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On the Importance of the Cost of Capital in the Emergence of Remote Renewable Energy Hubs

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Abstract:

Remote Renewable Energy Hubs (RREHs) enable the harvesting of renewable energy in regions where it is most abundant. From this harvested renewable energy, RREHs allow the synthesis of e-fuels (electrical-fuels), such as CH_4 and NH_3, for export to load centers. Load centers are locations characterized by high energy consumption but often limited renewable energy potential. As a result, these load centers have difficulties in meeting their energy demands through only renewable sources. RREHs offer new opportunities for load centers to decarbonize their energy consumption. Many locations worldwide have significant technical potential for RREHs installation due to their vast renewable energy sources. Once a suitable location is identified, the RREH must be properly sized and operated. This involves determining the optimal capacities for each technology (e.g., battery storage capacity) and defining operational strategies (e.g., when to charge or discharge the battery). To size and operate a hub optimally, both technical and economic parameters must be considered. One key economic factor in hub optimization is the Weighted Average Cost of Capital (WACC), which can significantly impact the economic viability of potential projects in a given location. In this paper, we model the entire energy supply chain for synthetic gas production across various countries and its export to Northern Europe (Belgium). We analyze the trade-off between WACC and load factors to minimize the cost of synthetic fuel production and identify the most promising locations. Our results indicate that while some countries may be technically promising, they may not be economically attractive. This highlights the need for innovative financing mechanisms in regions with high load factors but less favorable economic conditions in order to install RREHs at a lower cost.

Keywords:

Energy Systems, Remote Renewable Energy Hub, Renewable Energy, WACC.

1. Introduction

To address climate change, transforming our energy systems from fossil-based energy systems to a low-carbon energy mix is one of the most important levers to pull. As highlighted by [1], expanding renewable energy production is essential to achieve this transformation. However, since some sectors are difficult to electrify, complementing this transition in the electricity mix with the synthesis of low-carbon fuels is essential for decarbonizing these hard-to-abate sectors [2–4].

Low-carbon synthetic fuels are produced using power-to-X technologies [5]. These technologies convert low-carbon electricity into a molecule X, such as hydrogen (H_2) via electrolysis, or further into molecules like methane (CH_4), ammonia (NH_3), or methanol (CH_3OH) through synthesis processes. Power-to-X has a dual benefit: first, the molecules produced are low carbon, and second, these high energy density molecules can store and transport energy efficiently [6–8]. Such molecules are often referred to as e-fuels (electro-fuels).

In load centers such as Western Europe, there are challenges in producing renewable energy for power-to-X purposes [9]. Indeed, the potential of renewable energy is limited due to lack of space availability because of strong urbanization and geographical constraints. It is also limited due to the low-quality of renewable energy sources. To address these limitations the concept of Remote Renewable Energy Hubs (RREHs) has been proposed. These hubs make it possible to harvest renewable energy in regions with abundant resources and export e-fuels to demand centers such as the European Union (EU), potentially reducing infrastructure needs and costs [10].

To the best of the author's knowledge, the first reference in the scientific literature discussing RREHs is [11]. It proposes the export of energy, as e-CH_4, from Egypt to Japan; however, no techno-economic assessment was conducted. Then [5], proposed a techno economic assessment for export of e-CH_4 from North of Africa towards Finland. In [12], they did a similar analysis but with export towards Germany.

More recently, [13] proposed an RREH exporting e-CH_4 from Algeria to Belgium. Building on this, [14] and [15] suggested a similar hub but with the additional option of importing CO_2 from load centers where it is more abundant. Furthermore, [16–18] extended the scope of export commodities beyond e-CH_4 to include NH_3, CH_3OH, Fischer–Tropsch liquids, and H_2.

The growing number of RREHs discussed in the literature has motivated the development of a taxonomy to characterize them [19]. This taxonomy relies on a technological graph in which nodes represent the different production units of an RREH, and hyperedges represent the exchange of commodities between them. Based on this graph, the taxonomy identifies distinct sets of commodities: imports, exports, byproducts, and local opportunities. For instance, [13] considers no import commodities and defines e-CH_4 as the export commodity, whereas [14, 15] propose the same export commodity but also include the import of CO_2.

Nevertheless, these studies overlooked some economic parameters that can have significant impact to the cost of e-fuel production. Indeed, as mentioned in [20], the Weighted Average Capital Cost (WACC) is often used as an estimate for the cost of capital that a company should pay to raise capital to finance a project.

In this paper, the impact of this cost of capital on the cost of e-fuel synthesis in RREHs is investigated. To do so, case studies in 7 different locations are performed. The trade off between renewable energy potential and low risk economic environment is discussed.

The rest of the article is organized as follows: in Section 2., the modeling framework of the energy systems is discussed (cfr. subsection 2.1.) as well as the methodology to evaluate the WACC is discussed (cfr subsection 2.2.). In Section 3., the case studies are introduced. In Section 4., the results are introduced and discussed. Section 5. concludes this paper.

2. Methodology

This section describes the modeling framework used to size and operate the RREH, as well as the methodology for computing the WACC.

2.1. Modeling Framework: GBOML

In this study, the Graph-Based Optimization Modeling Language (GBOML) [21] is used to model the economic and technical aspects of RREHs. The GBOML framework is open source and particularly suited for energy systems. Indeed, energy systems can be viewed as graphs, where nodes represent technologies and hyperedges represent the exchange of commodities between these technologies.

The objective is to minimize the total cost of the system, which corresponds to the sum of the CAPEX and OPEX of each node, subject to various equality and inequality constraints representing physical and operational limitations over a given time horizon.

A detailed explanation of the optimization problem solved can be found in [13]. The same methodology is employed in this study.

The underlying modeling assumptions are the following:

- **Central Planning and Operation:** Investment decisions are made by a single entity that also operates the system, with the objective of minimizing total system costs while meeting the energy demand.

- **Perfect Foresight and Knowledge:** The single entity is assumed to have perfect foresight and knowledge. Future weather events, demand patterns, and all technical and economic parameters are known with certainty.
- **Investment and Operational Decisions:** A static investment model is used. Investment decisions are made at the beginning of the time horizon, and assets are considered immediately available. Operational decisions are made at an hourly resolution. Both investment and operational decisions are determined simultaneously.
- **Technology and Process Models:** All objective functions and constraints are linear.

Because different technologies have different lifetimes, the CAPEX must be adjusted to avoid favoring technologies with shorter lifetimes and lower upfront costs over those with higher CAPEX but longer operational life. To address this, an annualized CAPEX is computed. The annualized CAPEX ζ_i of a technology i can be calculated from its raw $CAPEX_i$, lifetime L_i, and the WACC as follows:

$$\zeta_i = \text{CAPEX}_i \times \frac{WACC}{1-(1+WACC)^{-L_i}} \quad . \tag{1}$$

This annualized CAPEX represents the annual cost for borrowing the CAPEX over the lifetime of the technology, while paying an interest rate of $WACC$. This formulation yields an equivalent annual cost, which can be interpreted as the constant yearly payment required to finance the investment over its lifetime at the given WACC. It facilitates comparability across technologies of varying lifetimes, but also implicitly assumes reinvestment over the long-term horizon and may therefore underestimate the relative burden of long-lived assets compared to repeated short-lived ones. This limitation should be kept in mind when interpreting the results.

2.2. WACC estimation

In this section, the concept of the Weighted Average Cost of Capital (WACC) is introduced along with the methodology used to compute it. Subsequently, the procedure to derive a country-specific WACC is explained.

The WACC represents an estimate of the minimum return required on the assets by the capital providers. Since directly determining the return on an asset can be complex, it is more practical to compute the WACC from the company's liabilities. This value can then be used to evaluate whether a company should invest in a new project. If the expected return of the project exceeds the company's minimum return, the investment may be considered value-adding and the company could decide to invest in it.

WACC is generally computed as:

$$WACC = \left(\frac{E}{E+D} \times R_e\right) + \left(\frac{D}{E+D} \times R_d \times (1-T_c)\right) \quad , \tag{2}$$

where E is the market value of equity (i.e., the total value of shares held by shareholders), D is the market value of debt (i.e., the total borrowed capital), R_e is the cost of equity, R_d is the cost of debt, and T_c is the corporate tax rate.

The cost of equity, R_e, represents the required rate of return for equity investors and is typically higher than the cost of debt, R_d, as debt providers are reimbursed first in case of bankruptcy, while shareholders are the last to recover their capital. However, if a company borrows excessively, this increases its financial risk, potentially raising R_d above R_e. The proportions $\frac{E}{E+D}$ and $\frac{D}{E+D}$ define the capital structure of the company. An optimal capital structure can reduce the overall cost of capital by minimizing the WACC. Finally, the term $(1-T_c)$ reflects the adjustement applied to the cost of debt thanks to the tax shield T_c on interest payments, as debt expenses are tax-deductible in many jurisdictions.

Estimating the parameters in Equation 2 (e.g., R_e, R_d) is not straightforward due to limited availability of public financial data. A common practice is to identify a set of comparable firms within a sector and extract these values from their financial statements. In this study, publicly available data from [22] is used, which provides the WACC and its components for specific sectors in the United States.
To account for country-specific investment risks, Equation 2 is adapted as follows:

$$WACC_{USD} = \left(\frac{E}{E+D} \times (R_e + CRP)\right) + \left(\frac{D}{E+D} \times (R_d + ADS) \times (1 - T_c)\right) \quad , \tag{3}$$

where CRP is the Country Risk Premium and ADS is the Adjusted Default Spread, both retrieved from [23], which estimates them from the perspective of a U.S. investor.
It is assumed that project finance is employed, i.e., that a Special Purpose Vehicle (SPV) is created in the target country. An SPV is a subsidiary company established specifically to implement a single project. This structure limits the financial exposure of the parent company to the capital it injects into the SPV. For further details on project finance, see [24]. Since the SPV is assumed to generate its cash flows in the host country, the corresponding country-specific tax rate T_c from [23] is applied. Moreover, the cash flows generated by the project are assumed to be repatriated in the home country of the investor.
It is important to note that using CRP as an equity risk premium is an approximation. The value reflects country-level rather than sector-specific risk. Similarly, ADS captures the country's borrowing risk, not that of a particular sector or project. These are proxies that allow us to make use of open data rather than relying on proprietary financial datasets or firm-level data, which are difficult to access, particularly for hydrogen projects in emerging markets. Nonetheless, this methodology offers a reasonable approximation to account for location-specific risk.
An overview of the parameters used in Equation 3, their specificity, and sources is provided in Table 1. Finally, the economic parameters in our model are expressed in euros, while the values from [22, 23] are reported in U.S. dollars. Therefore, the WACC computed in USD ($WACC_{USD}$) is converted to euros using the Fisher equation:

$$WACC_{EUR} = \frac{(1 + WACC_{USD})}{1 + \pi_{US}} \cdot (1 + \pi_{EUR}) - 1 \quad , \tag{4}$$

where π_{US} and π_{EUR} represent the inflation rates in the United States and the Euro Area, respectively. These are sourced from [25].

Parameter	**Sector or Country Specific**	**Source**
$\frac{E}{E+D}$	Sector (Green Energy, US)	[22]
R_e	Sector (Green Energy, US)	[22]
CRP	Country specific	[26]
$\frac{D}{E+D}$	Sector (Green Energy, US)	[22]
R_d	Sector (Green Energy, US)	[22]
ADS	Country specific	[26]
T_c	Country specific	[26]

Table 1: Overview of parameters, their specificity, and data sources used in financial modeling.

3. Case Studies

The case studies evaluating the cost of methane synthesis in RREHs follow the same system design as in [13]. However, CAPEX and OPEX values have been updated using the most recent data from [27] and are provided in Table 3. A schematic representation of the technologies involved is shown in

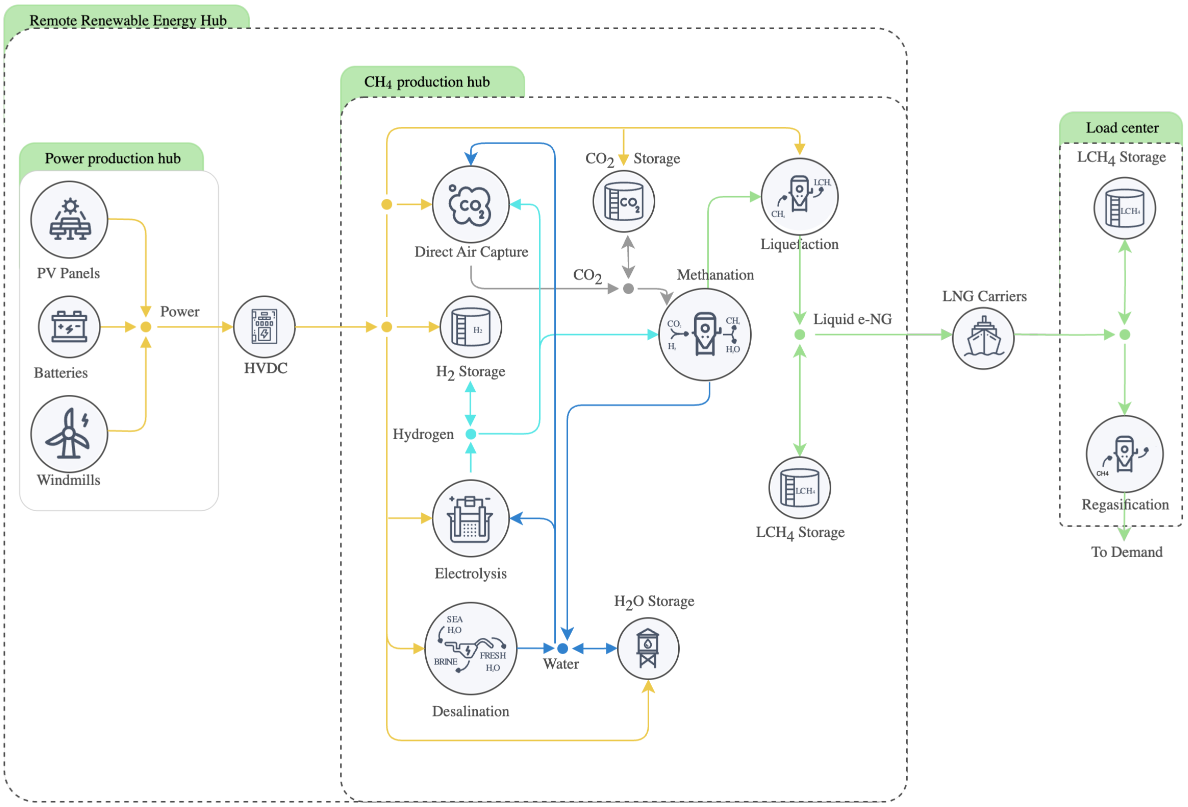

Figure 1: The RREH supply chain modeled. The RREH can be divided into three parts: production, conversion and export facilities.

Figure 1. The code used to perform the simulations and reproduce the results is open-source and publicly available online[1].

The RREH is divided into two parts: a power production hub and a CH_4 production hub. The power hub integrates onshore or offshore wind turbines (depending on the location), photovoltaic (PV) panels, and a battery. Curtailment of renewable energy production is allowed.

The electricity generated is transmitted via a High Voltage Direct Current (HVDC) link to the CH_4 production hub, where e-CH_4 is produced through methanation (Sabatier reaction). This process uses hydrogen generated via electrolysis (powered by the renewable energy hub) and CO_2 captured from the atmosphere. A desalination unit is also modeled to supply water for the electrolysis process. The synthetic CH_4 is subsequently liquefied and exported via ships.

The main differences between case studies lie in the locations considered, which result in different renewable energy load factors (evaluated over five years based on [28]), differentiated WACC values (in one of the scenarios), and varying ship travel times to the final destination (Belgium).

The parameters for each location are summarized in Table 2. Additionally, for the two European countries (Germany and Spain), liquefaction, maritime transport, and regasification units from Figure 1 are excluded, as direct injection into the European gas grid is assumed. For the remaining countries, transport via ships traveling at 19 knots and regasification before delivery to Belgium is modeled.

All scenarios assume a constant energy demand equivalent to 10 TWh per year.

The locations considered are Algeria, Argentina, Chile, Germany, Greenland, Namibia, and Spain. Below, the rationale for selecting these locations is discussed.

The area near Málaga in Spain is selected to represent a location closer to major European demand centers, with high renewable energy potential and access to the European gas network. It allows for a comparison between domestic supply within EU zones and external sources.

The region near Bremerhaven in Germany provides another perspective on domestic e-fuel synthesis,

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[1] `https://github.com/GBOML/GBOML-examples`

Country	WACC	Travel Time
Algeria	10,67%	116
Argentina	15,79%	390
Belgium	6,13%	-
Chile	6,28%	390
Germany	5,36%	-
Greenland	5,69%	116
Namibia	9,36%	312
Spain	7,08%	-

Table 2: WACC per country.

although it has lower renewable energy potential compared to Spain and RREHs.

The southern region of Namibia, near the South African border, is chosen due to its hydrogen Memorandum of Understanding with Belgium as part of the national hydrogen strategy of Belgium, and its abundant renewable energy resources. It is also representative of Southern Africa more broadly.

The locations of Chile and Argentina, near the southern tip of South America, are identified in [17] as having high renewable energy potential, with direct access to the Atlantic Ocean for export to Belgium.

Two different scenarios are performed: the first applies a common WACC of 7%, while the second applies a differentiated WACC per country, computed using the methodology described in subsection 2.2..

4. Results and Discussion

As shown in Figure 2, in the scenario where the WACC is constant across countries, Algeria has the lowest production cost of e-methane at 153€/MWh, while the highest cost is found in Germany at 203€/MWh. In this constant WACC scenario, only the renewable energy potential and distance to the energy demand center matters. Therefore, RREH to harness high quality renewable energy potential makes sense even when accounting for additional costs such as liquefaction and maritime transport.

However, in the differentiated WACC scenario, the picture changes. Germany's cost to produce and export e-methane to Belgium drops to 180€/MWh, whereas Algeria's cost increases to 192€/MWh. Three countries emerge as more favorable under differentiated WACC: Chile, Greenland, and Germany. Chile becomes the location with the lowest cost of methane synthesis, reaching 153€/MWh which is identical to Algeria's cost in the constant WACC scenario. Greenland also proves competitive, with a cost of 166€/MWh, which is lower than those of Algeria, Namibia, and Argentina.

Spain and Germany exhibit similar production costs, at 182€ and 180€/MWh, respectively. This suggests that installing renewable energy hubs within Europe, rather than RREHs in Algeria, Namibia or Argentina, may be advantageous, especially when considering Belgium as importing country. Indeed, Belgium participates in shared institutions such as the EU, NATO, OECD, and the Eurozone, which facilitate cross-border exchanges and collaboration between countries participating in these institutions.

By contrast, Algeria, Namibia, and Argentina perform worse under the differentiated WACC scenario. Their production costs increase by 26%, 17%, and 65%, respectively. Exhibiting significant rises relative to the constant 7% WACC. The case of Argentina is particularly concerning: the cost nearly doubles compared to Chile, despite the two locations being geographically close (southern South America).

While the constant WACC scenario provides a purely technical comparison of locations, the differentiated WACC scenario incorporates investment risk. This raises the question: is it possible to reduce the WACC in technically attractive locations to make them economically viable?

First, let us recalling that the WACC and especially the differentiated WACC takes into account several risks for the investors: business risk, financial risk and political risk. Nevertheless, not all investors

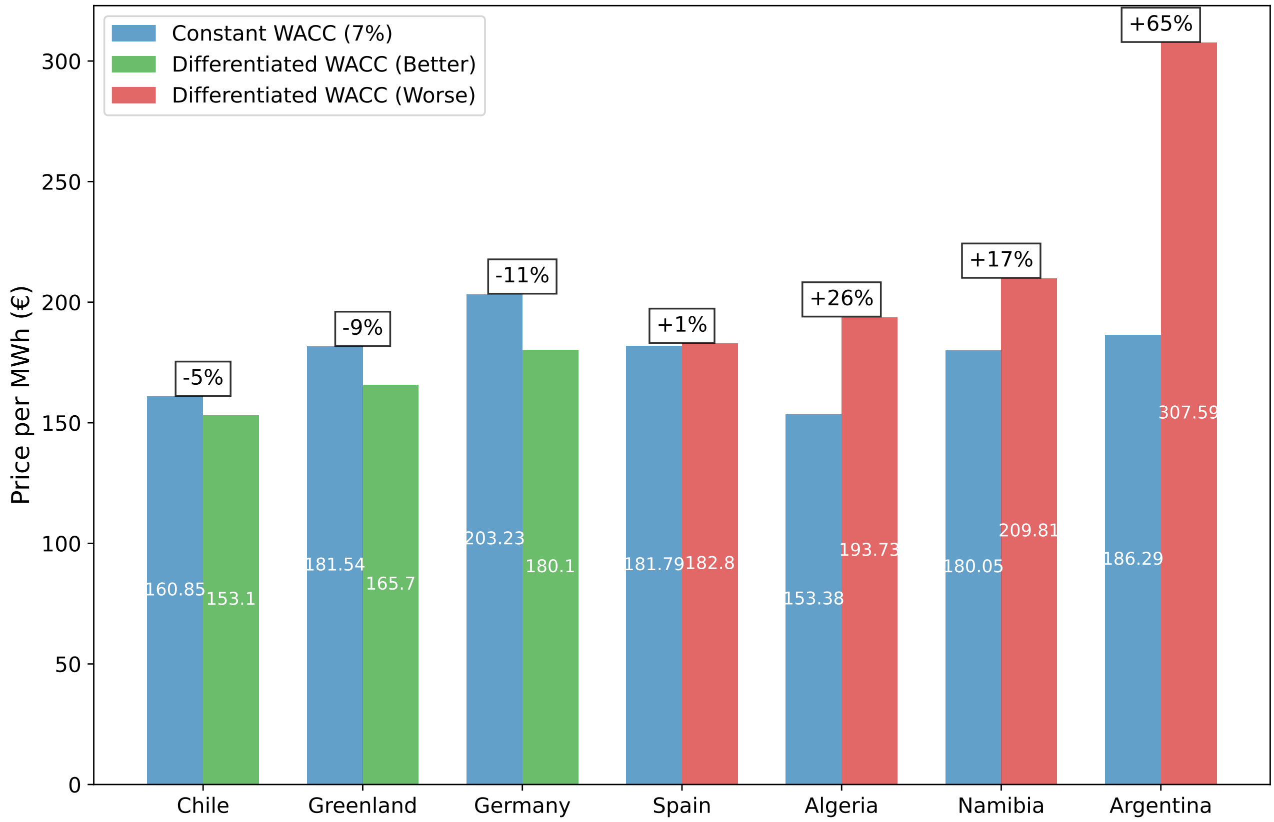

Figure 2: Price per MWh per country under constant and differentiated WACC Scenarios. Countries are ranked by increasing cost of energy for the differentiated WACC scenarios. Percentage changes indicate the impact of differentiated WACC on energy costs.

have the same investment criteria. Some may be motivated by environmental, social, and governance (ESG) considerations or long-term strategic interests, leading them to accept lower returns. Identifying and attracting such investors can reduce the effective cost of capital, thereby lowering the WACC and making RREHs more economically viable.

Second, consider the formulation of Equation 3. The ADS, used to estimate the local credit spread (or the risk premium on debt), is a proxy for a country's borrowing risk. However, this proxy introduces a potential bias. In practice, the cost of debt for a project may differ substantially from that of sovereign debt. For example, if local banks or development finance institutions in Argentina can provide loans at more favorable conditions than suggested by the country's sovereign risk, Argentina may become a more attractive location for RREH deployment than the model currently indicates. In order to reduce such potential bias, one could use the credit spread of a publicly traded company from the country.

[29] discussed the importance of reducing the cost of capital in developing countries in order to accelerate the energy transition and achieve climate neutral policies. However, they assess that more renewable energy assets are installed in developing countries if they get access to cheaper capital than they have actually. Nevertheless, they acknowledge the challenges in achieving these reductions of cost. Indeed, as an example, the CRP that an investor adds for its return on equity depends notably on the risk of currency changes which depend notably on inflation. Therefore, independent central banks that may mitigate inflation thanks to effective monetary policy are essential institutions to decrease the cost of capital in emerging markets.

De-risking RREH project can also be a possibility to decrease the WACC. This can be done with off-taker that provide guarantees of buying the e-fuel over a given period at a given price. More complex mechanisms can be imagined. For example, [30] proposes a de-risking strategy for renewable energy investments in developing economies. They propose that renewable energy projects use a multilateral guarantee mechanism involving donor countries, the host country, investors, developers, and international financial institutions. This mechanism helps reduce the cost of capital in developing countries and demonstrates how it can accelerate decarbonization in the developing world, with potential global savings of up to $1.5 trillion by 2030.

Finally, this paper focuses on e-CH_4, however other e-fuels such as ammonia or methanol may also emerge as viable alternatives. The analysis presented here can be extended to other e-fuels, as the cost of capital would similarly affect different locations regardless of the specific e-fuel supply chain considered. Indeed, as shown in [16] for H_2, CH_4, CH_3OH and NH_3, the most capital-intensive assets tend to be installed in comparable capacities across different e-fuels.

5. Conclusion

In this study, case studies are conducted for seven locations to assess the feasibility of e-methane production. The entire supply chain is modeled as a linear program and optimized at an hourly resolution over a five-year time horizon. These case studies help to better understand the role of the cost of capital or Weighted Average Cost of Capital (WACC) in the emergence of RREHs. The results demonstrate that WACC significantly affects the economic viability of such projects.

Nevertheless, due to the difficulty of obtaining accurate financial data and the challenges of properly capturing the cost of capital, it is not possible to definitively identify which countries will become leading exporters of low-carbon synthetic fuels. Nonetheless, the results highlight promising candidates. For example, Chile combines high-quality renewable energy resources with a relatively stable economic environment.

This study suggests focusing on locations where both strong renewable potential and favorable financing conditions are met or developing strategies to reduce the cost of capital. Potential strategies include accessing subsidy programs, securing large offtakers to reduce revenue uncertainty and improve financing terms, and attracting impact investors.

Finally, since WACC plays a critical role in evaluating project viability, it is recommended to systematically conduct uncertainty analyses on this parameter to assess its influence. Focusing solely on technically promising locations without considering financial risk may obscure other key factors that determine the emergence of successful RREHs.

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Competing interests

The authors declare no competing interests.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to correct the readiness, grammar and spelling of the writing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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A Annexes

Technology	**CAPEX**	**FOM**	**VOM**	**Lifetime**
	[M€/unit]	[M€/unit–yr]	[M€/GWh]	[yr]
Solar Photovoltaic Panels[b]	380.0	9.5	0.0	25.0
	GW$_{\mathrm{el}}$	GW$_{\mathrm{el}}$–yr	GWh$_{\mathrm{el}}$	
Onshore Wind Turbines[b]	1110.0	13.4	0.00144	30.0
	GW$_{\mathrm{el}}$	GW$_{\mathrm{el}}$–yr	GWh$_{\mathrm{el}}$	
Offshore Wind Turbines[b]	1800.0	39	0.00389	30.0
	GW$_{\mathrm{el}}$	GW$_{\mathrm{el}}$–yr	GWh$_{\mathrm{el}}$	
Battery Storage (Flow)[a]	160.0	0.5	0.0	10.0
	GW	GW–yr	GWh	
Battery Storage (Stock)[a]	142.0	0.0	0.0018	10.0
	GWh	GWh–yr	GWh	
HVDC[a]	480.0	7.1	0.0	40.0
	GW$_{\mathrm{el}}$	GW$_{\mathrm{el}}$–yr	GWh	
Electrolysis[a]	600.0	30	0.0	15.0
	GW$_{\mathrm{el}}$	GW$_{\mathrm{el}}$–yr	GWh	
Methanation[a]	735.0	29.4	0.0	20.0
	GW$_{\mathrm{CH_4}}$	GW$_{\mathrm{CH_4}}$–yr	GW$_{\mathrm{CH_4}}$	
Desalination[a]	28.08	0.0	0.000315	20.0
	kt$_{\mathrm{H2O}}$/h	kt$_{\mathrm{H2O}}$/h–yr	kt$_{\mathrm{H2O}}$	
Direct Air Capture[a]	4801.4	0.0	0.0207	30.0
	kt$_{\mathrm{CO2}}$/h	kt$_{\mathrm{CO2}}$/h–yr	kt$_{\mathrm{CO2}}$	
$\mathrm{CH_4}$ Liquefaction[a]	5913.0	147.825	0.0	30.0
	kt$_{\mathrm{LCH_4}}$/h	kt$_{\mathrm{LCH_4}}$/h–yr	kt$_{\mathrm{LCH_4}}$	
$\mathrm{LCH_4}$ Carriers[a]	2.537	0.12682	0.0	30.0
	kt$_{\mathrm{LCH_4}}$/h	kt$_{\mathrm{LCH_4}}$/h–yr	kt$_{\mathrm{LCH_4}}$	
$\mathrm{LCH_4}$ Regasification[a]	1248.3	29.97	0.0	30.0
	kt$_{\mathrm{CH_4}}$/h	kt$_{\mathrm{CH_4}}$/h–yr	kt$_{\mathrm{CH_4}}$	

Table 3: Economical parameters used for modeling conversion nodes (2030 estimate). The HVDC line CAPEX includes the cost of two substations and assumes a transmission length of 1000 km.
[a] Data reused from [13].
[b] Data reused from [27].