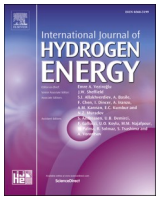
International Journal of Hydrogen Energy 282 (2026) 157958



Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he





From potential to impact: A composite indicator framework for ex-ante assessment of local impacts of green hydrogen in Sub-Saharan Africa

Amin Lahnaoui [a,*], Kouamé Jean Didier Kouakou [b], Maman Maarouhi Inoussa [b], Bruno Korgo [c], Sascha Stark [a], Sandra Venghaus [a,d]

[a] Jülich Systems Analysis (ICE-2), Forschungszentrum Jülich, Jülich, D-52425, Germany
[b] Faculty of Science and Technology, University Abdou Moumouni, Niamey, Niger
[c] Faculty of Applied Physics, University Joseph Ki-Zerbo, Burkina Faso
[d] School of Business and Economics, RWTH Aachen University, Aachen, D-52072, Germany

ARTICLE INFO

Keywords:
Green hydrogen
Composite indicators
Impact assessment
Resources and socio-economic trade-offs
Sub-Saharan Africa

ABSTRACT

The utilization of green hydrogen as a means of achieving decarbonization targets is a concept that is receiving increasing levels of attention. One region that is emerging as a potential host for large-scale deployment of this technology is Sub-Saharan Africa. The present paper puts forward a methodological framework for the quantification of the multidimensional socio-economic and environmental impacts of green hydrogen projects before their deployment. This framework is composite in nature and indicator-based. The framework incorporates 26 indicators, which are structured across four core dimensions. These dimensions are as follows: Employment and Skills Development, Economic Value Creation, Domestic System Integration, and Resources and Environmental Footprint. The dimensions are then aggregated into a Green Hydrogen Impact Index (GHII). A significant contribution lies in operationalizing impact indicators through transparent assumptions and proxy variables, thus enabling application in contexts where data is scarce and hydrogen projects are not yet operational. The framework has been designed as a transferable and scalable methodological decision-support tool. It intends to support subsequent cross-country comparison and policy analysis rather than project-level prediction.

1. Introduction

The notion of green hydrogen as a pivotal vector in the decarbonization of sectors with significant challenges in terms of electrification is gaining increasing traction in academic discourse [1,2]. Beyond its mitigation relevance [3], this interest is supported by continued advances across hydrogen and hydrogen-carrier production pathways. Recent studies have, for example, investigated electrified structured catalysts for methane reforming and ammonia cracking [4], intensified ethanol reforming processes [5], and electrochemical hydrogen production routes with particular attention to their technological, economic, and sustainability performance [6]. These developments, together with declining renewable-generation and electrolysis costs, are expanding the technical and economic conditions under which hydrogen deployment may become feasible [7–9]. In this context, Sub-Saharan Africa (SSA) stands out with its natural resource availability [10–12]. Cost–potential mapping studies indicate that green hydrogen could be produced in several SSA countries at costs as low as 1.6 €/kg by 2050 [8]. As a result, the region has attracted growing attention in research, pilot initiatives, and early-stage project development, alongside emerging discussions of potential socio-economic impacts [13].

Existing research has examined several complementary aspects of hydrogen feasibility. Spatial studies have mapped renewable hydrogen cost potentials and resource availability across SSA [10,14], while technology-focused analyses have investigated electrolyser efficiency, investment costs, and prospective learning effects [15,16]. Other studies have assessed the competitiveness of African hydrogen exports to Europe and the costs associated with transporting hydrogen and its derivatives [17]. Environmental and techno-economic studies have further evaluated the resource requirements and lifecycle implications of large-scale electrolysis [18]. Nevertheless, these contributions primarily address whether and where hydrogen can be produced competitively; they provide more limited quantitative evidence on how

This article is part of a special issue entitled: H2EURES (Crema) published in International Journal of Hydrogen Energy.

* Corresponding author.
E-mail address: a.lahnaoui@fz-juelich.de (A. Lahnaoui).

https://doi.org/10.1016/j.ijhydene.2026.157958
Received 9 March 2026; Received in revised form 10 August 2026; Accepted 2 October 2026
Available online 9 October 2026
0360-3199/© 2026 The Authors. Published by Elsevier Ltd on behalf of Hydrogen Energy Publications LLC. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
Open access funding enabled and organized by Projekt DEAL.

deployment benefits and pressures are distributed within host economies and territories, and = the local socio-economic and environmental impacts remain limited [19]. This gap is particularly relevant for SSA, where the implementation of large-scale energy infrastructure projects is expected to significantly affect labor markets, public finance, infrastructure provision, and natural resource systems. Furthermore, many green hydrogen projects in SSA remain in the planning or early development stages, which limits the availability of operational data for post-evaluation. Consequently, policymakers and investors are obligated to evaluate prospective impacts in scenarios characterized by elevated uncertainty and limited data availability.

To address these challenges, this paper develops a composite indicator-based methodological framework for the ex-ante assessment of the local socio-economic and environmental impacts of green hydrogen projects. The methodological contribution adapts established composite-indicator principles to a distinct assessment problem that remains insufficiently addressed in the hydrogen literature: the prospective quantification of local development benefits and resource pressures before project implementation and under conditions of limited operational data in the SSA region.

Existing hydrogen assessment frameworks predominantly evaluate production feasibility, techno-economic competitiveness, policy readiness, or hydrogen-economy maturity at national or regional scales. In contrast, the proposed framework focuses on project-induced local impacts, linking project characteristics and country-specific conditions to explicit impact pathways covering Employment and Skills Development, Economic Value Creation, Domestic System Integration, and Resources and Environmental Footprint. These pathways are operationalized through transparent proxy variables and reproducible estimation procedures, allowing qualitative impact mechanisms to be translated into measurable and comparable indicators while explicitly accounting for data scarcity and uncertainty. The contribution of this work therefore lies in the development of a transparent operational architecture that explicitly links project assumptions, contextual adjustment factors, indicators, sub-dimensions, dimensions, and the final composite index, thereby providing a reproducible basis for prospective impact assessment across different projects and national contexts.

The scope of this paper is intentionally methodological. It focuses on the definition of the assessment construct, indicator selection, proxy operationalization, hierarchical index design, and methodological evaluation through external plausibility benchmarking and uncertainty analysis. It is therefore intended to provide the methodological foundation upon which subsequent comparative applications and policy-oriented analyses can be built.

The remainder of the paper is structured as follows: Section 2 describes a literature review driven by the main pillars of the developed index. Section 3 presents the methodological framework by defining the core impact dimensions and their internal architecture. It further details the operationalization of the framework, including indicator selection, estimation pathways, and the use of proxy-based approaches to address data limitations. Section 4 applies the methodology to a country-level case study, using an existing green hydrogen project to validate selected indicators and assess the robustness of the results. Finally, Section 5 concludes with key findings and outlines implications for policy design, future research, and practical implementation.

2. Literature review

Existing hydrogen research has provided substantial advances in production technologies, techno-economic assessment, and hydrogen system planning. However, comparatively less attention has been devoted to systematically quantifying the local socio-economic and environmental impacts of project deployment. To identify the methodological requirements of such an assessment framework, the following review is structured according to four impact dimensions to allow for a systematic synthesis of relevant evidence while directly informing the conceptual design of the proposed composite indicator.

2.1. Macroeconomic and employment impacts

From a macroeconomic perspective, green hydrogen production has been associated with employment creation, industrial development, and export opportunities [19,20]. Existing studies indicate that renewable-based hydrogen value chains can generate both direct and indirect employment, contributing to income generation and improved living standards [20]. In addition, local utilization of hydrogen has been highlighted as a potential driver of sustainable job creation and domestic value chains, particularly in sectors such as fertilizer production and energy-intensive industries [20,21]. Several studies emphasize that access to low-cost green hydrogen could enhance the competitiveness of domestic industries by reducing exposure to volatile fossil fuel prices, with positive spillovers for rural incomes and food security [20]. At the regional level, green hydrogen has been framed as a potential catalyst for export-led growth, industrialisation, and foreign direct investment in SSA [22–24].

However, the literature also highlights structural constraints related to skills availability and workforce preparedness. Multiple studies underline the need for targeted training and skills development to enable local populations to capture employment benefits along the hydrogen value chain [25,26]. Despite these insights, quantitative ex-ante tools capable of jointly capturing employment, skills development, and macroeconomic integration remain largely absent.

2.2. Social and infrastructure impacts

Beyond economic effects, large-scale renewable energy and green hydrogen projects are frequently associated with broader social and infrastructural co-benefits. Empirical evidence from renewable energy deployment suggests potential improvements in electricity access, local service provision, and infrastructure development, particularly in rural areas [27,28]. Improved energy access has been linked to enhanced productivity, health outcomes, safety, and gender equality [27–31]. Inclusive project design and local participation mechanisms have also been identified as pathways for advancing social equity, including gender inclusion and community engagement [32–35]. Renewable energy projects, such as green hydrogen, have the potential as well to enhance water access in rural regions [36]. Furthermore, case studies have reported additional benefits, including company-funded community development initiatives, upgrades to local infrastructure, and microgrids serving local villages [27,37,38]. However, the aging infrastructure of the region has been known to slow down the socio-economic advantages associated with green hydrogen projects [39].

2.3. Environmental and resource impacts

In terms of environmental impact, green hydrogen projects have the potential to reduce local air pollution and greenhouse gas emissions. Thus, the use of green hydrogen for transport could improve urban air quality. Nevertheless, the generation of green hydrogen has the potential to exert an impact on natural resources, necessitating considerable quantities of water and the utilization of substantial land areas, in addition to the use of critical materials. Thus, studies have shown that water linked to green hydrogen production may intensify competition with farming, households, and existing industries [21]. In regions already experiencing water scarcity, this poses significant risks to food security and ecosystem integrity [40]. Furthermore, large-scale solar and wind energy projects have the potential to interfere with grazing land and biodiversity, and land availability issues could slow down hydrogen adoption [41], while being limited by critical materials used in electrolyzer manufacturing [42]. Consequently, the risk associated with the procurement of these limited resources should be evaluated in a manner analogous to considerations of costs and greenhouse gas

emissions [18].

2.4. Composite indicator approaches in energy and hydrogen assessment

Composite indicator (CI) has been increasingly employed to assess complex, multidimensional phenomena in energy and sustainability research. In the hydrogen literature, CI-based frameworks have been used for benchmarking Power-to-Gas systems on a global level [43], evaluating the competitiveness of hydrogen based on selected case studies [44]. Regional CI-based frameworks have been developed, including a Hydrogen Economy Index for the MENA region [45] and a Green Hydrogen Feasibility Index for the SSA region [22].

The reviewed literature identifies a wide range of prospective hydrogen impacts, but four methodological limitations remain. First, technological feasibility, economic competitiveness, and development impacts are generally assessed separately. As a result, studies that identify low-cost hydrogen locations do not necessarily determine whether projects create local employment, retain value domestically, improve infrastructure, or intensify pressure on land and water.

Second, social and distributional effects are frequently discussed qualitatively or assessed after project implementation. This limits their integration into early planning decisions, particularly in SSA, where most projects are not yet operational and project-level data remain scarce.

Third, existing composite hydrogen indices predominantly evaluate national readiness, production competitiveness, or policy and infrastructure conditions. These are important enabling conditions but are conceptually distinct from the impacts generated by a specific project configuration.

Furthermore, particularly in the case of Sub-Saharan Africa, structural constraints such as data availability [46,47] and institutional weaknesses [48–50] have also made it difficult to carry out a quantitative analysis.

Consequently, the methodological gap is not the absence of composite indicators per se, but the absence of an operational framework capable of translating prospective local impact pathways into transparent, quantitative, and reproducible indicators under data-scarce conditions. Addressing this gap constitutes the primary contribution of the methodological framework presented in the following section.

3. Methodological framework

3.1. Scope and indicator design framework

The conceptual basis of the framework is derived from the need to assess the prospective local impacts of green hydrogen projects in SSA under conditions of limited operational data. Indicator selection follows two guiding principles: First, indicators are chosen to remain measurable in data-scarce contexts either directly from open sources or via transparent proxy variables so that the framework remains applicable at early project stages; Second, the framework translates key qualitative impact pathways into quantifiable indicators that enable consistent comparison across national contexts while retaining interpretability for local decision-making.

The framework is structured into four dimensions, 13 sub-dimensions as illustrated in Fig. 1, and 26 indicators as detailed in Annex A. While interlinkages between dimensions are acknowledged, each indicator is assigned to a single dominant impact channel to avoid double counting. This design choice enhances internal consistency and supports robust cross-country comparison.

The selection of the indicators followed a structured screening process based on three methodological criteria: First, relevance, meaning that each indicator needed to capture a clearly identifiable impact pathway discussed in the literature on green hydrogen deployment, renewable energy transitions, or large-scale infrastructure development in emerging economies. The literature review presented in Section 2 served as the primary basis for identifying these pathways across economic, social, and environmental dimensions; Second, measurability

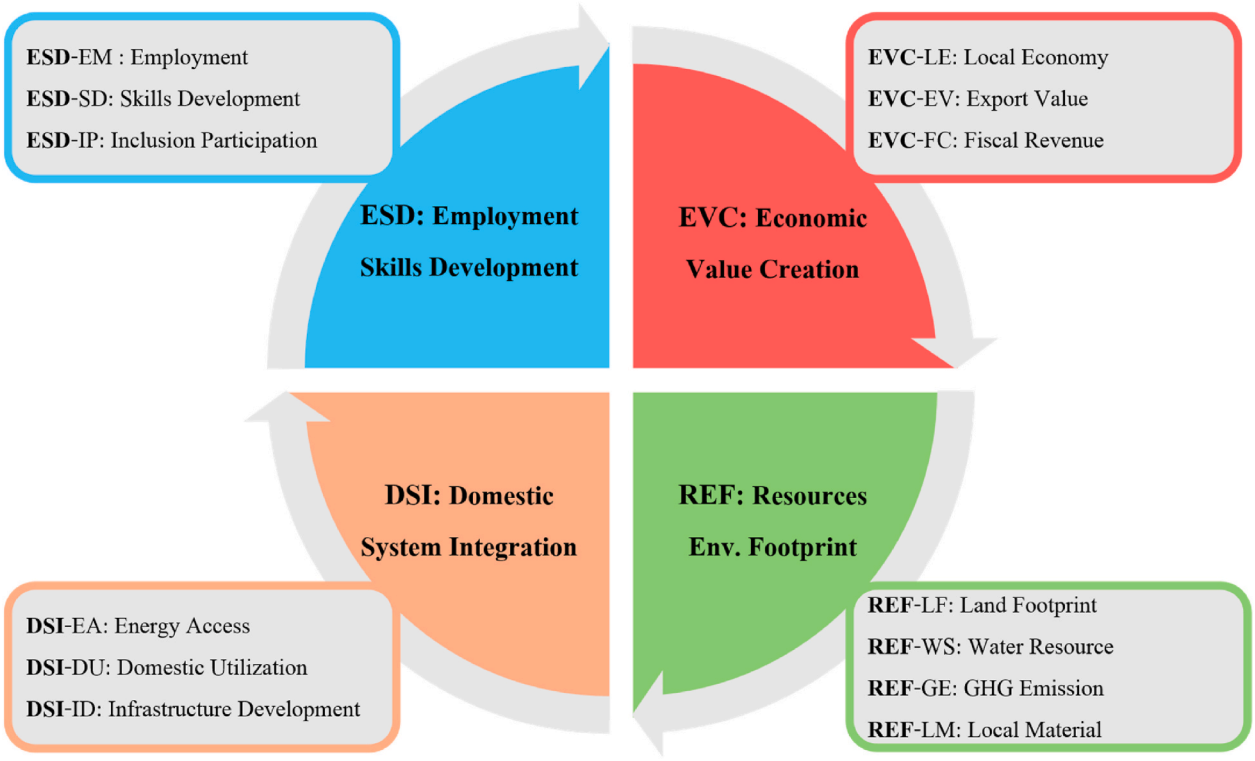


Fig. 1. Dimensions and sub-dimensions of the Green Hydrogen Impact Index (GHI). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

under data-scarce conditions was considered essential, given that most green hydrogen projects in SSA remain at early planning stages. Indicators were therefore retained only if they could be estimated using publicly available datasets, internationally harmonized statistics, or transparent proxy variables derived from comparable technologies such as solar, wind, or hydrogen pilot projects; Third, methodological independence and non-redundancy were ensured to limit overlap between indicators and avoid double counting of impacts. Candidate indicators that captured similar mechanisms were consolidated into single representative metrics where possible.

Before detailing the individual indicators and their operationalization, the following subsections first introduce the four main dimensions and their associated sub-dimensions**,** which structure the conceptual architecture of the framework.

3.1.1. Employment and skills development (ESD)

This dimension captures potential labor-market and human-capital impacts of green hydrogen projects, including distributional aspects. It consists of three main sub-dimensions: First, Employment (**ESD-**EM) quantifies total direct jobs along the value chain and the share retained locally; Second, Skills Development (**ESD-**SD) estimates the skilled-job component of local employment, reflecting technical capability requirements across project phases; Finally, Inclusive Participation (**ESD-**IP) approximates distributional outcomes through youth and gender participation proxies and a regional equity measure.

3.1.2. Economic Value Creation (EVC)

This dimension captures the extent to which project-related spending and revenues translate into domestic economic value, export margins, and fiscal inflows. It is disaggregated into three sub-dimensions: Local Economy (**MEI-**LE) approximates domestic value retention through locally captured CAPEX and direct wage income; Export Value (**MEI-**EV) estimates potential export margins under assumed market and support conditions; and Fiscal Revenue (**MEI-**FR) approximates public revenue channels linked to profits, investment expenditure, and employment.

3.1.3. Domestic System Integration (DSI)

This dimension captures potential co-benefits of green hydrogen deployment for energy access, infrastructure, and domestic end-use value creation. It is disaggregated into: Electricity Access (**DSI-**EA), which estimates the potential contribution of a Power-to-Power (PtP) allocation to electrification outcomes, expressed as population-equivalent access and access-gap reduction; Secondly, Infrastructure Development (**DSI-**ID) approximates infrastructure spillovers using a logistics performance proxy adjusted by an assumed improvement factor. Finally, Domestic Utilization (**DSI-**DU) captures the orientation of the project toward domestic utilization (as opposed to export-only deployment) through a discrete scoring approach reflecting the absence of harmonized local-use targets across SSA.

3.1.4. Resources and Environmental Footprint (REF)

This dimension captures resource requirements and environmental pressures associated with green hydrogen production, alongside potential emissions offsetting benefits. It consists of four sub-dimensions: The Land Footprint (**REF-**LF) estimates land requirements for renewable generation and associated hydrogen infrastructure relative to available land. The Water Resource (**REF-**WR) indicator adds electrolysis-related water demand to national water stress levels. The GHG emission (**REF-**GE) estimates avoided emissions relative to national totals through substitution of grey hydrogen. Lastly, the Local Material (**REF-**LM) approximates electrolyser material requirements (by material type) and the implied local manufacturing share.

3.2. Indicator operationalization and data sources

After identifying the relevant categories and sub-categories of the theoretical framework, this section details how each indicator is selected and operationalized for each sub-category using explicit assumptions, proxy variables, and publicly available open-data sources. Given that most green hydrogen projects in Sub-Saharan Africa are at an early stage, direct empirical measurements of local impacts are generally unavailable. The operationalization strategy therefore relies on proxy-based estimation pathways that draw on comparable technologies, sectoral benchmarks, and internationally harmonized datasets. For each indicator, the choice of proxy is guided by three criteria: (i) relevance to the underlying impact pathway, (ii) transparency and reproducibility, and (iii) applicability under data-scarce conditions. Where necessary, simplifying assumptions are introduced and documented explicitly to preserve interpretability and comparability across countries. In all equations, *j* reflects a specific project or country location.

3.2.1. Employment (ESD-EM)

ESD-EM was aggregated based on two proxies: total jobs (*EM0*) and local employment (*EM1*).

$EM0_j$ was calculated based on the employment factors methodology [51,52]. This approach is particularly suitable for ex-ante assessment, as it links installed capacity to employment outcomes without requiring project-level employment data. The methodology applies stage-specific employment factors per installed capacity for manufacturing M_j, construction and installation (C&I) CI_j, and operation and maintenance (O&M) OM_j, and adjusts results using a regional job multiplier [10]. A distinction is made between locally manufactured components and imported equipment to approximate domestic job capture. The proxy is expressed as below:

$$EM0_j = M_j + OM_j + CI_j \quad \text{(Equation 1)}$$

$EM1_j$ estimates the share of employment retained locally along the value chain. While jobs associated with local manufacturing LM_j are assumed to be fully domestic, employment in the C&I and O&M stages may be partially filled by non-local labour due to skills constraints and reliance on external expertise. To reflect this, corrective coefficients $LWF_{CI,j}$ and $LWF_{OM,j}$ are used respectively as expressed below:

$$EM1_j = \left(LM_j + LWF_{CI,j} \times CI_j + LWF_{OM,j} \times OM_j\right) \Big/ EM0 \quad \text{(Equation 2)}$$

The localization coefficients are estimated using the World Bank income classification [53] as a proxy for national industrial and labour-market maturity. Higher-income economies are assumed to possess more developed engineering capabilities, contractor networks, and technical expertise, resulting in greater local participation throughout the project lifecycle.

3.2.2. Skills development (ESD-SD)

ESD-LS was calculated based on local skilled employment (*SD0*) as a proxy.

SD0 estimates the number of skilled jobs expected to be filled by the domestic workforce throughout the hydrogen value chain. Since large-scale hydrogen industries are still emerging and project-specific workforce statistics remain limited, the indicator relies on employment evidence from comparable renewable energy and clean technology sectors in the region.

A baseline skilled labour share (LSI_s) is derived from reported proportions of skilled and unskilled employment for manufacturing, construction and installation (C&I), and operation and maintenance (O&M) activities in SSA [54]. This baseline is subsequently adjusted using stage-specific complexity factors (ε_s) to reflect the higher technical requirements associated with different phases of hydrogen projects.

For each project stage *s*, the number of local skilled jobs is estimated as shown below:

$$SD0_{s,j} = EM1_{s,j} \times LSI_{s,j} \quad \text{(Equation 3)}$$

To account for differences in national workforce capacity, the

baseline skilled labour shares are further adjusted using educational attainment as a proxy [55] for the availability of qualified human capital.

3.2.3. Inclusive Participation (**ESD**-IP)

ESD-IP was aggregated based on three indicators: youth participation (*IP0*), gender inclusion (*IP1*), and regional equity (*IP2*).

$IP0_j$ represented the share of the local employment opportunities allocated to youth workers. In the absence of hydrogen-specific demographic employment data, the indicator combines two proxy components: observed youth participation rates Y in decentralized renewable energy systems [56,57], and youth engagement in STEM education across the SSA region Y_{STEM} [58]. An adjusted Youth Participation Rate is computed as a weighted average based on the share of youth Y_j. A coefficient α_j is used to control the relative importance of sectoral participation versus educational readiness, as shown below and detailed:

$$IP0_j = EM1_j \times \left(\alpha_j \times Y_r + (1-\alpha_j) \times \frac{Y_{STEM}}{Y_j} \right) \quad \text{(Equation 4)}$$

To account for differences in national youth labour-market participation, the regional baseline youth participation rate is further adjusted using the employment-to-population ratio for people aged 15–24 as a country-specific proxy [59].

$IP1_j$ estimates women's local participation in green hydrogen employment. Due to the lack of hydrogen-specific gender data, the indicator applies observed female participation rates τ_j from the renewable energy sector as a proxy [33]:

$$IP1_j = \tau_j \times EM1_j \quad \text{(Equation 5)}$$

To account for differences in women's participation across national labour markets, the renewable-energy sector baseline is further adjusted using the female employment-to-population ratio in industry [60].

$IP2_j$ captures the proportional distribution of total employment $EM0$ relative to installed hydrogen capacity IC_j in each country compared to the whole SSA region as shown in the equation below.

$$IP2_j = \left(EM0_j \Big/ \sum_j EM0_j \right) \Big/ \left(IC_j \Big/ \sum_j IC_j \right) \quad \text{(Equation 6)}$$

3.2.4. Local economy (**MEI**-LE)

MEI-LE was aggregated using two indicators: local procurement Value (*LE0*) and local labor income (*LE1*).

$LE0_j$ quantifies, in monetary terms, the portion of total capital investment *CAPEX* that remained within or directly benefited the local economy based on total installed capacity IC_j and local content share ls_j. These included expenditures related to local engineering services, construction, civil works, and, where applicable, local manufacturing of components:

$$LE0_j = IC_j \times CAPEX \times ls_j \quad \text{(Equation 7)}$$

ls_j represents an assumed proportion of capital expenditure retained domestically and was expected to increase over time as national industrial capabilities and supply chains developed. While this indicator provided a comparative approximation of local economic integration, it was acknowledged that the total investment-related spillovers may be underestimated due to the exclusion of indirect and induced effects.

To account for differences in national industrial capacity, the Local Procurement Factor is adjusted using Manufacturing Value Added (MVA) as a percentage of GDP as a proxy for the maturity of the domestic industrial base [61].

$LE1_j$ estimated the total wage income generated by direct local employment associated with green hydrogen project development. The methodology considered only wages from direct local employment across different stages of the value chain. Monthly average national wages $Wage_{j,avg}$ are expressed in purchasing power parity [62] adjusted using a sectoral multiplier μ_j to reflect the higher skill intensity and technical specialization of green hydrogen activities. The average annual wage was calculated as shown below:

$$LE1_j = EM1_j \times Wage_{j,avg} \times \mu_j \times 12 \quad \text{(Equation 8)}$$

3.2.5. Export Value (**MEI**-EV)

MEI-EV was calculated using a proxy potential financial export profitability (*EV0*) that could be generated by green hydrogen exports under assumed market and policy conditions.

$EV0_j$ is calculated based on the international market price of hydrogen (or its derivatives) MP, the adjusted levelized cost of hydrogen ($LCOH_{j,adj}$), and exported production capacity EC_j as shown below:

$$EV0_j = \left(MP - LCOH_{j,adj} \right) \times EC_j \quad \text{(Equation 9)}$$

Where $LCOH_{j,adj} = LCOH_{j,avg} \times (1-s) + LgC$

In fact, current average $LCOH_{j,avg}$ estimates derived from the H_2 Atlas are generally higher than expected international market prices [17,63]. To reflect plausible future deployment scenarios rather than current market outcomes, a subsidy parameter s expressed as a share of production cost was introduced. This term represents financial support mechanisms and is treated as a policy assumption rather than a technological cost reduction. Logistics costs LgC accounted for expenditures related to the transport of hydrogen or its derivatives.

3.2.6. Fiscal revenue (**MEI**-FR)

MEI-FR is aggregated using three principal fiscal channels: corporate tax revenue (*FR0*), indirect taxes revenue linked to domestic investment expenditure (*FR1*), and employment-related social contributions (*FR2*):

$FR0_j$ is approximated based on gross export profits, using the $EV0_j$ indicator as a proxy for the taxable profit based on the rate of corporate income taxes $R_{C,j}$ [64]:

$$FC0_j = EV0_j \times R_{C,j} \quad \text{(Equation 10)}$$

$FR1_j$ captures indirect fiscal revenues generated through local capital expenditure associated with hydrogen projects. A share of domestic investment value (*LE0*) is assumed to be subject to an indirect taxation rate $R_{FDI,j}$, including value-added taxes, import duties, and taxes on locally sourced materials and services [65]:

$$FCR1_j = LE0_j \times R_{FDI,j} \quad \text{(Equation 11)}$$

$FR2_j$ represents public revenue generated through employment-related wage income $LE1_j$ using the social contributions rate $R_{SC,j}$ [66]:

$$FR2_j = LE1_j \times R_{SC,j} \quad \text{(Equation 12)}$$

3.2.7. Electricity access (**DSI**-EA)

DSI-EA is aggregated based on two indices: total population equivalent served (*EA0*) and electrification gap reduction (*EA1*).

$EA0_j$ compares the energy allocated to PtP applications PtP_j to total national electricity consumption, approximated as per capita electricity consumption $E_{c,j}$ [67] multiplied by total population PoP_j [68]:

$$EA0_j = \mathrm{PtP}_j \Big/ \left(E_{c,j} \times \mathrm{PoP}_j \right) \quad \text{(Equation 13)}$$

$EA1_j$ was assessed by estimating the number of people that could be supplied with electricity PtP_j and expressing this value as a proportion of the population currently without access based on the national electricity access rate EAr_j [69].

$$EA1_j = \left(\mathrm{PtP}_j / E_{c,j} \right) \Big/ \left(\mathrm{PoP}_j \times (1 - \mathrm{EAr}_j) \right) \quad \text{(Equation 14)}$$

3.2.8. Domestic utilization (DSI-DU)

Due to the absence of clearly defined national strategies and quantitative targets for local hydrogen use across sectors in SSA, a scenario-based scoring approach was used as a proxy for DU0.

A discrete score was assigned to $LU0_j$, with higher values indicating stronger prioritization of domestic consumption relative to export-oriented deployment based on regional roadmap and current planned projects.

$$DU0_j \in]0, 2] \quad \text{(Equation 15)}$$

3.2.9. Infrastructure development (DSI-ID)

Given the broad scope of infrastructure affected, the Logistics Performance Index (LPI) was used as a baseline [70,71]. To account for the expected contribution of green hydrogen projects to infrastructure enhancement, a scenario-based improvement factor was applied.

$ID0_j$ reflected the extent to which hydrogen-related investments in transport corridors, ports, grid infrastructure, and water systems could strengthen national logistics performance using an infrastructure improvement factor δ :

$$ID0_j = LPI_j \times \delta_j \quad \text{(Equation 16)}$$

Where $\delta_j \in]1, 2]$

3.2.10. Land footprint (REF-LF)

REF-LF was aggregated based on two indicators: *LF0* represented the effective surface area to meet the targeted production, and *LF1* the land footprint.

$LF0_j$ was estimated using the Hydrogen Production Target HP_j compared to the maximum technical hydrogen potential per unit area $TP_{max,j}$ based on H_2 Atlas results [72]:

$$LF0_j = HP_j / TP_{max,j} \quad \text{(Equation 16)}$$

$LF1_j$ was subsequently expressed as a share of the nationally available land after exclusion zones ExA_j were deducted from the total area TA_j. To ensure realistic estimation of available land, exclusion zones were applied to remove areas unsuitable for development. Protected areas were excluded using the World Database on Protected Areas (WDPA) [73], urban zones were excluded based on the Global Human Settlement Layer (GHSL) [74], and inland water bodies (lakes and rivers) were excluded using Natural Earth datasets [75].

$$LF1_j = LF0_j \,/\, (TA_j - ExA_j) \quad \text{(Equation 17)}$$

3.2.11. Water resource (REF-WR)

REF-WR was approximated using the new national stress level *WR0* after accounting for the additional impact induced by the green hydrogen project.

$WR0_j$ is the current water stress CWS_j [76] and added water stress from hydrogen production AWS_j. The latter is calculated as the ratio of additional water demand required for hydrogen production to the total renewable internal freshwater resources per country [77]

$$WR0_j = CWS_j + AWS_j \quad \text{(Equation 18)}$$

3.2.12. GHG emission (REF-GE)

*GE*0 was assessed based on potential emissions reduction achieved by replacing conventional hydrogen production methods with green hydrogen.

The avoided emissions are calculated based on the carbon intensity of grey hydrogen gHI_{CO_2} [78] and total hydrogen production HP_j. This was compared to the total national emissions NE_j [79] as a proxy for $GE0_j$:

$$GE0_j = \left(gHI_{CO_2} \times HP_j\right) \Big/ NE_j \quad \text{(Equation 19)}$$

3.2.13. Local Material (REF-LM)

LMm proxy used in the estimation relied on technical specifications reported in Ref. [80], which documented the material *m* composition of a typical 1 MW alkaline electrolyser detailed in Annex B $M_{m,j}$.

The total demand for each materialwas calculated based on planned installed capacity IC_j. This allows to approximate $LM_{m,j}$ using materials share for manufacturing $Ms_{m,j}$ and quantity that can reasonably be supplied locally $ML_{m,j}$:

$$LM_{m,j} = \min\left(IC_j \times \mathrm{Ms_{m,j}}, \mathrm{ML_{m,j}}\right) \quad \text{(Equation 20)}$$

Domestic availability is primarily approximated using national production data. Where current production is absent or unavailable, documented mineral reserves may be used as a secondary proxy for potential domestic availability (Annex B).

3.3. Composite indicator architecture, normalization, weighting, and aggregation

Once individual indicators have been defined and operationalized, the next step consisted of structuring them within a coherent composite indicator architecture. This required specifying the hierarchical relationships between indicators, sub-dimensions, and dimensions, as well as applying appropriate normalization, weighting, and aggregation procedures. These steps ensured that multidimensional impacts were synthesized into interpretable composite scores while preserving transparency and traceability throughout the assessment process.

3.3.1. Index structure

The proposed architecture was based on a hierarchical, multi-level structure, as summarised in Fig. 2 and detailed in Annex A. At Level 1, the framework comprised 26 elementary indicators. These indicators were aggregated into thematic sub-dimensions at Level 2, which were subsequently aggregated into the four core impact dimensions at Level 3. Finally, the four dimensions were aggregated to form the GHI at Level 4. Each indicator was assigned to a parent node, which controls its contribution to higher-level aggregates and ensures internal consistency within the hierarchy. Indicator directions were explicitly defined: positive directions denoted desirable outcomes or beneficial impacts, whereas negative directions captured environmental pressures, resource constraints, or trade-offs associated with green hydrogen production.

3.3.2. Normalization, weighting, and aggregation

Given the diversity of the indicators (units, scales, interpretations), a uniform normalization method is essential for comparability. Mainly, it transforms indicators and discusses the presence of outliers in the data set, as they may become unintended reference points [81]. However, several normalization techniques exist, and each may give a different output. Thus, the selection of appropriate normalization schemes is recommended to follow both the theoretical framework and the data structure [81].

In the case of the GHII, a goalpost (distance-to-frontier) normalization is applied. This approach rescales each indicator relative to predefined minimum and maximum reference values, rather than to observed country distributions. It is particularly well suited for ex-ante assessment and data-scarce contexts, as it allows indicator values to be interpreted as distances to theoretically or policy-relevant performance bounds, even when the application focuses on a single country [81]:

$$x_i^n = \frac{x_i - min}{max - min} \times 100 \quad \text{(Equation 21)}$$

Where x_i^n is the normalized value of an indicator x_i, and *min* and *max* denote the lower and upper goalposts of indicator *i*, respectively.

Following normalization, indicators are aggregated using weighted techniques. Weights are assigned at the indicator level such that the sum

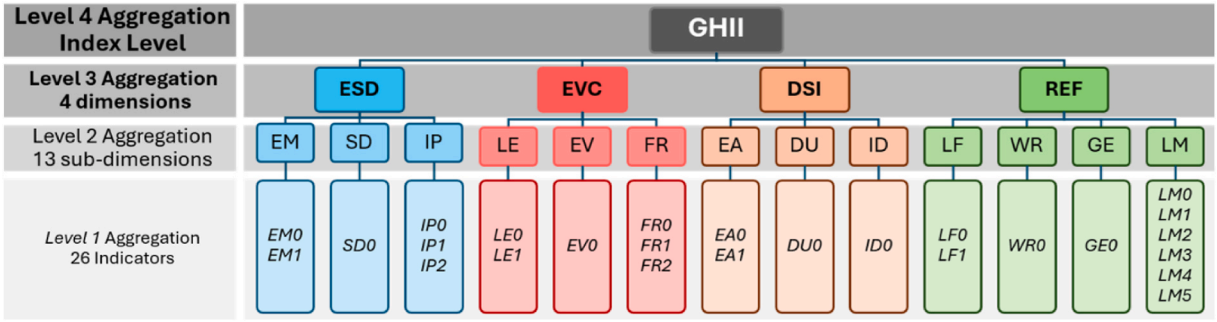


Fig. 2. Structure of GHI index at different aggregation levels.

of weights within each dimension is preserved, irrespective of the number of indicators composing that dimension. This ensures internal consistency and avoids mechanical bias arising from unequal indicator counts across pillars.

Two aggregation functions are considered to reflect alternative conceptual assumptions regarding compensability among indicators and dimensions.

$$GHII = \begin{cases} \sum_{i=1}^{n} \omega_i \times x_i^n \\ \prod_{i=1}^{n} \left(x_i^n\right)^{\omega_i} \end{cases} \quad \text{(Equation 22)}$$

Where *GHII* is the composite Index, ω_i is the weight assigned to the indicator x_i.

The arithmetic aggregation is used as the baseline specification, consistent with exploratory policy analysis. Geometric aggregation is employed in the robustness analysis to test the sensitivity of results.

4. Illustrative application: Namibia

This section illustrates the application of the proposed GHII using Namibia as a reference case. The objective is not to provide a comprehensive national assessment, but to demonstrate indicator operationalization, internal coherence, and order-of-magnitude plausibility using a concrete country example. Namibia is selected due to the availability of publicly reported data on green hydrogen development and its relevance as an early mover in Sub-Saharan Africa.

4.1. Data collection and indicator application

The parameters in Annex B were used as the foundation of the framework quantification. It lists the main assumptions used in the study. These assumptions are method-wide and apply uniformly across all country applications of the framework. They define the technical performance envelope and socio-economic proxy structure within which country-specific indicators are computed.

For the illustrative case of Namibia, the application considers a standardized project configuration consisting of 100 MW of installed electrolyzer capacity, of which 25% is assumed to be dedicated to export markets by 2030. Table 1 summarizes the estimated values of each indicator, along with their corresponding units, underlying assumptions, and the data sources.

4.2. Indicator magnitude validation against the hydrogen hyphen project

Given the limited number of operational green hydrogen projects with available data in Sub-Saharan Africa (SSA), indicators for which publicly reported project-level information is available are limited. Consequently, the objective of this assessment is not to calibrate the proposed framework against observed project outcomes, but rather to evaluate whether the proxy-based estimation pathways generate results that are consistent with publicly available information from one of the most advanced hydrogen projects currently under development in the region. This benchmarking exercise therefore focuses on the plausibility of the methodological framework and the order of magnitude of selected indicators, rather than on predictive accuracy.

The Hyphen Hydrogen Energy project located in Namibia was selected as the reference case as it represents one of the largest green hydrogen initiatives currently under development in SSA and provides publicly accessible information on installed capacity, land use, investment scale, employment creation, and anticipated GHG emission reductions [84,85].

The employment-related indicators were assessed by comparing the estimation pathways presented in Section 3.2 with the employment information disclosed for the Hyphen project. For the employment indicator, reported project information indicates the creation of up to 15,000 jobs during the construction and installation (C&I) phase and

Table 1
Indicator calculation and assumptions for the illustrative case.

Indicaor	Value	Unit	Key assumption/Proxy	Source
EM0	3407	Jobs	100 MW and Regional multipliers	[51,82]
EM1	85	%	$\beta_1 = \beta_2 = 90\%$	[53]
SD0	2555	Jobs	$\varepsilon_1 = 20\%$, $\varepsilon_2 = 15\%$, and $\varepsilon_3 = 25\%$	[54,55]
IP0	40.00	%	13.7% in STEM, and 34.1% of youth	[59,83]
IP1	929	Jobs	Women's representation in the RE sector	[33,60]
IP2	1.00	-	Jobs are fairly distributed	-
LE0	70.00	M€	CAPEX = 1.4 M€/MW and 50% local procurement	[16,61]
LE1	52.70	M PPP$	Earnings of employees and μ = 1.5	[62]
EV0	4.63	M€	Shipping cost = 0.84 €/kg, LCOH = 2.87 €/kg, Subsidy = 40% of LCOH, and market prices = 3.5 €/kg	[17,41], [63,72]
FR0	1.50	M€	Corporate tax rate = 32.40%	[64]
FR1	10.50	M€	Tax rate on FDI (standard VAT rate) = 15%	[65]
FR2	0.47	M PPP$	Social contribution rate = 0.9%	[66]
EA0	1.17	%	PtP Capacity = 10 MW, Electricity consumption per capita = 1231 kWh, and Total population = 3,030,131	[67,68]
EA1	0.03	%	Electricity access rate = 56.7%	[69]
DU0	2.00	-	Full participation	-
ID0	3.05	-	δ = 1.05 (infrastructures have been improved by 5%)	[71]
LF0	35.44	km^2	Maximal technical potential = 12.36 kWh/m^2 (weighted average)	[72]
LF1	0.01	%	Useable land area = 613835.39 km^2	[73–75]
WR0	0.31	-	Level of water stress = 0.31 and renewable internal freshwater resource = 6 billion m3	[76,77]
GE0	−0.14	%	carbon intensity of grey hydrogen = 7.5 to 13 kgCO2eq./kgH2	[78,79]

3000 permanent jobs during operation and maintenance (O&M). Applying the proposed employment-factor methodology to the announced electrolyser capacity of 3 GW resulted in approximately 5 jobs per MW, which closely matched the median EF value identified for this phase. For the O&M phase, the employment factor accounted for the maintenance of both renewable energy installations and electrolysers. The median EF obtained for this phase was 0.37 jobs per MW, which was consistent with the magnitude implied by the Hyphen project estimates. The manufacturing component, estimated independently using literature-based employment factors, yielded approximately 1.86 jobs per MW.

The contextual adjustment applied to estimate local employment also produced results consistent with the expected characteristics of the Hyphen project. The assumption yielded a local employment share of approximately 85.22%. This estimate was broadly consistent with the project's stated objective of sourcing 90% of its workforce locally. Finally, regarding Inclusive Participation, the framework estimated youth participation at approximately 40%, whereas the Hyphen project reported a target of around 20% youth employment. Given that the framework derives youth participation from regional labour-market and educational proxies rather than project-specific recruitment strategies, this comparison primarily supports the plausibility of the adopted estimation pathway rather than demonstrating exact predictive agreement.

A similar benchmarking exercise was conducted for the Land Footprint indicator by comparing land-use estimates derived from the framework with land-use figures reported by the Hyphen project. Using a maximum technical hydrogen potential of 12.36 kWh/m^2 for Namibia and a targeted annual production of approximately 2 million tonnes of hydrogen derivatives, the framework estimated a required land area of around 5393 km^2. This value was of the same order of magnitude as the land-use figure reported by the project (approximately 4000 km^2). The observed discrepancy can be attributed to differences between region-specific maximum technical potential values obtained from the Global Hydrogen Atlas [77] and the country-level weighted averages applied in the framework. To contextualize land-use impacts, using the available land area of 613,835.39 km^2, the Hyphen project footprint represented approximately 0.88% of Namibia's available national territory. This relative indicator provides a more meaningful interpretation of land-use pressure in relation to national spatial constraints.

4.3. Sensitivity and uncertainty analysis

Given the proxy-based and ex-ante nature of the proposed framework, a sensitivity and uncertainty analysis was conducted to assess the robustness of the GHII.

4.3.1. Monte Carlo sensitivity design

Monte Carlo simulations were implemented by repeatedly perturbing indicators, weights, and aggregation rules within predefined bounds. A total of 500 iterations were performed for each perturbation configuration. For each simulation run, the full index computation chain, including normalization, weighting, and aggregation, was executed to generate a distribution of GHI scores.

In indicator perturbation, values were randomly varied within a 5% interval around their baseline estimates. This relatively narrow perturbation range reflects the structured nature of the proxy-based operationalization: although proxies introduce uncertainty, they are derived from published benchmarks, national statistics, and explicitly documented parameters.

In weight perturbation, indicator weights were randomly varied within wider bounds of 15% while preserving their sum. This captures normative uncertainty in weight choices. Unlike indicator values, weights reflect value judgements and policy priorities; therefore, broader variability is justified to reflect potential stakeholder heterogeneity.

Finally, each perturbation strategy was evaluated under both arithmetic and geometric aggregation to test sensitivity to alternative conceptual assumptions regarding compensability across dimensions.

As shown in Fig. 1 (left), indicator perturbations generate moderate variability under both arithmetic and geometric aggregation, with coefficients of variation of 1.45% and 1.36%, respectively. Weight perturbations produce lower variability under arithmetic aggregation but higher variability under geometric aggregation, highlighting the greater sensitivity of non-compensatory aggregation to normative weighting choices. When indicators and weights are perturbed simultaneously, overall variability increases but remains limited, with coefficients of variation of 1.72% under arithmetic aggregation and 2.45% under geometric aggregation.

Fig. 3 (right) compares mean GHI scores under arithmetic and geometric aggregation. Arithmetic aggregation yields a mean score of **60.27**, while geometric aggregation results in a lower mean score of **50.71**, consistent with the non-compensatory structure of the geometric mean. Importantly, uncertainty ranges around both means remain narrow (standard deviations of **1.03** and **1.24**, respectively), indicating that aggregation choice affects the level of the index rather than its stability.

Overall, the results demonstrate that the GHI is structurally robust: uncertainty is primarily driven by indicator-level variability rather than weighting assumptions, and aggregation choices reflect alternative conceptual interpretations of compensability rather than sources of numerical instability.

5. Conclusion

This study introduces a novel, development-oriented framework to the field of green hydrogen research. The framework provides a structured methodology for assessing the prospective impact of green hydrogen projects at the national or regional level in Sub-Saharan Africa (SSA). While existing literature often focuses on technical feasibility or qualitative impact narratives in the region, the proposed framework translates the broader implications of green hydrogen deployment into structured, transparent, and reproducible analytical architecture. By doing so, it enables the systematic exploration of trade-offs that are essential for informed decision-making in emerging hydrogen economies.

A central contribution of the study lies in structuring green hydrogen impacts as inherently multidimensional. Building on insights from the literature review, the framework is explicitly designed around four core dimensions, including employment and skills development, macroeconomic integration, social and infrastructural benefits, and environmental and resource footprint. This structure reflects the recognition that green hydrogen deployment intersects with economic systems, labor markets, infrastructure networks, and natural resource constraints simultaneously. This framework provides a transparent architecture through which potential interactions and tensions between these dimensions can be examined. For example, export-oriented project configurations that strengthen macroeconomic indicators may simultaneously increase land, water, or material intensity. While the illustrative application does not aim to exhaustively quantify such trade-offs, it demonstrates the analytical capacity of the framework to make them visible and comparable.

The framework further demonstrates the importance of localizing impact assessment. The linking of hydrogen initiatives with the labor market, fiscal system, infrastructure networks, and natural resources of nations captures development pathways that are typically overlooked in aggregated or global-scale assessments. This localized perspective is relevant for SSA, in a way that green hydrogen projects are expected to be transformative rather than incremental. Moreover, social acceptance and long-term viability will depend on tangible local benefits and minimal pressure on resources.

Another key insight relates to the feasibility of ex-ante impact quantification in data-scarce environments. Through the use of explicit assumptions, proxy-based indicators, and directional logic, the

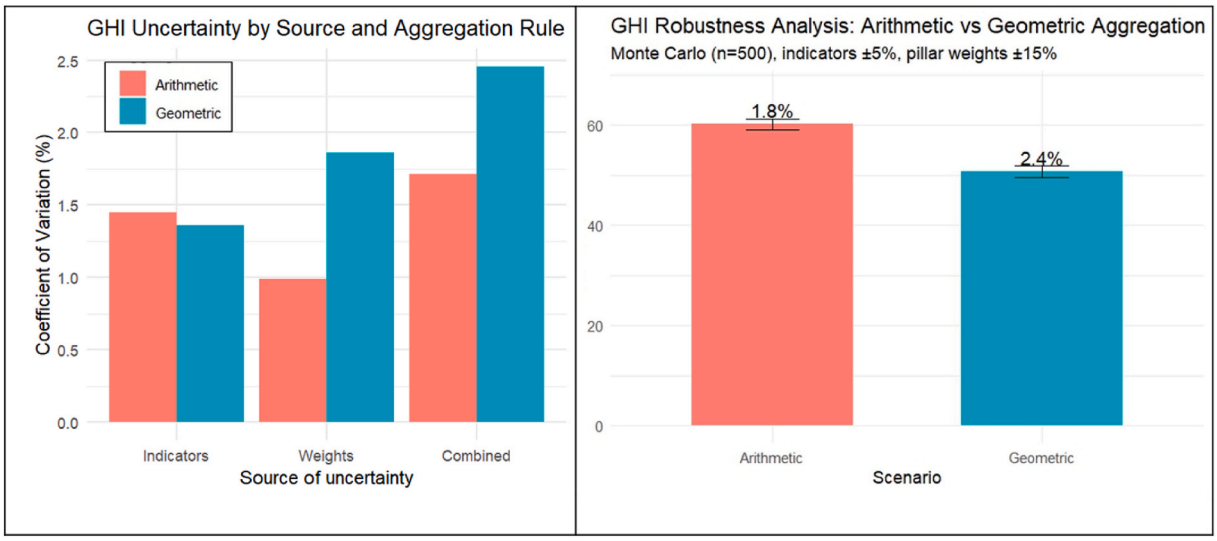


Fig. 3. Summarizes the robustness of the GHI under Monte Carlo perturbations of indicators, weights, and aggregation rules. Across all configurations, the index exhibits low variability, with coefficients of variation remaining belo2.5%, indicating a high degree of stability.

framework demonstrates that it is possible to approximate the order of magnitude and relative importance of project impacts before implementation. The illustrative validation against publicly available information from the Hyphen Hydrogen project in Namibia shows that estimated employment and land-use indicators are broadly aligned with reported benchmarks. While not intended as calibration, this comparison supports the plausibility of the proxy-based approach. The aggregation of individual indicators into the Green Hydrogen Impact Index (GHII) further provides a synthetic overview of impacts while preserving traceability across dimensions, reinforcing the role of the index as a diagnostic rather than a predictive tool.

Finally, the sensitivity and robustness analysis confirms that the GHI is structurally robust. Monte Carlo simulations show that index variability is driven primarily by indicator-level uncertainty rather than by weighting assumptions, while aggregation choices mainly affect index levels rather than stability. This finding underscores the suitability of the framework for exploratory, ex-ante assessment, where robustness to normative choices is essential.

CRediT authorship contribution statement

Amin Lahnaoui: Writing – original draft, Visualization, Supervision, Methodology, Conceptualization. **Kouamé Jean Didier Kouakou:** Writing – original draft, Methodology, Formal analysis, Data curation. **Maman Maarouhi Inoussa:** Writing – review & editing, Supervision. **Bruno Korgo:** Writing – review & editing, Supervision, Resources, Project administration. **Sascha Stark:** Writing – review & editing, Validation, Supervision. **Sandra Venghaus:** Writing – review & editing, Validation, Supervision, Resources.

Funding

This article was written as part of the project "WASCAL International Master's Programme in Energy and Green Hydrogen Technology (IMP-EGH)," funded by the German Federal Ministry of Education and Research (BMBF) under the funding code 03SF0626C.

This work was supported by the Helmholtz Association under the program "Energy System Design".

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Annex

Annex A
Design of composite indicator framework

Dimension	Sub-dimension	Description	Indicators	Data availability	Direction
Employment & Skills Development (ESD)	Employment (EM)	Estimate total direct employment in the Power-to-hydrogen value chain	- Total jobs (M + C&I + O&M) (EM0) - Local employment (EM1)	Scenario-based calculation	+1
	Skills Improvement (SD)	The extent to which the green hydrogen project contributes to improving local workforce skills and creating new vocational opportunities.	- Local skilled employment (SD0)	Proxy-based calculation	+1
	Inclusive Participation (IP)	Youth rate in the workforce, gender inclusion rate, and equitable distributional effect	- Youth participation (IP0) - Gender Inclusion (IP1) - Regional distribution (IP2)	Proxy-based calculation	+1
Economic Value Creation (EVC)	Local Economy Integration (LE)	Economic value is retained domestically through local manufacturing, construction, and services	- Local procurement value (LE0) - Local labor income (LE1)	Scenario-based calculation	+1

(*continued on next page*)

Annex A (*continued*)

Dimension	Sub-dimension	Description	Indicators	Data availability	Direction
	Export Value (EV)	Money earned when exporting green hydrogen or derived products	- Export profitability (EV0)	Scenario-based calculation	+1
	Fiscal Revenue (FR)	Assess the potential public revenues from green hydrogen projects	- Corporate tax revenue (FR0) - Indirect tax revenue (FR1) - Social Contribution (FR2)	Scenario-based calculation	+1
Domestic System Integration (DSI)	Electricity access (EA)	To what extent will the project improve access to electricity or energy for neighboring populations	- Population equivalent served (EAI0) - Access gap reduction (EAI1)	Scenario-based calculation	+1
	Domestic Utilization (DU)	Measure the extent to which a green hydrogen project contributes to the local economy use	- Domestic utilization score (DU0)	Score-based indicator	+1
	Infrastructure development (ID)	Assess the extent to which the infrastructure created for a green hydrogen project (roads, power lines, ports, etc.)	- Infrastructure development Index (ID0)	Proxy-based calculation	+1
Environmental & Resource Footprint (ERF)	Land Footprint (LF)	Influence of hydrogen energy on land availability	- Land requirements for renewable generation (LF0) - Land footprint (LF1)	Scenario-based calculation	−1
	Water Resource (WR)	Potential exacerbation of water scarcity	- Water stress impact (WR0)	Scenario-based calculation	−1
	GHG emission (GE)	To what extent does the project improve GHG emissions at the national level	- Avoided GHG Emissions (GE0)	Scenario-based calculation	+1
	Local Material (LM)	Assesses the volume of raw materials needed for the local manufacturing of alkaline electrolyzers deployed for hydrogen production	Quantity needed of: Steel (LM0), Aluminum (LM1), Plastic (LM2), Copper (LM3), Zirconium (LM4), and Nickel (LM5).	Scenario-based calculation	−1

Annex B.1
General assumptions used for computation

Parameter	Value	Description	Sources
Capacity Factor	50%	Expected electrolyzer capacity factor	Assumption based on [86,87]
Water consumption	9 litters	The quantity of water required to produce 1 kg of hydrogen	[82]
Learning Factor	12% by 2030	Decline (in employment factors) over time due to technological productivity gains.	Assumption based on [16,88]
Local Manufacturing share	50% by 2030	Regional capacity share for manufacturing hydrogen infrastructure and equipment jobs.	[51]
Regional Employment Multiplier	5.00 by 2030	Regional adjustment of global employment factors to reflect SSA's higher labor intensity.	[51]

Annex B.2
Technical specifications for alkaline electrolyzer manufacturing

Material	Quantity (kg/MW) [81]	Source
Steel	38,131.2	[80]
Aluminum	160	
Plastic + elastomer	672.5	
Copper	616.7	
Zirconium	73	
Nickel	2884.9	

References

[1] Jayachandran M, Gatla RK, Flah A, Milyani AH, Milyani HM, Blazek V, et al. Challenges and opportunities in green hydrogen adoption for decarbonizing hard-to-abate industries: a comprehensive review. IEEE Access 2024;12:23363–88. https://doi.org/10.1109/ACCESS.2024.3363869.

[2] Franco A, Rocca M. Renewable electricity and green hydrogen integration for decarbonization of "Hard-to-Abate" industrial sectors. Electricity 2024;5:471–90. https://doi.org/10.3390/electricity5030024.

[3] Patel GH, Havukainen J, Horttanainen M, Soukka R, Tuomaala M. Climate change performance of hydrogen production based on life cycle assessment. Green Chem 2024;26:992–1006. https://doi.org/10.1039/D3GC02410E.

[4] Meloni E, Iervolino G, Palma V. Highly-efficient hydrogen production through the electrification of OB-SiC nickel structured catalyst: methane steam reforming and ammonia cracking as case studies. Int J Hydrogen Energy 2024;65:42–9. https://doi.org/10.1016/j.ijhydene.2024.03.349.

[5] Palma V, Ruocco C, Meloni E, Ricca A. Oxidative reforming of ethanol over CeO2-SiO2 based catalysts in a fluidized bed reactor. Chem Eng Process Process Intensif 2018;124:319–27. https://doi.org/10.1016/j.cep.2017.08.010.

[6] Aslam S, Rani S, Lal K, Fatima M, Hardwick T, Shirinfar B, Ahmed N. Electrochemical hydrogen production: sustainable hydrogen economy. Green Chem 2023;25:1463–9262. https://doi.org/10.1039/d3gc02849f.

[7] IRENA. Green hydrogen cost reduction: scaling up electrolysers to meet the 1.5^{0}C climate goal. 2020. Abu Dhabi.

[8] Segovia-Hernández JG, Hernández S, Cossío-Vargas E, Juarez-García M, Sánchez-Ramírez E. Green hydrogen production for sustainable development: a critical examination of barriers and strategic opportunities. RSC Sustain 2025;3:134–57. https://doi.org/10.1039/D4SU00630E.

[9] Sakthimurugan V, Lakshmikanth G, Balaji N, Roopashree R, Kumar D, Devarajan Y. Green hydrogen revolution: advancing electrolysis, market integration, and sustainable energy transitions towards a net-zero future. Results Eng 2025;26:104849. https://doi.org/10.1016/j.rineng.2025.104849.

[10] Winkler C, Heinrichs H, Ishmam S, Bayat B, Lahnaoui A, Agbo S, et al. Participatory mapping of local green hydrogen cost-potentials in Sub-Saharan Africa. Int J Hydrogen Energy 2025;112:289–321. https://doi.org/10.1016/j.ijhydene.2025.02.015.

[11] Sawadogo W, Reboita MS, Faye A, da Rocha RP, Odoulami RC, Olusegun CF, et al. Current and future potential of solar and wind energy over Africa using the RegCM4 CORDEX-CORE ensemble. Clim Dyn 2021;57:1647–72. https://doi.org/10.1007/s00382-020-05377-1.

[12] Koshikwinja PM, Cavana M, Sechi S, Bochiellini R, Leone P. Review of the hydrogen supply chain and use in Africa. Renew Sustain Energy Rev 2025;208:115004. https://doi.org/10.1016/j.rser.2024.115004.

[13] AbouSeada N, Hatem TM. Climate action: prospects of green hydrogen in Africa. Energy Rep 2022;8:3873–90. https://doi.org/10.1016/j.egyr.2022.02.225.
[14] Ishmam S, Heinrichs H, Winkler C, Bayat B, Lahnaoui A, Agbo S, et al. Mapping local green hydrogen cost-potentials by a multidisciplinary approach. Int J Hydrogen Energy 2024;87:1155–70. https://doi.org/10.1016/j.ijhydene.2024.08.501.
[15] Saravanan T, Shnain AH, Sharma H, Sathiya Naveena S, Rajurkar AU, Sherje N, et al. Hydrogen production via electrolyzers: enhancing efficiency and reducing costs. E3S Web of Conferences 2024;591:06003. https://doi.org/10.1051/e3sconf/202459106003.
[16] Detz R, Weeda M. Projections of electrolyzer investment cost reduction through learning curve analysis. 2022. Amsterdam.
[17] Egli F, Schneider F, Leonard A, Halloran C, Salmon N, Schmidt T, et al. Mapping the cost competitiveness of African green hydrogen imports to Europe. Nat Energy 2025;10:750–61. https://doi.org/10.1038/s41560-025-01768-y.
[18] Terlouw T, Bauer C, McKenna R, Mazzotti M. Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. Energy Environ Sci 2022;15:3583–602. https://doi.org/10.1039/D2EE01023B.
[19] Hamukoshi SS, Mama N, Shimanda PP, Shafudah NH. An overview of the socio-economic impacts of the green hydrogen value chain in Southern Africa. J Energy South Afr 2022;33:12–21. https://doi.org/10.17159/2413-3051/2022/v33i3a12543.
[20] Dagnachew AG, Solf S, Ibrahim SI, Harmen-Sytze de B. The opportunities, challenges and potential for hydrogen in Africa. 2023.
[21] Dagnachew AG, Yalew SG, Tesfamichael M, Okereke C, Abraham E. A green hydrogen revolution in Africa remains elusive under current geopolitical realities. Clim Policy 2025;25:291–302. https://doi.org/10.1080/14693062.2024.2376740.
[22] Lahnaoui A, Aniello G, Barberis S, Agbo SN, Kuckshinrichs W. Assessing the feasibility of a green hydrogen economy in selected African regions with composite indicators. Int J Hydrogen Energy 2025;101:1387–405. https://doi.org/10.1016/j.ijhydene.2024.12.233.
[23] Sadik-Zada ER, Gatto A, Schäfer N. African green hydrogen uptake from the lens of African development and European energy security: a blessing or curse? Technol Forecast Soc Change 2025;215:123974. https://doi.org/10.1016/j.techfore.2025.123974.
[24] UNIDOS, IRENA, IDOS. Green hydrogen for sustainable industrial development: a policy toolkit for developing countries. 2023.
[25] McHenry R, Krishnan S, Tuck L. Knowledge, skills, and attributes needed for developing a hydrogen engineering workforce: a systematic review of literature on hydrogen engineering education. Int J Hydrogen Energy 2024;72:380–7. https://doi.org/10.1016/j.ijhydene.2024.05.380.
[26] Bindi J, Bartolomei F, Pellegrini-Masini G, Agostini A, Padovan D. Assessing social impacts and energy justice along green hydrogen supply chains: a capability-based framework. Energy Res Social Sci 2025;126:104149. https://doi.org/10.1016/j.erss.2025.104149.
[27] IRENA. A just energy transition for communities: large-scale wind and solar projects in Sub-Saharan Africa. 2025. Abu Dhabi.
[28] Msweli N, Nnachi GU, Richards CG. A review of green hydrogen technologies and their role in enabling sustainable energy access in remote and off-grid areas within Sub-Saharan Africa. Energies 2025;18:5035. https://doi.org/10.3390/en18185035.
[29] Ayodele TR, Mosetlhe TC, Yusuff AA, Ogunjuyigbe ASO. Off-grid hybrid renewable energy system with hydrogen storage for South African rural community health clinic. Int J Hydrogen Energy 2021;46:19871–85. https://doi.org/10.1016/j.ijhydene.2021.03.140.
[30] Ba-swaimi S, Verayiah R, Ramachandaramurthy VK, Alahmad AK, Padmanaban S. Optimal configuration and sizing of integrated hybrid renewable energy systems for sustainable power supply in healthcare buildings. Results Eng 2025;26:104800. https://doi.org/10.1016/j.rineng.2025.104800.
[31] Moner-Girona M, Fahl F, Kakoulaki G, Kim D-H, Maduako I, Szabó S, et al. Empowering quality education through sustainable and equitable electricity access in African schools. Joule 2025;9:101804. https://doi.org/10.1016/j.joule.2024.12.005.
[32] Oyinlola OK, Mojeed TA, Olushola OO, Ali AS, Muhammad SE. Renewable energy transitions and gender justice: women's empowerment through solar mini-grids in rural Nigeria. World J Adv Res Rev 2025;28:1214–29. https://doi.org/10.30574/wjarr.2025.28.1.3527.
[33] IRENA. Renewable energy. A gender perspective. 2019. Abu Dhabi.
[34] International Bank for Reconstruction And Development. Mini-grids & gender equality: inclusive design, better development outcomes: key issues, and potential actions. 2017.
[35] Alda-Vidal C, Khalid R, Foulds C, Royston S, Greene M. Gender imaginaries in energy transitions: how professionals construct and envision gender equity in energy access in the Global South. World Dev 2023;168. https://doi.org/10.1016/j.worlddev.2023.106258.
[36] Jovanović N, Mpambo M, Willoughby A, Maswanganye E, Mazvimavi D, Petja B, et al. Feasibility of solar-powered groundwater pumping systems in rural areas of greater giyani municipality (Limpopo, South Africa). Appl Sci 2023;13:3859. https://doi.org/10.3390/app13063859.
[37] van der Waal EC. Local impact of community renewable energy: a case study of an Orcadian community-led wind scheme. Energy Policy 2020;138:111193. https://doi.org/10.1016/j.enpol.2019.111193.
[38] Toledano P, Albin-Lackey C, Andres MD, Brauch MD. Community benefit sharing and renewable energy and green hydrogen projects: policy guidance for governments. 2023.
[39] Schnurr T, Kalvelage L. Towards inclusive path transplantation: local agency for green hydrogen linkage creation in Namibia. Reg Sci Pol Pract 2025;17:100246. https://doi.org/10.1016/j.rspp.2025.100246.
[40] Komorowski P, Grzywacz M. Green hydrogen in Africa: opportunities and limitations. J Manag Financ Sci 2023;XVI:61–79.
[41] Agyekum EB. Is Africa ready for green hydrogen energy takeoff? – a multi-criteria analysis approach to the opportunities and barriers of hydrogen production on the continent. Int J Hydrogen Energy 2024;49:219–33. https://doi.org/10.1016/j.ijhydene.2023.07.229.
[42] Xun D, Liu M, Hao H, Sun X, Geng Y, You F, et al. Sustainable supply of critical materials for water electrolysers and fuel cells. Commun Earth Environ 2025;6:627. https://doi.org/10.1038/s43247-025-02621-6.
[43] Heymann F, Rüdisüli M, vom Scheidt F, Camanho AS. Performance benchmarking of power-to-gas plants using composite indicators. Int J Hydrogen Energy 2022;47:24465–80. https://doi.org/10.1016/j.ijhydene.2021.10.189.
[44] Yin Y, Wang J, Li L. An assessment methodology for international hydrogen competitiveness: seven case studies compared. Sustainability 2024;16:4981. https://doi.org/10.3390/su16124981.
[45] Baumgarten J, Schneider CP, Möst D. Hydrogen economy index – a comparative assessment of the political and economic perspective in the MENA region for a clean hydrogen economy. Int J Hydrogen Energy 2025;101:1503–17. https://doi.org/10.1016/j.ijhydene.2024.11.345.
[46] Lahnaoui A, Venghaus S, Kuckshinrichs W. Assessing the drivers of energy supply and demand in Sub-Saharan Africa. Energy Strategy Rev 2024;54:101483. https://doi.org/10.1016/j.esr.2024.101483.
[47] Avila N, Carvallo JP, Shaw B, Kammen DM. The energy challenge in Sub-Saharan Africa: a guide for advocates and policy makers: part 1: generating energy for sustainable and equitable development. 2017.
[48] Imam MI, Jamasb T, Llorca M. Sector reforms and institutional corruption: evidence from electricity industry in Sub-Saharan Africa. Energy Policy 2019;129:532–45. https://doi.org/10.1016/j.enpol.2019.02.043.
[49] Akrofi MM, McLellan BC, Okitasari M. Characterizing 'injustices' in clean energy transitions in Africa. Energy Sustain Dev 2024;83:101546. https://doi.org/10.1016/j.esd.2024.101546.
[50] Ikejemba ECX, Schuur PC. The empirical failures of attaining the societal benefits of renewable energy development projects in Sub-Saharan Africa. Renew Energy 2020;162:1490–8. https://doi.org/10.1016/j.renene.2020.08.052.
[51] Ram M, Aghahosseini A, Breyer C. Job creation during the global energy transition towards 100% renewable power system by 2050. Technol Forecast Soc Change 2020;151:119682. https://doi.org/10.1016/j.techfore.2019.06.008.
[52] Rutovitz J, Dominish E, Downes J. Calculating global energy sector jobs: 2015 methodology. 2015.
[53] World Bank Group. How does the world bank classify countries? n.d. https://datahelpdesk.worldbank.org/knowledgebase/articles/378834-how-does-the-world-bank-classify-countries (accessed January 12, 2026).
[54] Breloff P, Munjal K, Hill K. Forecasting green jobs in Africa. 2024.
[55] World Bank Group. Educational attainment, at least completed upper secondary, population 25+, total (%) (cumulative) n.d. https://data.worldbank.org/indicator/SE.SEC.CUAT.UP.ZS. [Accessed 12 January 2026].
[56] Irena AfDB. Renewable energy market analysis: africa and its regions. Abu Dhabi and Abidjan; 2022.
[57] AFSIA. Solar can be the engine for youth employment across Africa. 2022.
[58] STEMpedia. STEM education in Africa - the past, present, and future. 2019.
[59] World Bank Group. Employment to population ratio, ages 15–24, total (%) (modeled ILO estimate) n.d. https://data.worldbank.org/indicator/SL.EMP.1524.SP.ZS (accessed January 12, 2026).
[60] World Bank Group. Employment in industry, female (% of female employment) (modeled ILO estimate) n.d. https://data.worldbank.org/indicator/SL.IND.EMPL.FE.ZS (accessed January 12, 2026).
[61] World Bank Group. Manufacturing, value added (% of GDP) n.d. https://data.worldbank.org/indicator/NV.IND.MANF.ZS (accessed January 12, 2026).
[62] ILO. Earnings - ILOSTAT n.d. https://ilostat.ilo.org/data/snapshots/earnings/ (accessed July 10, 2025).
[63] EUROPEEN COMISSION. A hydrogen strategy for a climate-neutral Europe. 2020. Brussels.
[64] PwC. Statutory corporate income tax rates n.d. https://taxsummaries.pwc.com/quick-charts/corporate-income-tax-cit-rates. [Accessed 12 January 2026].
[65] PwC. Standard value-added tax (VAT) rates n.d. https://taxsummaries.pwc.com/quick-charts/value-added-tax-vat-rates. [Accessed 12 January 2026].
[66] International Social Security Association (ISSA). Contribution rates n.d. https://www.issa.int/databases/country-profiles/contribution-rates (accessed January 12, 2026).
[67] World Bank Group. Electric power consumption (kWh per capita)| Data n.d. https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC. [Accessed 18 January 2026].
[68] World Bank Group. Population, total | Data n.d. https://data.worldbank.org/indicator/SP.POP.TOTL. [Accessed 18 January 2026].
[69] World Bank Group. Access to electricity (% of population)| Data n.d. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS. [Accessed 18 January 2026].
[70] Arvis J-F, Ojala L, Shepherd B, Ulybina D, Christina Wiederer. The logistics performance index and its indicators. 2023.
[71] World Bank Group. Logistics performance index: overall (1=low to 5=high) - sub-saharan Africa | Data n.d. https://data.worldbank.org/indicator/LP.LPI.OVRL.XQ?locations=ZG&view=map. [Accessed 11 July 2025].
[72] Juelich Systems Analysis (ICE-2). H2 Atlas Africa - Institute of energy and climate research (ICE) n.d. https://africa.h2atlas.de/africa. [Accessed 15 December 2025].

[73] WDPA. Explore the world's protected areas n.d. https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA. [Accessed 1 July 2025].
[74] JRC. Global human settlement - Download - European commission n.d. https://human-settlement.emergency.copernicus.eu/download.php. [Accessed 1 July 2025].
[75] Natural Earth. Natural Earth » 1:10m cultural vectors - free vector and raster map data at 1:10m, 1:50m, and 1:110m scales n.d. https://www.naturalearthdata.com/downloads/10m-cultural-vectors/(accessed July 1, 2025).
[76] World Bank Group. Annual freshwater withdrawals, total (% of internal resources) | data n.d. https://data.worldbank.org/indicator/ER.H2O.FWTL.ZS (accessed July 11, 2025).
[77] World bank Group. Renewable internal freshwater resources, total (billion cubic meters) | Data n.d. https://data.worldbank.org/indicator/ER.H2O.INTR.K3 (accessed July 11, 2025).
[78] Incer-Valverde J, Korayem A, Tsatsaronis G, Morosuk T. "colors" of hydrogen: definitions and carbon intensity. Energy Convers Manag 2023;291. https://doi.org/10.1016/j.enconman.2023.117294.
[79] World Bank Group. Total greenhouse gas emissions including LULUCF (Mt CO2e) - | Data n.d. https://data.worldbank.org/indicator/EN.GHG.ALL.LU.MT.CE.AR5?locations=ZG. [Accessed 11 July 2025].
[80] Stam Tekinologi. JGA manufacturing roadmap - Assessment of African H2 value chain manufacturing capability and how to enhance it. https://doi.org/10.3030/101101469; 2025.
[81] Oecd JRC. Handbook on constructing composite indicators: methodology and user guide. 2008.
[82] Squadrito G, Maggio G, Nicita A. The green hydrogen revolution. Renew Energy 2023;216. https://doi.org/10.1016/j.renene.2023.119041.
[83] Gehrig BGPE. Some challenges to building STEM capacity in emerging economies: the case of Namibia. ASEE (American Society for Engineering Education) Annual Conference & Exposition. 2019.
[84] Hyphen Hydrogen Energy. Hyphen hydrogen energy and SDG Namibia one fund agree on equity stake in country's first gigawatt-scale green hydrogen Project. 2023. https://hyphenafrica.com/hyphen-hydrogen-energy-and-sdg-namibia-one-fund-agree-on-equity-stake-in-countrys-first-gigawatt-scale-green-hydrogen-project/. [Accessed 6 January 2026].
[85] Hyphen Hydrogen Energy. The Hyphen Project. 2023. https://hyphenafrica.com/the-hyphen-project/ (accessed January 6, 2026).
[86] IRENA. Global hydrogen trade to meet the 1.5°C climate goal: part III – green hydrogen cost and potential. 2022. Abu Dhabi.
[87] IRENA. Global hydrogen trade to meet the 1.5°C climate goal: part I – trade outlook for 2050 and way forward. Abu Dhabi: International Renewable Energy Agency; 2022.
[88] Schoots K, Ferioli F, Kramer GJ, Van Der Zwaan BCC. Learning curves for hydrogen production technology: an assessment of observed cost reductions. 2008.