o comportamento do IHH para cobre, lítio, níquel e cobalto, respectivamente, desde 2020 até 2023, de acordo com dados estabelecidos pela IEA (2023).

O gráfico 1 demonstra que o cobalto apresenta a maior concentração no que se refere à extração, sugerindo que poucos países controlam a maior parte das minas em operação de cobalto.

Apesar de uma pequena redução em 2022, o mercado de cobalto mantém-se altamente concentrado. O IHH de lítio também é elevado e apresenta uma tendência relativamente estável. Quanto ao níquel, houve uma maior concentração principalmente a partir de 2022. Por fim, o índice de concentração de cobre mantém-se elevado, apesar de uma queda em 2023.

Figura 3 - IHH das reservas de materiais críticos

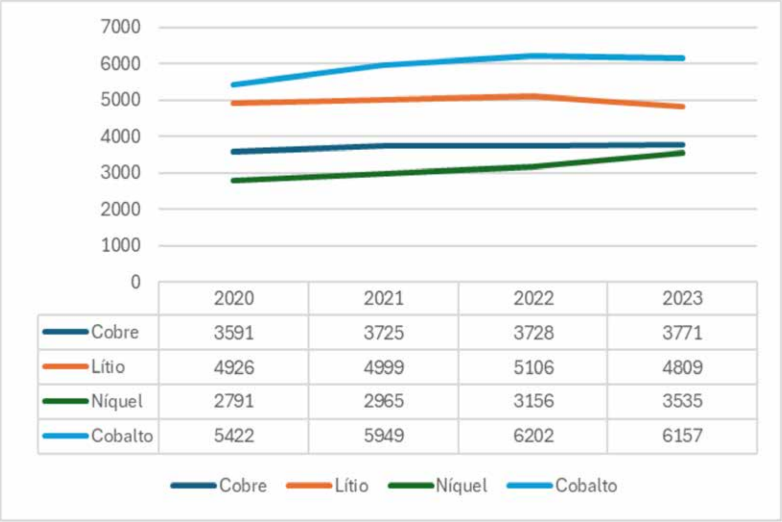


	2020	2021	2022	2023
Cobre	3110	3133	3262	2941
Lítio	3116	3241	3247	3168
Níquel	2678	2855	3419	3394
Cobalto	5479	5850	5736	5626

Fonte: Elaboração própria.

O gráfico 2 compara o comportamento do IHH no que se refere ao processamento desses materiais ao longo dos anos. O cobalto apresenta o maior índice de concentração, demonstrando que poucos países dominam o seu processamento. O níquel, embora relativamente menos concentrado em 2020, apresentou um aumento em 2023. O índice de concentração de cobre é elevado, mantendo-se constante. Por fim, o processamento de cobre é altamente concentrado, no entanto, manteve-se relativamente estável durante o período analisado.

Figura 4 - IHH do processamento de materiais críticos



	2020	2021	2022	2023
Cobre	3591	3725	3728	3771
Lítio	4926	4999	5106	4809
Níquel	2791	2965	3156	3535
Cobalto	5422	5949	6202	6157

Fonte: Elaboração própria.

5. DISCUSSÃO DOS RESULTADOS E COMENTÁRIOS FINAIS

Ao longo da realização deste trabalho, analisou-se os principais players do mercado de materiais críticos, considerando a distribuição global da produção e do processamento de níquel, cobalto, cobre e lítio. Dado que as energias renováveis compõem as estratégias globais para alcançar metas de descarbonização, optou-se por investigar se o aumento da demanda por materiais críticos pode produzir uma relação de dependência entre países que dominam essas cadeias de valor. Essa escolha deve-se à importância desses materiais para produção de tecnologias renováveis, essenciais para a transição energética e, consequentemente, para que os países sejam capazes de cumprir suas estratégias de mitigação e adaptação às mudanças climáticas.

A Agência Internacional para as Energias Renováveis – IRENA declarou que é pouco provável que os materiais críticos reproduzam a dinâmica geopolítica dos combustíveis fósseis, alegando que as reservas desses materiais são abundantes e podem ser processadas em diversos locais (IRENA, 2023). No entanto, ao avaliar o Índice de Herfindahl-Hirschman (IHH) do mercado de níquel, lítio, cobre e cobalto no período entre 2020 e 2023, constatou-se que tanto a extração quanto o processamento dos materiais selecionados são altamente concentrados, mantendo-se estáveis durante o período analisado. O alto índice de concentração do IHH indica que há pouca competição entre os países que compõem essa cadeia de valor. Ou seja, poucos países dominam o mercado dos materiais críticos analisados.

Assim, identificou-se que os principais volumes produzidos se concentram nos países em desenvolvimento, com exceção da Austrália, que possui grandes reservas de lítio. O Chile também se destaca na extração de lítio e concentra as principais minas em operação de cobre e lítio. A República Democrática do Congo lidera na extração de cobalto, enquanto a Indonésia destaca-se tanto na produção quanto no processamento de níquel. O Peru é um dos países mais relevantes em termos de volumes produzidos de cobre, assim como o Chile. Por outro lado, o processamento de níquel, cobalto, cobre e lítio é concentrado principalmente na China.

A análise do IHH ao longo do tempo revela que a atividade de mineração de materiais críticos permanece altamente concentrada em certas áreas geográficas. Essa concentração significa que a oferta global desses materiais depende fortemente de um pequeno número de países, evidenciando uma falta de diversificação. Da mesma forma, o processamento desses materiais é igualmente concentrado, com a capacidade de refino predominantemente localizada em poucos países.

Por exemplo, a China possui uma posição importante, controlando uma parte significativa da capacidade global de processamento de lítio e cobalto. Tal concentração amplifica os riscos associados à cadeia de suprimentos, pois qualquer interrupção na capacidade de refino desses poucos países pode impactar significativamente a disponibilidade global de materiais processados. Esse cenário sugere uma dinâmica de dependência e vulnerabilidade para países importadores que dependem do fornecimento desses materiais para fins industriais, tecnológicos e energéticos. A interrupção no fornecimento desses materiais processados pode produzir consequências significativas para a cadeia de valor global, visto que são necessários para o desenvolvimento tecnológico inerente à transição energética.

Como apontam Sattich et al. (2023), conquistas geopolíticas vinculadas às energias renováveis parecem depender, em grande parte, de avanços industriais. Nesse sentido, o domínio sobre esses mercados pode oferecer vantagens competitivas em termos de inovação e avanços tecnológicos. Países que controlam a mineração e o processamento de materiais críticos podem posicionar-se como líderes globais no fornecimento de materiais críticos para a transição energética, influenciando não apenas o mercado, mas também a geopolítica global. Apesar de possuírem uma geografia de comércio única que, em nível agregado, envolva os países em uma rede ampla de interdependência, a demanda constante por materiais, componentes ou produtos acabados pode tornar cadeias de abastecimento mais vulneráveis a riscos geopolíticos. Por fim, essa análise não sugere que os materiais críticos reproduzam a geopolítica dos combustíveis fósseis em torno da distribuição geográfica de suas reservas. No entanto, indica que a transição energética pode reconfigurar rotas comerciais e influenciar novas dinâmicas de poder global.

Ao analisar os resultados deste estudo, é fundamental considerar suas limitações. O foco na extração, sem incluir o total estimado das reservas, compromete uma interpretação mais detalhada de longo prazo sobre o mercado de materiais críticos, visto que o surgimento de novas tecnologias pode viabilizar a produção em outras regiões cuja extração era considerada inviável. Essa distinção é crucial porque o foco do estudo na extração atual pode não refletir o potencial de produção alternativo de longo prazo com a prospecção de novas jazidas e reclassificação de recursos. Para uma melhor análise, examinar como o surgimento de novas tecnologias de mineração e processamento viabiliza a extração em novas áreas, reduzindo o custo unitário de produção, contribui para compreender a dinâmica do mercado de materiais críticos.

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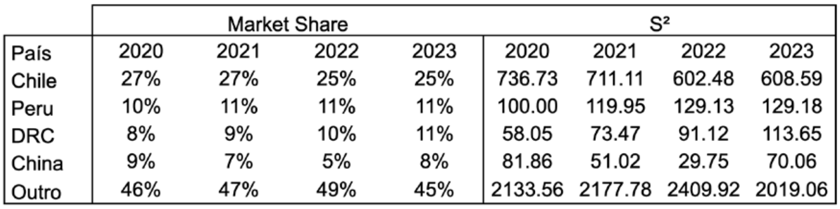
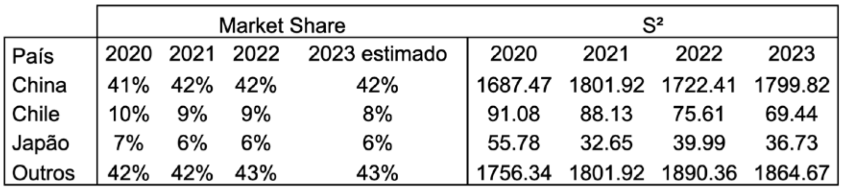
7. APÊNDICE A: TABELAS DE MARKET SHARE E S²

Tabela 10: Market Share e S² da extração do cobre



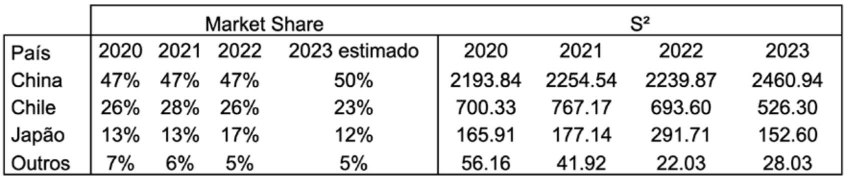
	Market Share				S²			
País	2020	2021	2022	2023	2020	2021	2022	2023
Chile	27%	27%	25%	25%	736.73	711.11	602.48	608.59
Peru	10%	11%	11%	11%	100.00	119.95	129.13	129.18
DRC	8%	9%	10%	11%	58.05	73.47	91.12	113.65
China	9%	7%	5%	8%	81.86	51.02	29.75	70.06
Outro	46%	47%	49%	45%	2133.56	2177.78	2409.92	2019.06

Tabela 11: Market Share e S² do processamento do cobre



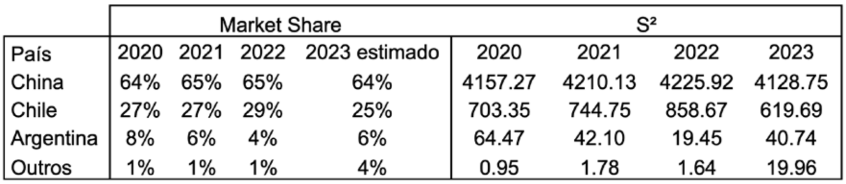
	Market Share				S²			
País	2020	2021	2022	2023 estimado	2020	2021	2022	2023
China	41%	42%	42%	42%	1687.47	1801.92	1722.41	1799.82
Chile	10%	9%	9%	8%	91.08	88.13	75.61	69.44
Japão	7%	6%	6%	6%	55.78	32.65	39.99	36.73
Outros	42%	42%	43%	43%	1756.34	1801.92	1890.36	1864.67

Tabela 12: Market Share e S² da extração do lítio



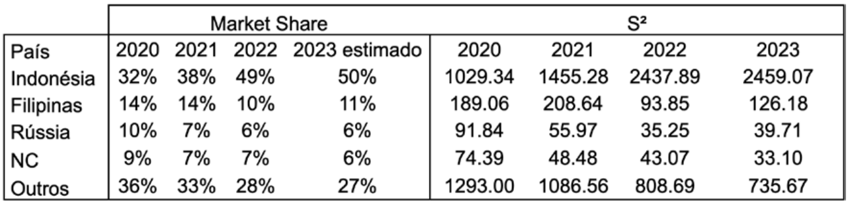
	Market Share				S²			
País	2020	2021	2022	2023 estimado	2020	2021	2022	2023
China	47%	47%	47%	50%	2193.84	2254.54	2239.87	2460.94
Chile	26%	28%	26%	23%	700.33	767.17	693.60	526.30
Japão	13%	13%	17%	12%	165.91	177.14	291.71	152.60
Outros	7%	6%	5%	5%	56.16	41.92	22.03	28.03

Tabela 13 Market Share e S² do processamento do lítio



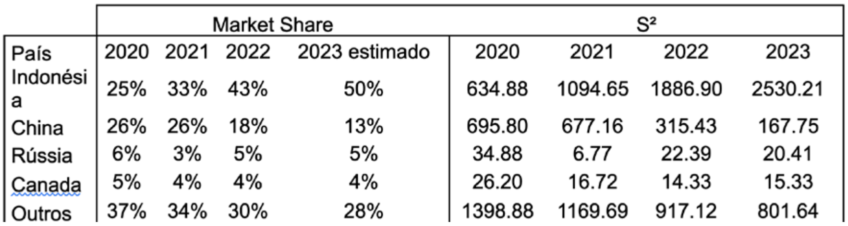
	Market Share				S²			
País	2020	2021	2022	2023 estimado	2020	2021	2022	2023
China	64%	65%	65%	64%	4157.27	4210.13	4225.92	4128.75
Chile	27%	27%	29%	25%	703.35	744.75	858.67	619.69
Argentina	8%	6%	4%	6%	64.47	42.10	19.45	40.74
Outros	1%	1%	1%	4%	0.95	1.78	1.64	19.96

Tabela 14: Market Share e S² da extração do níquel



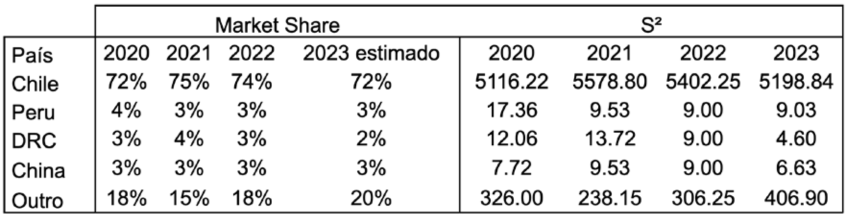
	Market Share				S²			
País	2020	2021	2022	2023 estimado	2020	2021	2022	2023
Indonésia	32%	38%	49%	50%	1029.34	1455.28	2437.89	2459.07
Filipinas	14%	14%	10%	11%	189.06	208.64	93.85	126.18
Rússia	10%	7%	6%	6%	91.84	55.97	35.25	39.71
NC	9%	7%	7%	6%	74.39	48.48	43.07	33.10
Outros	36%	33%	28%	27%	1293.00	1086.56	808.69	735.67

Tabela 15: Market Share e S² do processamento do níquel



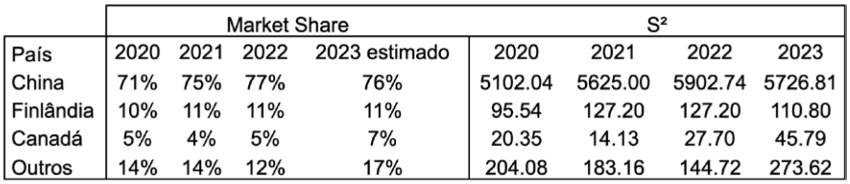
	Market Share				S²			
País	2020	2021	2022	2023 estimado	2020	2021	2022	2023
Indonésia	25%	33%	43%	50%	634.88	1094.65	1886.90	2530.21
China	26%	26%	18%	13%	695.80	677.16	315.43	167.75
Rússia	6%	3%	5%	5%	34.88	6.77	22.39	20.41
Canada	5%	4%	4%	4%	26.20	16.72	14.33	15.33
Outros	37%	34%	30%	28%	1398.88	1169.69	917.12	801.64

Tabela 16: Market Share e S² da extração do cobalto



	Market Share				S²			
País	2020	2021	2022	2023 estimado	2020	2021	2022	2023
Chile	72%	75%	74%	72%	5116.22	5578.80	5402.25	5198.84
Peru	4%	3%	3%	3%	17.36	9.53	9.00	9.03
DRC	3%	4%	3%	2%	12.06	13.72	9.00	4.60
China	3%	3%	3%	3%	7.72	9.53	9.00	6.63
Outro	18%	15%	18%	20%	326.00	238.15	306.25	406.90

Tabela 17: Market Share e S² do processamento do cobalto



	Market Share				S²			
País	2020	2021	2022	2023 estimado	2020	2021	2022	2023
China	71%	75%	77%	76%	5102.04	5625.00	5902.74	5726.81
Finlândia	10%	11%	11%	11%	95.54	127.20	127.20	110.80
Canadá	5%	4%	5%	7%	20.35	14.13	27.70	45.79
Outros	14%	14%	12%	17%	204.08	183.16	144.72	273.62

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