H2Atlas-Africa

Final project report

Impressum

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Foreword

Wind, sun and water are increasingly becoming geopolitical factors. We are at the beginning of a huge energy transformation. Africa could become a new global player in the emerging green energy market.

Green hydrogen has a historic opportunity to become the oil, gas and coal of the future. Its production with renewable energies is sustainable and climate-neutral. It is a game changer for the future energy supply in Africa and the world. With its help, a green industrialization of the continent and the development of global, sustainable energy systems is possible.

With the National Hydrogen Strategy and its last update, the German government aims to promote the use of climate-friendly hydrogen technologies and contribute to the diversification of energy imports and thus to Germany's security of supply. A separate import strategy complements the National Hydrogen Strategy. The German government assumes a national demand for hydrogen and its derivatives of 95 to 130 TWh in 2030. Around 50 to 70 % (45 to 90 TWh) of this will probably have to be imported from abroad. It can be assumed that the proportion of imports will continue to rise after 2030.

Research, innovation and education are central building blocks of the German hydrogen policy. At the Federal Ministry of Research, Technology and Space (BMFTR), we have placed green hydrogen at the center of political initiatives from the very beginning. The Atlas of Hydrogen Potential is a flagship and pioneering project.

With this Hydrogen Atlas (H2Atlas) Africa, Forschungszentrum Jülich is collaborating with African partners to analyze the opportunities of green hydrogen for the sustainable development of the African continent. The BMFTR Africa Centers WASCAL (West African Science Service Centre on Climate Change and Adapted Land Use) and SASSCAL (Southern African Science Service Centre for Climate Change and Adaptive Land Management) are anchor points for cross-national and cross-continental cooperation.

For the first time, the H2Atlas examines in detail the technological, ecological, economic and social feasibility of hydrogen production, taking into account current and future local energy requirements and climate scenarios. The availability and suitability of land and fresh water resources are also included. The primary aim is to consider local requirements and demands, but also opportunities for exporting green hydrogen to Europe and Germany.

The H2Atlas is the product of a unique collaboration: it brings together more than 30 countries in western, southern and eastern Africa, the lion's share of the entire African economic area. More than half of Africa's population lives here, and some countries are among the fastest growing economies in Africa and the world.

Africa's countries are growing and their hunger for energy is increasing. With the help of the H2Atlas, we are jointly exploring how sustainable energy systems based on green hydrogen can be developed. It is a compass for the implementation of a green hydrogen-based economy in sub-Saharan Africa. It is highly relevant for policy makers, investors, energy companies, technology developers and scientists in Africa, Europe and the world.

Cooperation is a key factor for the development of a hydrogen economy - globally and regionally. BMFTR therefore supports, for example, the development of a hydrogen policy and strategy for West Africa. The ECOWAS council of ministers adopted this regional hydrogen strategy and roadmap in 2023. This is mostly thanks to the results from the H2Atlas project, which provided the scientific basis.

BMFTR is taking further steps: for example, we are supporting the training of future specialists for a hydrogen economy on the continent and beyond. African students are being trained at four locations in West Africa as well as the German institutions Forschungszentrum Jülich, RWTH Aachen University, the University of Rostock and the German Biomass Research Center. This is part of an international master's degree course on green hydrogen. In Southern Africa, BMFTR is funding an extensive scholarship program for the academic and non-academic training of Namibian young people in the field of green hydrogen. The H2Atlas is a central basis for both programs. Its results are a guideline for training content and the development of future projects for a hydrogen economy in the participating countries.

I would like to thank all those involved in the H2Atlas for their special commitment to this flagship project of African-German scientific cooperation and hope you enjoy reading the project report!

Till Mansmann, Member of German Parliament
Innovation Commissioner for Green Hydrogen
German Federal Ministry of Research, Technology and Space (BMFTR)

H2Atlas - Africa project - Final report

Part I:

Policy brief[1]

Unlocking Africa's Green Hydrogen Potential for Sustainable Development

Introduction

'Africa possesses vast renewable energy potential, which, if harnessed effectively, can provide universal access to energy, unlock the potential for a sustainable hydrogen economy, and fuel growth across the continent'*. The H2Atlas-Africa project, funded by the German Federal Ministry of Research, Technology and Space and led by Forschungszentrum Jülich, aims to assess the feasibility of green hydrogen production in Africa. By leveraging partnerships with regional institutions such as the West and Southern African Science Service Centres on Climate Change and Adapted Land Use WASCAL and SASSCAL, and partners in East Africa the project evaluates renewable energy, land, and water resources, alongside socioeconomic and political factors, to determine the potential for green hydrogen production in various African countries. The project's findings, presented in a publicly accessible atlas, highlight the technical and economic viability of green hydrogen production and its role in driving sustainable development across the continent.*

Key messages

- **Total technical energy potential** of 578 PWh/a by 2030, with 88% from Open-field PV.
- **Total technical green hydrogen potential** of over 400,000 TWh/a, with PV the cheapest option.
- **Cost of production** with a cost of hydrogen as low as 2 €/kg already by 2030.
- **Need for desalination** in areas where sustainable groundwater supply alone cannot meet the demand required to achieve full hydrogen potential.
- **Potential local job impact** driven by operation and maintenance jobs, mainly from hydrogen production from PV.

Policy options

- **Targeted capacity building**: to develop local expertise in renewable energy technologies and hydrogen production.
- **Regional trade alliances:** to leverage complementary strengths in renewable energy production and infrastructure.
- **Address water scarcity:** to ensure the viability of green hydrogen production, including investment in desalination technologies.
- **Targeted skill development:** to stimulate job creation in manufacturing and the growth of regional renewable industries.

Potential drives the cost

By 2030, the combined potential for **'renewable energy sources in the selected 31 countries amounts to a maximum technical potential of 578 PWh/a'**[1]. Notably, open-field PV emerges as the dominant technology option, accounting for approximately 88% of the total potential, followed by onshore wind [1]. This underscores the significance of the solar industry's potential in Africa's energy transition. Solar energy generation is expected to play a pivotal role in driving clean energy generation, especially given that electricity access mainly in rural regions was identified as a priority by the surveyed African stakeholders. In addition, stand-alone systems and mini-grids were identified as a central objective for electrification, which further justifies the central role of solar energy, while also unlocking the potential use of onshore wind for industrial use and for a promising hydrogen economy as a further option. The northwest of Sub-Saharan Africa, particularly Mauritania, emerges as a hotspot for onshore wind development, offering vast opportunities for clean energy generation and economic growth in wind-rich regions. However, harnessing this potential requires careful planning, investment, and technological innovation to overcome challenges such as spatial heterogeneity and variable wind patterns.

Cost-effectiveness analysis reveals compelling prospects for renewable electricity sources, particularly **open-field PV, which emerges as the most cost-effective option – over 98% of its potential can be achieved at a levelized cost of electricity (LCOE) below 3Ct€/kWh by 2030**[1], signaling the economic viability of large-scale solar deployment. Affordability could thus become a driver for electrification. Conversely, onshore wind exhibits greater spatial heterogeneity in LCOEs due to regional wind variability, necessitating careful site selection and technological advancements to ensure cost-effectiveness[1].

Overall, the purely technical hydrogen potential based on RES sources is available in all countries[1]. This potential and low cost of electricity is the main driver for a cost-effective green hydrogen. By 2030, certain areas, such as North-Western Mauritania and Northern Kenya, will have competitive production costs, offering green hydrogen at levels as low as €2/kg[1].

On average, the variability in costs is comparatively low ranging between approximately 2.20 – 3.00 €/kg[1] so that costs will likely not become the decisive driver for divergent levels of feasibility. The reason is that the levelized cost of hydrogen (LCOH) depends almost exclusively on the RES technical potential. In reality, the divergence in country risk and consequent fluctuation in discount rates between regions can significantly influence the economic evaluation of hydrogen projects.

Mind the water!

The realization of green hydrogen's potential in Africa faces significant challenges, particularly concerning water resources. Regarding groundwater, coastal regions of West Africa exhibit higher sustainable yields, while certain countries in Southern East Africa demonstrate promising groundwater resources[1]. However, future projections in the context of climate change indicates a decrease in yield magnitude and many countries contend with limited groundwater reservoir, a challenge that cannot be easily mitigated by coastal access for desalinated water. In such contexts, the **'feasibility and sustainability of projects hinge upon robust power grid infrastructure and collaboration with neighbouring countries boasting abundant water resources, including desalinated water'**[1]. This becomes crucial when surface water is used for green hydrogen generation, either directly via electrolyser or indirectly using hydropower for green hydrogen generation. In such instances, apart from water scarcity concerns, the environmental impacts of green hydrogen generation from hydropower installations become urgent to address. Ecosystem disruption, habitat degradation, and altered river flow patterns underscore the need for cautious utilization and sustainable management practices.

However it is right to see that water resources hold a huge potential for the continent and the forecasted growth of hydropower installations appears promising, the reality is more nuanced.

While around 40% of the projected capacity could generate electricity at a cost below 3€ct/kWh, limitations in exploiting additional potential and meeting national electricity demands constrain feasible utilization to a range of 25% to 50%[1].

Leveraging the hydrogen economy for Socio-economic Development in Africa.

The interaction with stakeholders shows that African countries share a common vision with Germany in addressing climate change and transitioning to renewable energy sources. However, there exists a notable disparity in expectations regarding the immediate export of green hydrogen and that African partners are primarily interested in improving energy access and domestic industrial use in many regions on the continent. Nevertheless, this African perspective underscores the significance of a hydrogen economy in economic development.

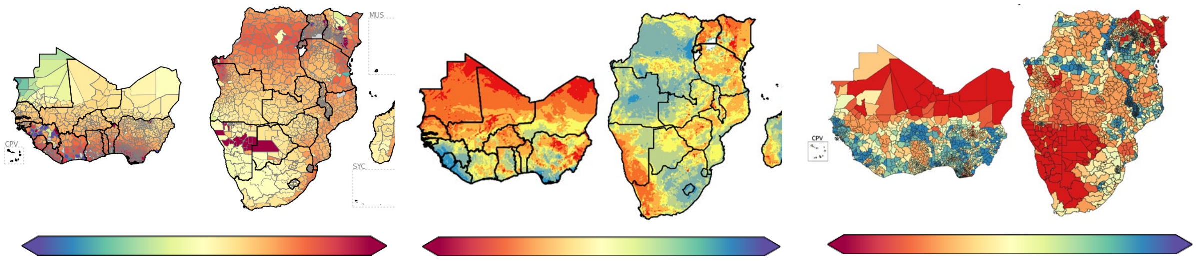
In this regard, high potential added value could be achieved around large bodies of water, along the Upper Guinea Coast and the African Great Lakes [1]). This impact is partially driven by employment that underscores the potential of the hydrogen economy to catalyse socio-economic development, particularly in regions with abundant labour resources [1]. In the short to medium term, local labour employment is projected to be driven by construction, installation, operation, and maintenance jobs. Notably, Nigeria and West Africa in general exhibit high potential due to their sizable labour force and comparatively lower labour costs. **'Green hydrogen production from solar emerges as a significant contributor to employment generation, offering up to 11 times more jobs per megawatt peak compared to the EU'**[1]. However, challenges persist in Southern African countries, with higher labour costs and high unemployment rates.

Therefore, emphasis has been placed on capacity building by the African partners, that emerges as a crucial priority in harnessing the benefits of the hydrogen economy. Beyond the construction and maintenance of facilities and infrastructure, there is a need to invest in training and skill development. **'With high potential prospects of competitive regional solar and wind manufacturing industries, this could add up to 30% and 11% more jobs respectively in the local market alone'**[1]. This could contribute significantly to the objectives of the African Continental Free Trade Agreement, provided that locally manufactured solar panels and wind turbines can achieve competitiveness within the African market. This focus on capacity building aligns with the broader goal of enabling African nations to take ownership of their energy transition and maximize the socio-economic benefits.

Techno-economic perspective Cost Potential

Sustainability perspective Groundwater

Socio-economic Perspective *Local added value*



1.7 2.55 3.4
€/kg

2.5 35 250
mm/year

Low High
Local impact

Levelized Cost of Hydrogen (LCOH) (at 25% technical potential) for the year 2030.
25% represents the degree of energy potential expansion, i.e. the 25 % best renewable energy generation locations only (economy of scale not considered) without including water constrains.

Groundwater sustainable yield that can be used under medium and optimistic scenario in 2020.
Medium scenario allows for the utilization of up to 40% of the annual groundwater recharge, while optimistic scenario accounts for climate scenario RCP2.6 with the lowest amount of greenhouse gases concentration pathway.

Composite indicator assessing the local impact of green hydrogen projects.
Accounts for the direct and indirect impact of green hydrogen on maximizing local added value without population displacement. It prioritizes areas lacking access to energy, and with high direct local labor employment potential.

About the method: H2Atlas involves a comprehensive analysis of land suitability for renewable energy installations, considering local preferences (see Ishmam et al. [2]). Detailed simulations assess electricity generation potential from various renewable sources, factoring in weather variations, and evaluates sustainable groundwater feasibility and seawater desalination costs. These findings are integrated into regional energy system models, considering climate change impacts. The approach emphasizes in parallel local socio-economic development, with results accessible through a user-friendly web tool. The underlying method and shown results is taken from Ishmam et al [2] and Winkler et al. [1,2] respectively.

Figure 1 Results from cost potential, ground water, and local added value of green hydrogen. [1]

Policy Recommendation for Cooperation on Green Hydrogen.

Regional Collaboration and capacity building

The critical importance of regional collaboration and policy coherence in promoting green hydrogen economies in Africa cannot be overstated. Effective power grid infrastructure, trade alliances, and investment frameworks are foundational to facilitating green hydrogen production and export. Therefore, policymakers must prioritize enhancing regional cooperation mechanisms to create a conducive environment for sustainable energy development. A significant barrier to the adoption of green hydrogen technologies in Africa is indeed the lack of infrastructure, not only physical but also in the form of skilled employees. Therefore, capacity building emerges as a crucial priority, not only in terms of constructing facilities and networks but also in training personnel. Foreign investment, particularly from countries like Germany, could play a pivotal role in addressing these infrastructure gaps and facilitating technology transfer. Moreover, partnerships with international actors can accelerate the development of energy infrastructure in African countries, laying the foundation for future renewable energy projects and potential green hydrogen exports.

Recommendation: Establishing regional platforms and partnerships dedicated to promoting green hydrogen collaboration can facilitate knowledge sharing, technology transfer, and joint investment initiatives. Additionally, harmonizing policy frameworks across African nations can create a level playing field for market participants and enhance investor confidence in green hydrogen projects.

Infrastructure Development.

Infrastructure remains a critical issue for hydrogen projects in Africa. The feasibility of green hydrogen production in Africa is contingent upon the development of robust infrastructure, particularly in terms of power grid connectivity and trade alliances. Effective infrastructure enables efficient production, distribution, and export of green hydrogen, thereby enhancing the competitiveness of African nations in the global renewable energy market.

While there is optimism that such projects could attract investment to address infrastructure gaps, additional funding sources may be necessary. Early green hydrogen projects are likely to benefit countries already supporting renewable energy transitions, but careful consideration of infrastructure needs is essential for project success.

Recommendation: Political commitment is important as funding sources for the investment options would have to be considered. Governments should prioritize investments in power grid infrastructure, including renewable energy capacity expansion and grid modernization initiatives. Furthermore, fostering cross-border trade alliances through regional energy corridors is imperative. Moreover, foreign policymakers and investors must be mindful of potential dependencies and ensure that investments contribute to long-term sustainability and socio-economic development on the continent.

Main overview

1. Executive Summary

The menace of climate change is a global threat and the urgent need to decarbonize calls for a global action. Africa, though being the least contributor to global warming, has a huge renewable energy potential, which if harnessed can suffice for a 100% electricity access to the local population as well as ensuring supply for the other sectors of the economy. Beyond meeting clean energy access for all, renewable energy resources such as wind and solar can be used to produce green hydrogen. It can open-up economic opportunities along the full value chain of green hydrogen and, hence, can create jobs for the local people. It will enable the region to actively participate in the upcoming future global hydrogen market.

The H_2Atlas-Africa project has investigated the potential of producing green hydrogen from selected countries in East, West and Southern Africa, taking into account technological, environmental and socioeconomic conditions prevailing in each country. This project funded by the German Federal Ministry of Research, Technology and Space (BMFTR) assesses the available renewable energy, land and water resources that are necessary for green hydrogen production as well as further logistic and political framework conditions that can affect green hydrogen production, its utilization in Africa and the possibility of export. The work done here leveraged the competence of an interdisciplinary team at the Forschungszentrum Jülich and the cooperation with African partners namely the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), Accra Ghana and the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL), Windhoek, Namibia and support teams in the different countries investigated. In close consultation with these partners, the local preferences, and peculiar contexts are factored in to ensure that there are no conflicts of resource use such as land and water.

For the assessment of the technical green hydrogen potentials within the considered countries a multidisciplinary approach was applied deeply embedding the views and preferences of the African partners. This approach includes identifying eligible placements for renewable energy technologies such as wind turbines and open-field photovoltaic as well as existing and planned hydropower plants and calculating their respective electricity feed-in time series. Those renewable energy potentials combined with the sustainable groundwater yield under different climate change scenarios form the basis for the optimized local energy system designs to produce green hydrogen at least cost. The maximum producible amount of green hydrogen represents the technical potential of green hydrogen in each region if all renewable energies are solely used for its production. These technical cost-potentials of green hydrogen under climatic and environmental constraints are complemented by socioeconomic indicators.

Through extensive workshops and bilateral meetings local regulations on 33 distinct criteria for siting renewable technologies were collected[2]. The aim was to incorporate the input of regional stakeholders, including community members, governmental bodies, and international institutions. Despite the vast size of the continental regions examined, our study revealed that only 25-35% of the land area could accommodate open-field PV parks, while approximately 16-32% of the land area could support onshore wind turbines [1].

Our findings demonstrate that renewable electricity has enormous technical potential of 577 PWh/a when aggregated across all evaluated countries and can be generated at relatively low costs. For instance, by 2030, Mauritania could produce electricity at just over 2 $Ct_€$/kWh, a figure that could potentially drop to 1.5 $Ct_€$/kWh by 2050. By 2050, most locations in the analyzed regions could produce electricity at costs below 2 $Ct_€$/kWh, offering a promising avenue for cost-effective and eco-friendly local electricity supply and green hydrogen production. [1]

To secure a sustainable water supply for green hydrogen production, groundwater sustainable yield was quantified. A first crucial step to estimate groundwater sustainable yield is to calculate groundwater recharge (i.e., the precipitation that can reach the aquifers). Next, we took into account that a part of this new groundwater is needed for nature and another part for water consumption by people, industry, and agriculture. The water that is then still left is groundwater sustainable yield available for green hydrogen production. Through comprehensive regional analysis in West Africa, we discovered a fascinating insight: the average groundwater sustainable yield varies between West African countries from 7 to 63 $l/m^2/yr^1$ in 2020, influenced by diverse climatic and environmental conditions. Looking ahead, we anticipate a slight shift, with projections indicating a range of 6 to 55 $l/m^2/yr^1$ by 2050. For the Southern East African region, in 2020, our findings indicate a potential groundwater sustainable yield ranging from 17 to 134 $l/m^2/yr^1$ depending on the scenarios. Looking forward to 2050, projections suggest a slight reduction, with estimates ranging from 15 to 122 $l/m^2/yr^1$. Our analysis suggests that the available groundwater resources are not only capable of meeting current human and environmental water needs in the selected regions but also have the capacity to support green hydrogen production, although under future climate conditions, there will be some decline. [1,2]

Based on the huge renewable energy potential the total maximum hydrogen potential in West Africa together with Southern and East Africa amounts to just over 400 000 TWh/a, more than twice the equivalent of today's global primary energy consumption. Within this hydrogen potential, open-field photovoltaic is mostly the cheapest option with nearly no increasing cost with increasing expansion rate. Overall, the hydrogen potential based on sustainable groundwater amounts only to roughly 16% of the total technical hydrogen potential limited only by energy constraints. However, seawater desalination is an alternative water supply option with negligible impact on hydrogen cost. [1]

The Sahara region, particularly towards the Mauritanian coast, and the Nama Karoo region in the border area between South Africa, Namibia and Botswana, are the most cost-effective locations for green hydrogen production. Additionally, countries such as Cape Verde and Lesotho also have potential in this regard. The production cost in the majority of West, East and Southern African regions ranges between ca. 2.20 – 3.00 €/kg for the year 2030. The average LCOH weighted by regional potentials is at roughly 2.6 €/kg in 2030. In 2050, West Africa is expected to have a slight cost advantage of approximately 1.9 €/kg when compared to Southern and East Africa. This is due to the large low-cost potentials in the Sahara, which outweigh the higher cost potentials in Southern and East Africa, particularly near the equator. The overall potential-weighted average levelized cost of hydrogen across the entire project at 25% expansion of the respective regional technical potential is approximately 2.7 €/kg in 2030 and is expected to reduce to 1.9 €/kg in 2050. [1]

In parallel, the analysis of socio-economic development opportunities showed high local impact potential around the African Great Lakes, the coastal regions of Upper Guinea, and inland regions of Nigeria and Burkina Faso. These areas exhibit significant potential due to factors such as energy access and macroeconomic impacts. On one hand, the higher potential effects correlate with targeting energy access disparities and show high impact in Malawi, Tanzania, Mozambique, Zimbabwe, and the Democratic Republic of Congo, as well as countries in West Africa such as Burkina Faso, Sierra Leone, and Liberia, which face challenges with low access to electricity and clean fuels. On the other hand, macroeconomic effects are driven by potential employment impacts, with Nigeria, Burkina Faso, and Cape Verde standing out in West Africa, and Eswatini, Lesotho, Malawi, and South Africa's northwest emerging as key areas in the Southern African context. This factor, however, shows different regional divergences. While Nigeria benefits from its large workforce, West Africa's advantage lies in comparatively lower labor costs. Conversely, countries like South Africa face high labor costs but also high unemployment rates, necessitating targeted interventions to address the employment potential of green hydrogen and renewable energy projects.[1]

2. Objectives and short project introduction

2.1 Introduction

Africa has a growing population of nearly 1.3 billion, which has been increasing at an average annual rate of 2.5% in the last 10 years (ref). The growing population directly implies growing demand for energy and for expanded infrastructure to match the growth. The overall sustainable development of Africa and indeed the global effort to reduce climate degradation will require an energy system driven by renewable energy. Sub-Saharan Africa is a promising region for green hydrogen production given its enormous renewable energy resources which can play a key role in drastically increasing energy access. A part of this can be harnessed and utilized for green hydrogen production to balance variable renewable energy feed-in and for export. This way, the region has a clear path towards a 100% green energy access but also for economic opportunities arising from a green hydrogen economy.

This challenge of reaching 100% renewable based energy systems will require joint effort and partnership across borders in order to find feasible climate-friendly solutions. It will require working together with stakeholders across the countries and ensuring that local views and preferences are considered in such a way that guarantees win-win situation for all sides.

The German government had launched a hydrogen strategy in 2020[3], which details steps to accelerate the roll out of technology for the sustainable production and utilization of hydrogen. For its domestic industries, it expects Germany to require 95-130 TWh of hydrogen and derivatives in 2030, with an import share of 50-70% [4], making international partnership of great relevance in the overall strategy. Collaboration between Germany and Africa in this context can be of great value to both sides, ensuring a clear pathway to a green economy enabled by hydrogen.

The H2Atlas-Africa project is a flagship project in which the German Federal Ministry of Research, Technology and Space (BMFTR) and African partners in selected countries in the Sub-Saharan region have worked together since 2020 to explore the potentials of green hydrogen production from the enormous renewable energy sources within the sub-region. The uniqueness of the partnership and the impact it has made in yielding results as it is popular across stakeholders in German and Africa stands out clearly. The aim is to support sustainable and economic development through a viable hydrogen economy in Africa that also enables the region to be an exporter of green hydrogen. The project results are presented in interactive web-based atlas (https://africa.h2atlas.de/) which have been made available to the public and have created a ripple positive impact resulting in several demonstration projects and national hydrogen strategy development in Africa.

Figure 2 H2Atlas-Africa project between Forschungszentrum Jülich and African partners formally commissioned: (LTR) Dr. Solomon Agbo (project coordinator), Mr. Thomas Rachel (former parliamentary state secretary of the Federal Ministry of Education and Research

2.2 Objectives

Sub-Saharan Africa in general is faced with the threat of an energy crisis primarily due to the growing population. Therefore, there is an urgent need to find sustainable and climate-smart ways of supplying energy for the growing population. Against this background, the H2Atlas-Africa project is focused on assessing the potential of producing green hydrogen in sub-Saharan Africa (West and Southern Africa, Mauritania, Kenya, Rwanda and Uganda) from the renewable energy resources in the region while considering detailed technical, environmental, economic, and social aspects.

The key objectives therefore are:

- Analysis of available renewable energy and water resources necessary for green hydrogen production.
- Determine the levelized cost of electricity generated from the different renewable energy sources.
- Determine the green hydrogen potential in each country in terms of total producible amount and the levelized cost of hydrogen.
- Investigate the potential impact of climate change on groundwater resources and in turn on green hydrogen production.

2.3 Project structure

The H2Atlas-Africa project has been funded by BMFTR and has been implemented by a team of scientists at the Forschungszentrum Jülich in partnership with the West African Science Service Centre for Climate Change and Adapted Land Use (WASCAL), the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL), selected institutions in Kenya, Rwanda, Uganda, and Mauritania and project teams in each of the 31 participating countries. Realizing that such initiative as the H2Atlas-Africa project will only thrive in true partnership with due consideration to local views and preferences, the project was designed to rely on the involvement and strong commitment of all partners. Conscious effort was made to galvanize stakeholders support at all levels through constant engagement via workshops, seminars, and consultations. At the sub-regional levels, WASCAL, SASSCAL, and the East African regional committee of the project helped with the coordination of the project and stakeholders' engagement for West, Southern and East African sub-regions respectively. These committees represented the different sub-regions technically and in every other issue related to the project. It also collated, reviewed, and ratified all data from the different national teams needed for the atlas. All regional sensitization, mobilization, and validation workshops related to the project were organized and coordinated by the regional technical committee.

In each country there was a project national team composed of experts selected from different government and non-governmental agencies whose roles interface with aspects that can relate to green hydrogen production. This included directors from ministries of energy and environmental, water resources and land use, economic development as well as university academics. The teams were led by leading scientists who are also the directors of WASCAL and SASSCAL in their different countries. In East Africa, the teams were led by experts from the partner institutions. To ensure local capacity building, each team had a young scientist. They receive training on the tools and approach that have been adopted for the development of the atlas at the Forschungszentrum Jülich. The national team coordinates the project at the national level, ensuring local data collection, mobilization, and sensitization. This team reports to the regional technical committee that collates inputs from the different countries.

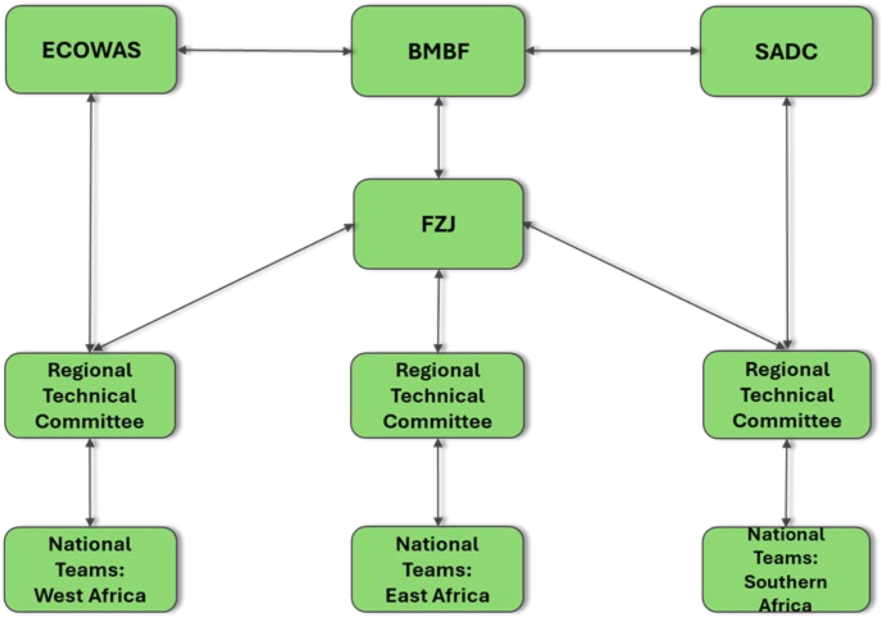


Figure 3 H2Atlas-Africa project operational and engagement paths.

2.4 Partners

Partners for the project were drawn from the different regions of Africa that participated in the project as shown in Figure 4.

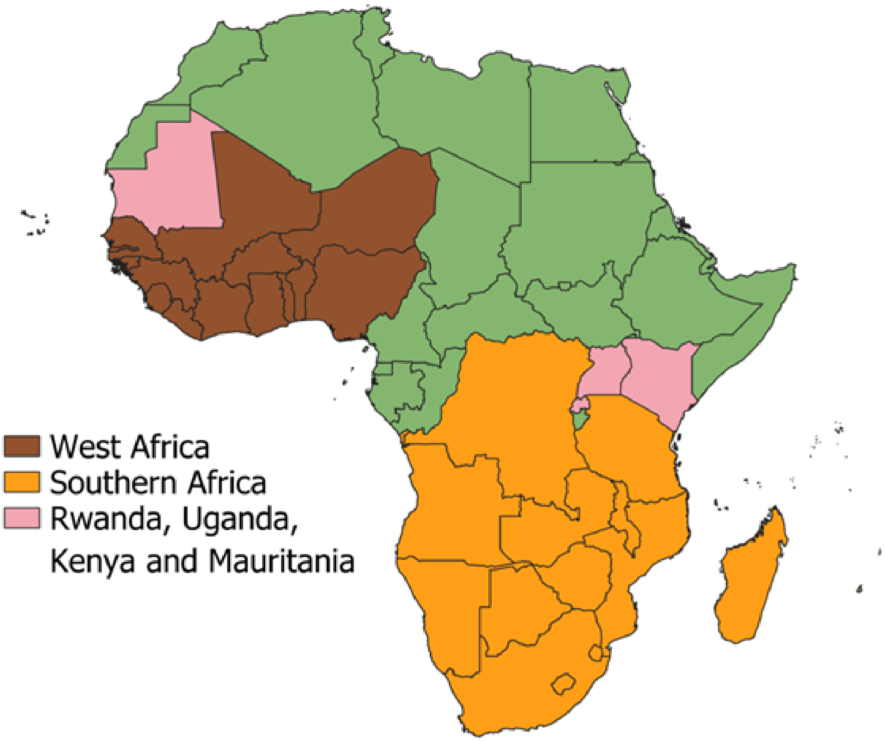


Figure 4 H2Atlas-Africa focus countries and regions

2.4.1 Forschungszentrum Jülich

Conducting research for a changing society: This is the mission of more than 7,000 employees working hand in hand at Forschungszentrum Jülich (FZJ). Based on driven interest to make impact via research, Forschungszentrum Jülich conducts research into the fundamentals, technologies, and systems of a digitalized society, a climate-friendly energy system, and a resource-efficient economy. At Jülich, natural, life and engineering sciences in the fields of information, energy, and the bioeconomy are closely linked with specialist expertise in high-performance computing and benefit from the use of unique scientific infrastructure. The research centre is one of the largest interdisciplinary research institutions in Europe and contributes to solving the grand societal challenges of our time as a member of the Helmholtz Association.

To undertake the task of developing the H2Atlas, FZJ pooled together a team of scientists from various related FZJ institutes. In this context, FZJ experts from the following Institutes: Energy Materials and Devices- Photovoltaics (IMD-3), Climate and Energy Systems- Jülich Systems Analysis (ICE-2) (formed by a merger of former Institute of Energy and Climate Research: Techno-Economic Systems Analysis- IEK-3 and Institute of Energy and Climate Research: Systems Analysis and Technology Evaluation -IEK-STE in April 2024) and the Institute of Bio- and Geosciences: Agrosphere (IBG-3) worked closely together. The project has been coordinated by the Corporate Development (UE) unit of the centre.

Corporate Development (UE) is responsible for research planning and scientific resource management as well as the associated scientific controlling. UE also coordinates all issues related to the Helmholtz Association on behalf of Forschungszentrum Jülich. Furthermore, Corporate Development supports the Board of Directors and the institutes in innovation and knowledge management as well as strategy development and handles strategic partnerships with universities and non-university cooperation partners, in particular as part of the Jülich Aachen Research Alliance (JARA) and the international relations of FZJ. Other central tasks are the continuous further development of FZJ's strategy for young talent and supervising EU affairs concerning FZJ.

UE represents an important interface between BMFTR, the African partners, and the cooperating institutes within Forschungszentrum Jülich. The entire H2Atlas project is managed and coordinated from the corporate development unit (UE) where the project office is situated. The project office ensures the general project coordination and management and serves as a first contact point for BMFTR and all other stakeholders. It ensures that all project partners (Germany and Africa) adhere to project plans, tasks and timelines. All project-related events (workshops, site visits, etc.) are organized in collaboration with all project partners.

Institute of Energy and Climate Research - Techno-economic Systems Analysis (IEK-3) conducts technologically neutral studies on technologies, technology paths, value chains, and market ramp-ups in future energy systems, taking into account sector synergies within the target framework of the COP-21 guidelines and those of the German federal government. The goal is to model the entire energy system of Germany, its regions, the European continent, and import-relevant global regions. The work serves to provide the necessary knowledge for action on the transformation of the energy system by decision-makers in politics and the economy, and to inform the public in general.

For this purpose, the ETHOS (Energy Transformation Pathway Optimization Suite) program was developed at the IEK-3 and is used to calculate total energy systems across all sectors with the lowest costs, within definable framework conditions. ETHOS is based on more than 14 post-graduate dissertations and is specifically dedicated to sector-coupling. It is based on extensively determined and verified publicly available data from technical publications, maps, statistics, and other sources. All sectors are covered, including the electricity and gas industries, as well as transportation, heavy industry, and households. More than 1300 technologies with more than 2000 links among them are considered, allowing the identification of important technically- and economically relevant pathways. Social considerations are also taken into account in the simulation through appropriate adaptation of the input data. The IEK-3 is well-connected throughout Germany via project work, and internationally through committee work, for example at the International Energy Agency.

The IEK-3 produces highly spatially and temporally resolved analyses of both the renewable energy potential in conjunction with land suitability assessments, as well as green hydrogen potential for West, Southern, and East Africa, thus making a significant contribution to the project. In particular, the team merges its own and the individual partners' results into a centralized system model. This permits analysis of the costs and potential of green hydrogen, taking into account all of the external factors considered, such as local energy demand or water scarcity. Energy transport options and their costs are also examined at various levels, from local synergies to export to Germany. The results are then visually processed by the team and made available to the public in the form of a Graphical User Interface (GUI) web application.

The Institute of Energy Materials and Devices - Photovoltaic (IMD-3) focusses on researching new materials and innovative device architectures for sustainable photovoltaics based on thin films. The IMD-3 deals with the fundamental physics of partly disordered materials used in solar cells. These can be amorphous or microcrystalline silicon and its alloys, organic or hybrid (organic-inorganic) materials or various functional oxides. In addition, components and devices for new applications such as passivation and contact layers for high efficiency silicon heterojunction solar cells or multijunction solar cells for efficient water splitting are developed. At the same time, the IMD-3 develops the technology to fabricate solar cells with a particular focus on the industrial application and on issues of scaling up the technology. A central requirement for the successful development of materials, devices and production technology is an extensive set of characterization methods and simulation capabilities that are used to analyze the optoelectronic properties of thin-film materials and related devices. These activities include all relevant length scales from atomistic resolution of nanostructures and elementary processes up to the yield analysis of modules or photovoltaic systems.

IMD-3 was involved in work Package 3 (WP3): Potentials of volatile renewable energy sources. The working group verified the PV performance model implemented for determining the renewable energy potential. To this end PV data sets of ground weather stations with PV module data for verification is used. In addition, the impact of spectral effects is investigated as most data for modelling assumes an air mass of 1.5, which is less appropriate for the African climate.

Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation (IEK-STE) aims to investigate the long-term characteristics of future energy systems and the consequences of its adoption on the development of the studied regions. On this basis, IEK-STE focusses on the analysis and evaluation of transformation pathways, targeting not only techno-economic efficiency but as well the social feasibility and the socio-technical interactions. This approach allows for providing the required political, economic, and social knowledge to transform the energy system based on technological assessment, taking into account the perspectives and conflicting goals of the various stakeholders. Meanwhile, the methodology developed integrates model-based scenarios as well on social context, transformation pathways, stakeholders' preferences and behaviour patterns, and sustainability development.

Within the project, IEK-STE assessed the socio-political context and analyzed the development opportunities of the 31 countries. To do so, the current regional situation was addressed via analysing the demographic and socio-economic indicators impacted by energy, water, and power consumption. The future regional perspectives assessed the impact of green hydrogen on employment and socio-economic improvements, and how to overcome investment limitations. As the project aims to geo-localize the green hydrogen potential, a parallel outcome would be to translate national and regional analysis to spatial distribution results. This was mainly done qualitatively, by reviewing the main trends on the indicators impacting the supply demand. This includes for instance the urbanization rate, regional migration, electrification rates, or industry distribution.

Institute of Bio- and Geosciences- Agrosphere (IBG-3) considers climate and land use change as key drivers influencing terrestrial environmental systems that need to be managed by society in the coming decades. These changes act on all compartments of terrestrial systems and provoke system reactions on different spatial and temporal scales. The development of management and adaptation strategies to cope with these changes defines the key research fields in the Agrosphere: 1) Modelling of terrestrial systems, 2) Environmental processes and technologies and 3) Terrestrial biogeochemistry. The institute`s research findings can be translated into management options that can be used by political organizations and decision makers to address pressing societal challenges.

Work Package 4 (WP4) of the H2Atlas project focused on evaluating the availability of water resources and the suitability of environmental conditions for green hydrogen production in Africa. This includes especially the potential of local groundwater resources for ensuring sustained water supply. Moreover, understanding climate change impacts on local groundwater resources in Africa is highly relevant for planning a sustainable production of green hydrogen. WP5 additionally assessed climate change impacts on the long-term availability of groundwater that can affect the life cycle of green hydrogen production in the future.

To this end, experts in IBG-3 employed various modeling and remote sensing tools and products to quantitatively assess groundwater availability, accessibility, and renewability within the project. Further, IBG-3 utilized land surface process modeling to investigate various climate change scenarios and quantify their impacts on local groundwater resources.

Figure 5 H2Atlas-Africa project team at Forschungszentrum Jülich

2.4.2 West African Science Service Centre on Climate Change and Adapted Land Use, WASCAL

The West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) is a BMFTR-funded large-scale research-focused and capacity building climate service centre with headquarters in Accra Ghana. It is designed to help tackle climate change challenges in West Africa by enhancing the resilience of human and environmental systems to climate change and increased variability. This is made possible through the strengthening of the research infrastructure and capacity in West Africa related to Climate Change and by pooling the expertise of twelve West African countries. There are twelve contributing member countries of WASCAL: Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, The Gambia, Ghana, Guinea, Mali, Niger, Nigeria, Senegal and Togo.

WASCAL has three main activity areas namely capacity building, research and climate and environmental services provision. It is a leading academic and trans-disciplinary organization building graduate-level scientific capacity. The Competence Centre, located at Ouagadougou, Burkina-Faso carries out research and provides science-based advice to policymakers and stakeholders on climate change impacts, mitigation, and adaptation measures. Its vision is to be the leading institution in the provision of climate and environmental services in and for West Africa.

The mission of WASCAL is to provide information and knowledge at the local, national, and regional levels to its West African member countries experts to cope with the adverse impacts of climate change and devise integrated mid and long-term options to build up resilient and productive socio-ecological landscapes. This is done through capacity building, research, climate, and environmental services provision.

In the H2Atlas project, WASCAL collected local data which is needed to depict the models developed at FZJ. Further, WASCAL leveraged its wide reach to mobilize stakeholders across the region. From the beginning, workshops were held at the headquarters and in the different countries to ensure the buy-in of all relevant stakeholders. WASCAL together with the ECOWAS Center for Renewable Energy and Energy Efficiency (ECREEE) had developed and published ECOWAS green hydrogen policy which has also been adopted for use within the region.

2.4.3 Southern African Science Service Centre on Climate Change and Adapted Land Management, SASSCAL

The Southern African Science Service Center for Climate Chance and Adaptive Land Management (SASSCAL) is a joint initiative of Angola, Botswana, Namibia, South Africa, Zambia, and Germany in response to challenge of global change. The centre is conceptualised and operationalised to complement the existing research and capacity development institutions and infrastructure in the region. Its research addresses common climate change and land management issues beyond national borders recognising the flow of energy and ecosystems services thereby contributing markedly to regional integration and addressing cross-border challenges. It conducts problem-oriented research in the area of adaptation to climate change and sustainable land management and provides evidence-based advice for all decision-makers and stakeholders.

Through its network of Automatic Weather Stations, SASSCAL provides weather and climate data and information and services for decision making to reduce risk. SASSCAL has developed a network of scientists in Southern Africa and Germany and continues to promote collaboration among scientists and stakeholders from different disciplines and sectors to effectively respond to global, multi-national and multi-sectorial climate change challenges. SASSCAL aspires to seek long term solutions to climate change through its interdisciplinary research between areas of climate services, water resources management, agriculture and food security, forestry and biodiversity as its priority areas. The establishment`s long-time goals are to improve the livelihoods of people in the region and to contribute to the creation of an African knowledge-based society.

In the H2Atlas project, SASSCAL took the lead in organizing and mobilizing the SADC countries for their participation in the project. They could leverage their wide network of stakeholders to constitute a regional technical team made up of experts in the different relevant fields for the project. SASSCAL organized several stakeholders' meetings both at national and regional levels to educate, mobilize and galvanize support for green hydrogen development in the region. The data required for the project were collated and validated under the supervision of SASSCAL before being implemented in the H2Atlas development algorithm.

2.4.4 East African regional Team

The following countries from East Africa participated in the project: Kenya, Rwanda and Uganda. Also considered within this block is Mauritania though geographically not in East Africa. Like in the other regions, each of these countries had a national team that provided relevant data for their countries. For Kenya, Machakos University served as the national as well as regional coordinator. In Uganda, Rwanda and Mauritania three institutions provide leadership for data collection in their respective countries: Uganda Cleaner Production Centre – UCPC, Kampala, University of Rwanda, Kigali and Engineering and Global Consulting SARL – EGC, Nouakchott.

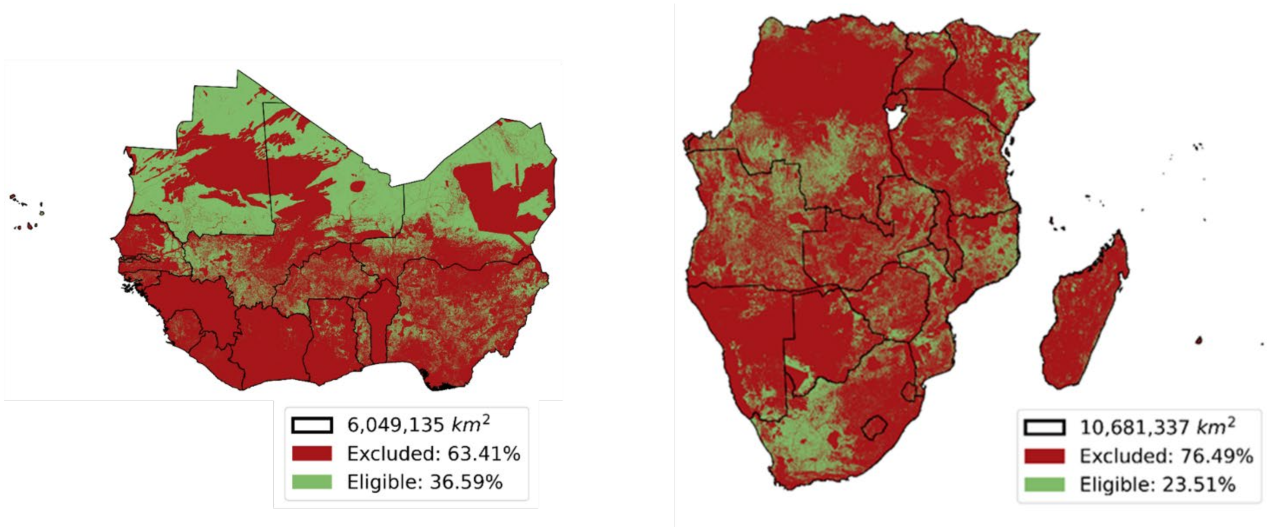
Figure 6 National and regional coordinators of H2Atlas Project team in Africa

3. Key findings

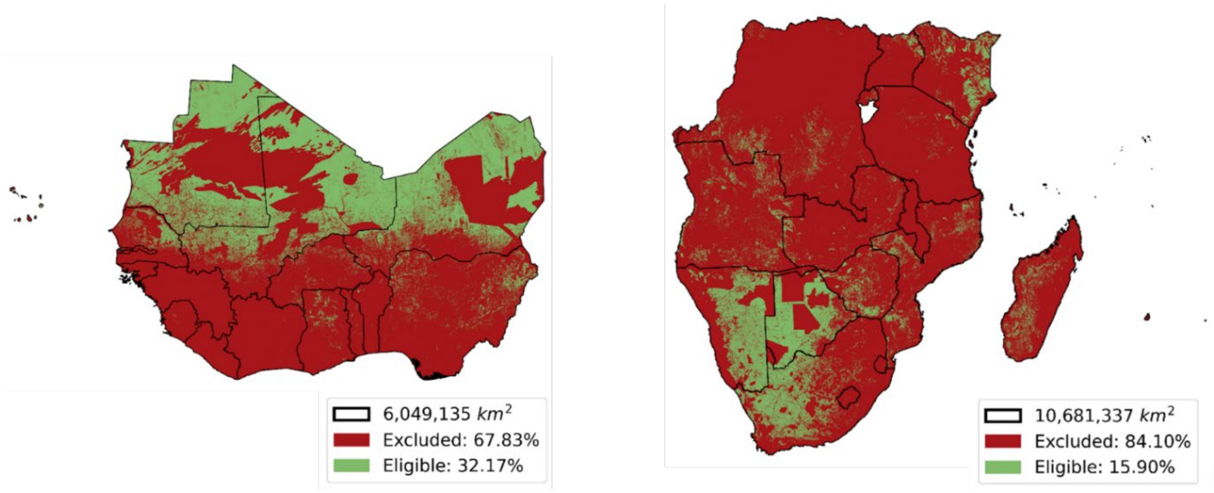
Based on our joint efforts and the developed methodology (see more details in Ishmam et al.[2]) we gained new insights, which cumulated in the following key findings [1]. These we perceive as most relevant for decision makers. The further detailed results are provided through our web-based GUI (https://africa.h2atlas.de/) and are listed in part II of this report complementing these key findings and form the basis of several new research projects in Sub-Saharan Africa. The key findings are based on Ishmam et. al. [2] and Winkler et. al. [1]

3.1 Land eligibility for placing renewable energy technologies

The preferences of each country have been gathered through a series of workshops, and these preferences have been used to determine the areas of land that are suitable for the placement of renewable energy technologies, such as open-field PV and onshore wind turbines. Figure 7 Figure 7 provides an overview of the potential land areas that could be eligible for open-field PV parks in West, Southern and East Africa. As shown in Figure 7 (a), in the case of western Africa, approximately 36% of the available land is eligible for open-field PV, with larger areas of eligibility in the northern part of the region and smaller patches throughout the southern parts. Eligibility rates per country vary from ~0.1% in Guinea to around 50% in Niger, Mali, and Mauritania. In southern and eastern Africa, larger areas of eligibility are found in the central and southern parts of the region. Approximately 24% of the available land in these regions is eligible for open-field PV, with eligibility rates per country ranging from ~0.1% in Seychelles to around 36% in Mozambique. Protected forests and pastures are key constraints to the eligible land areas in both regions, while sand dunes in West Africa also exclude large areas from eligibility. Taking into account local preferences Figure 7(b) displays the areas of land eligible for onshore wind turbines. West Africa boasts a 32% eligibility rate, whereas southern Africa only has a 16% eligibility rate. Within West Africa, eligibility ranges from >0.1% in Cote d'Ivoire and Guinea to approximately 55% in Mauritania. In Southern and East Africa, the border region between Namibia, Botswana, and South Africa has a particularly high eligibility rate, while national eligibility rates range from ~0% in Seychelles to about 50% in Botswana. However, it's worth noting that the largest shares of land areas are excluded due to isolated and connected settlements, forests, and pastures, in both cases.



(a)



(b)

Figure 7 Land eligibility according to the local preferences for (a) open-field PV and (b) onshore wind parks. [1]

3.2 Renewable energy potentials

Given the generally beneficial conditions for renewable energy technologies and the comparable high eligible land area in our analyzed regions, the total technical energy potential for onshore wind turbines and open-field photovoltaic combined with existing and planned hydropower plants sums up to 577 PWh/a across all considered regions in 2030. This cumulative potential exceeds the renewable energy contribution in the global electricity mix of 2021 by a factor of more than 50x [5]. Among the three renewable energy technologies open-field PV dominates the overall potential with ~88%, compared to onshore wind and hydropower with 12% and 0.1% respectively. Generally, it is unlikely that the full potential can be exploited in the future as it represents a technical potential. However, given the huge magnitude of the technical potential this will most likely not be necessary and, hence, no hard constraints in the renewable energy potentials are expected to appear.

The renewable electricity potential of open-field PV is not only the largest with above 500 PWh/a in 2030 but also often the cheapest renewable electricity source as nearly the full potential (~98%) can be yielded at levelized cost of electricity (LCOE) below 3Ct€/kWh already in 2030 (see Figure 8). In 2050 even the full potential is below 3 Ct€/kWh. This comparable cheap renewable electricity potential is stretched across nearly all considered regions if eligible area is present with slightly less productive regions near the equator. This can be explained as an effect of the general climate conditions such as rain and clouds present comparably larger cloud presence in The Intertropical Convergence Zone (ITCZ)[6].

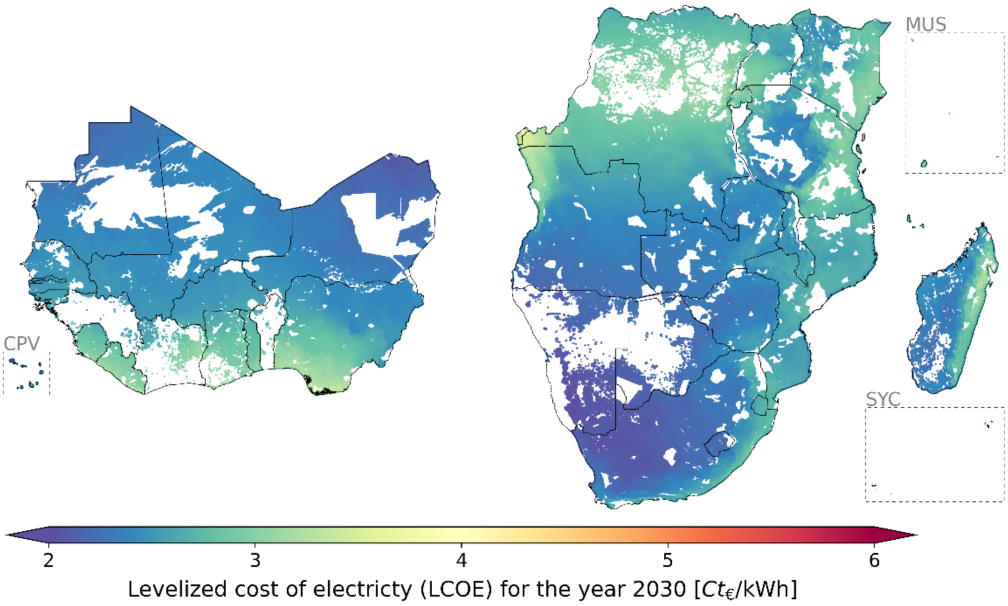


Figure 8 Open-field PV levelized cost of electricity for the year 2030. [1]

While the LCOE of open-field PV shows a comparatively low-cost spread, the LCOEs for onshore wind turbines are spatially much more heterogeneous (see Figure 9). This results from the higher variability of wind energy across regions. In total the renewable electricity potential of onshore wind turbines sums up to 69 PWh/a in 2030 across all regions, which is much smaller compared to the open-field PV potential. Of this potential only nearly 1% can be yielded at LCOE below 3Ct€/kWh mostly located in the Northwest of Mauritania. However, it is important to note that independent of the cost level of electricity from onshore wind turbines there is still the option to utilize synergies within the different time series of the different renewable energy sources.

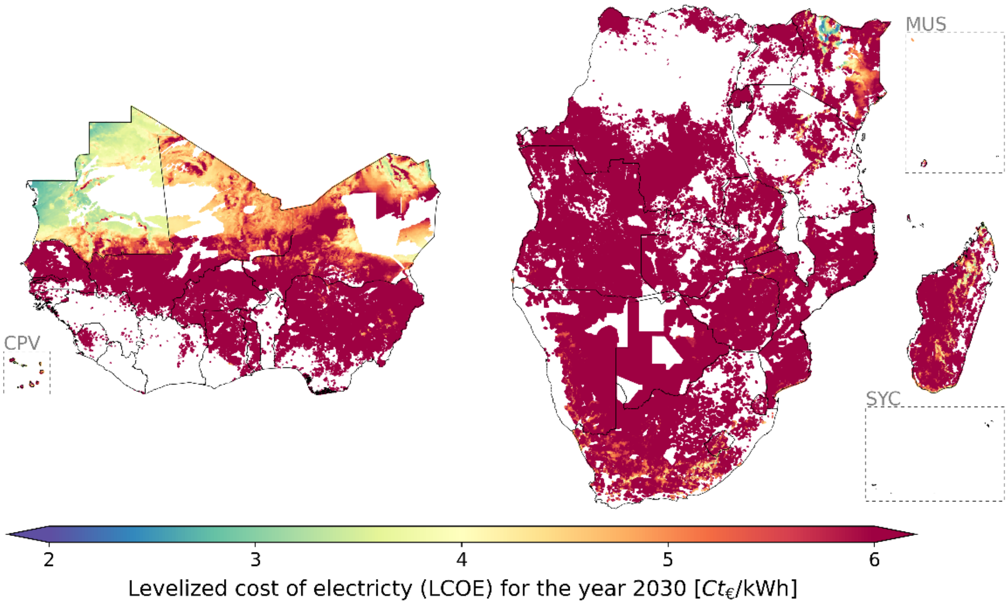


Figure 9 Onshore wind levelized cost of electricity for the year 2030. [1]

The hydropower plants considered contain the existing and planned but not all potential future power plants as their power potential highly depends on each other and, hence, can only be derived for specific energy scenarios. Independent from this we identified a total power capacity of 74 GW in 2030 (see Figure 10), which will increase by further 10 GW until 2050. This results in an electricity generation of roughly 340 TWh/a and 370 TWh/a in 2030 and 2050 respectively. Of this electricity roughly 55 – 60% can be generated at a LCOE below 3$Ct_€$/kWh with the smaller share in 2050. Nonetheless, it has to be considered that most of these hydropower plants are already utilized for local electricity supply and, hence, cannot be fully utilized for green hydrogen production.

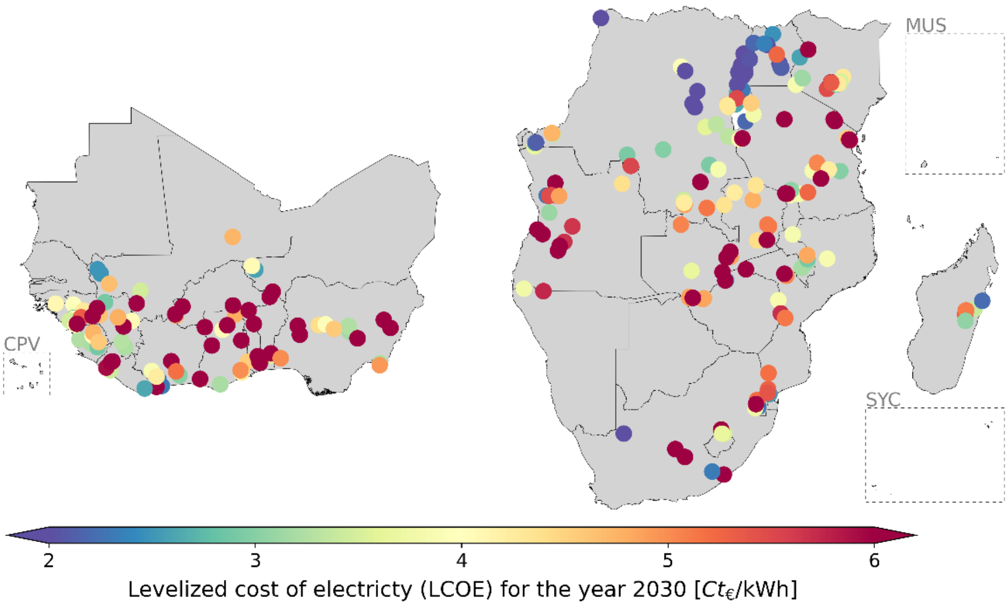


Figure 10 Hydropower levelized cost of electricity for the year 2030. [1]

3.3 Hydrogen potentials

Generally, the total technical potential of green hydrogen within the analyzed regions is huge with approximately 400 PWh/a in 2050, which amounts to more than twice the global primary energy demand of 2021 [5]. Driven by renewable electricity potentials, the largest green hydrogen potentials per area are located in the sparsely vegetated and populated Sahara and Sahel zone in West Africa as well as the Nama Karoo ecoregion in South Africa. Showing hydrogen potentials per area is most insightful here as otherwise the size of regions would distort the first impression of results.

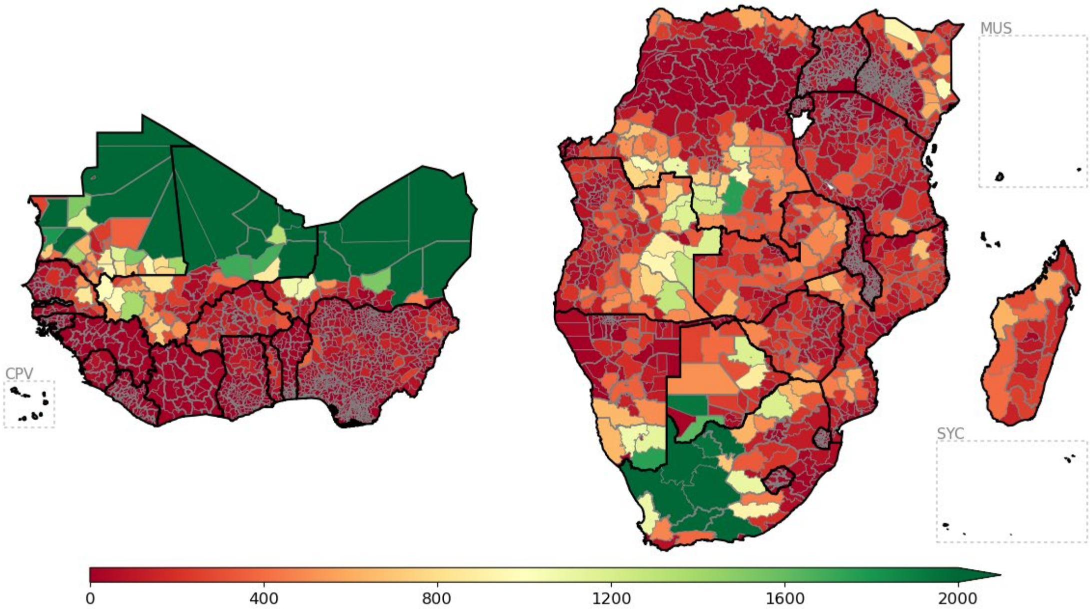


Figure 11 Technical hydrogen potential per area, limited only by energy [kWh/(a*m²)]. [1]

Regarding cost for hydrogen, the cheapest levelized cost of hydrogen (LCOH) of around 2 €/kg in 2030 at an expansion of 25% of the technical potential can be achieved in North-Western Mauritania. Excellent solar potentials meet good wind potentials here in particular along the cost, which complement the solar production time series at night and increase electrolysis utilization rate significantly. Similar effects occur in Northern Kenya. Beyond very attractive hydrogen production cost can also be achieved in the Sahara and Sahel zone, the arid zones in Southern Africa, in Northern Kenya and in Madagascar. The production cost in the majority of the Western, Eastern and Southern African regions ranges between ca. 2.20 – 3.00 €/kg for the year 2030. The average LCOH weighted by regional potentials is at ~2.7 €/kg. Levelized cost of hydrogen based on solar power tend to be nearly independent of the potential expansion degree. Isolated high LCOH such as for example in central Namibia and Botswana primarily occur in regions with negligible solar photovoltaic capacity potential and low wind speeds. On the other hand, regions with strikingly low green hydrogen production cost such as in Southern ECOWAS are mostly characterized by a high share of low-cost hydropower generation. It is imperative to assess such regions on a case-by-case basis, however, since most hydropower generation is usually being used to fulfill the national electricity demand and should not be used for hydrogen production alone.

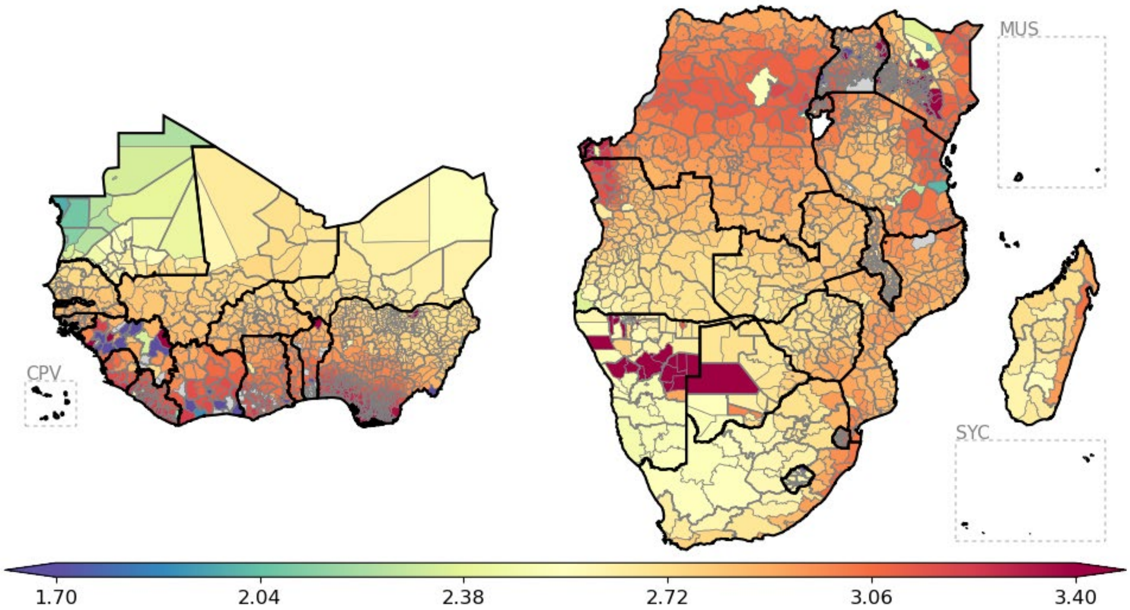


Figure 12: Levelized cost of hydrogen at 25% of the technical potential in 2030 [EUR/kg]. [1]

Strong cost decreases can be expected until the year 2050. Production cost as low 1.5 EUR/kg will be possible in Mauritania and the potential-weighted average cost drops down to 1.9 EUR/kg. The greatest cost decreases of up to nearly 30% will occur in regions dominated by solar photovoltaic power sources. It should be noted that these numbers represent pure cost assessment and do not yet include margins, tariffs, safety, and political implications at this stage. This means that moderately higher production cost can still be the most economical option in many cases, especially when hydrogen can be produced and consumed domestically.

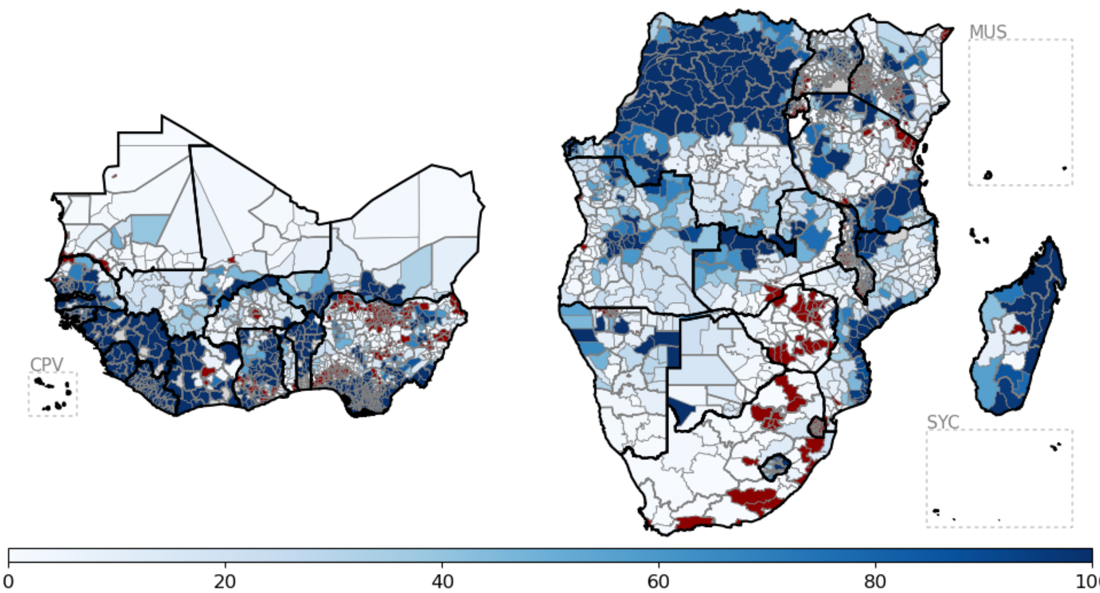


Figure 13: Share of technical hydrogen potential that can be produced with sustainable local groundwater [%]. [1]

In an additional step, the above hydrogen potentials were compared against the hydrogen volume that can be produced sustainably from local groundwater (see following section). In 2/3 of the considered regions, sustainable groundwater is insufficient to cover the water demand for production of the full technical hydrogen potential, roughly half the regions cannot even provide sufficient water for a moderate expansion degree of 25% of the technical potential. It should be further highlighted that the high-potential regions are particularly prone to water scarcity. To a certain degree, the central North of Kenya, Madagascar and Northern Namibia can be considered an exception to this. However, sustainable green hydrogen production is not necessarily limited to local water resources, but it is imperative that options for sustainable water supply e.g. from desalination are considered in the early stages of sustainable green hydrogen projects. Independent from the water source its associated cost is negligible for the hydrogen cost.

3.4 Sustainable groundwater

We present the key findings of groundwater availability for the years 2020, 2030 and 2050 for the medium scenario (as an optimum case) allowing for the utilization of up to 40% of the annual groundwater recharge for the green hydrogen production. Additionally, we accounted for two climate scenarios: RCP2.6, and RCP8.5. Climate scenarios are hypothetical representations of future climatic conditions based on greenhouse gas (GHG) emissions, used to assess vulnerability to climate change [7]. These hypothetical representations are captured in different setups designed to represent a range of possible emissions trajectories and corresponding radiative forcing levels called representative concentration pathways (RCP). Four main RCPs exist specifying particular radiative forcing levels by the year 2100 [8]. Noteworthy are the implications of the RCPs on temperature. The projected global mean surface temperature change ranges from 0.3°C to 0.7°C for the period 2016-2035, and by the end of the 21st century, it is likely to hit 1.7°C for RCP2.6, and 4.8°C for RCP 8.5 compared to the historical industrial period. This study utilizes RCP 2.6 and RCP 8.5, representing optimistic and pessimistic emission scenarios, respectively.

Groundwater sustainable yield in 2020

The groundwater availability in 2020, calculated as the average of 2015 - 2035, for the medium scenario, is shown in Figure 14 under the RCP2.6 (Figure 14a) and RCP8.5 (Figure 14b) scenarios. In the West Africa region, the findings indicate that both the coastal areas (such as Gambia, Guinea, Sierra Leone, Liberia, and Cote d'Ivoire) and those situated in the Southern region (including Nigeria, Benin, and Ghana) consistently exhibit higher groundwater sustainable yields under both the RCP2.6 and RCP8.5 scenarios. The regional assessment reveals that across West Africa as a whole, the average groundwater sustainable yield for the year 2020 under the RCP2.6 (RCP8.5) scenario is estimated at 35.0 (33.0) mm yr^{-1}. In Southern East Africa, the research findings suggest that countries such as Angola, the Democratic Republic of Congo, Zambia, Tanzania, and Madagascar consistently demonstrate higher sustainable groundwater yields compared to other countries in the region. Furthermore, our analysis reveals that the southern part of the region, including countries such as South Africa, Lesotho, Namibia, and Botswana, exhibits a high sustainable groundwater yield in 2020 under both the RCP2.6 and RCP8.5 scenarios. Regional analysis indicates that in 2020 under the RCP2.6 (RCP8.5) scenario, Southern East Africa is projected to achieve average groundwater sustainable yields of 75.8 (72.6) mm yr^{-1}.

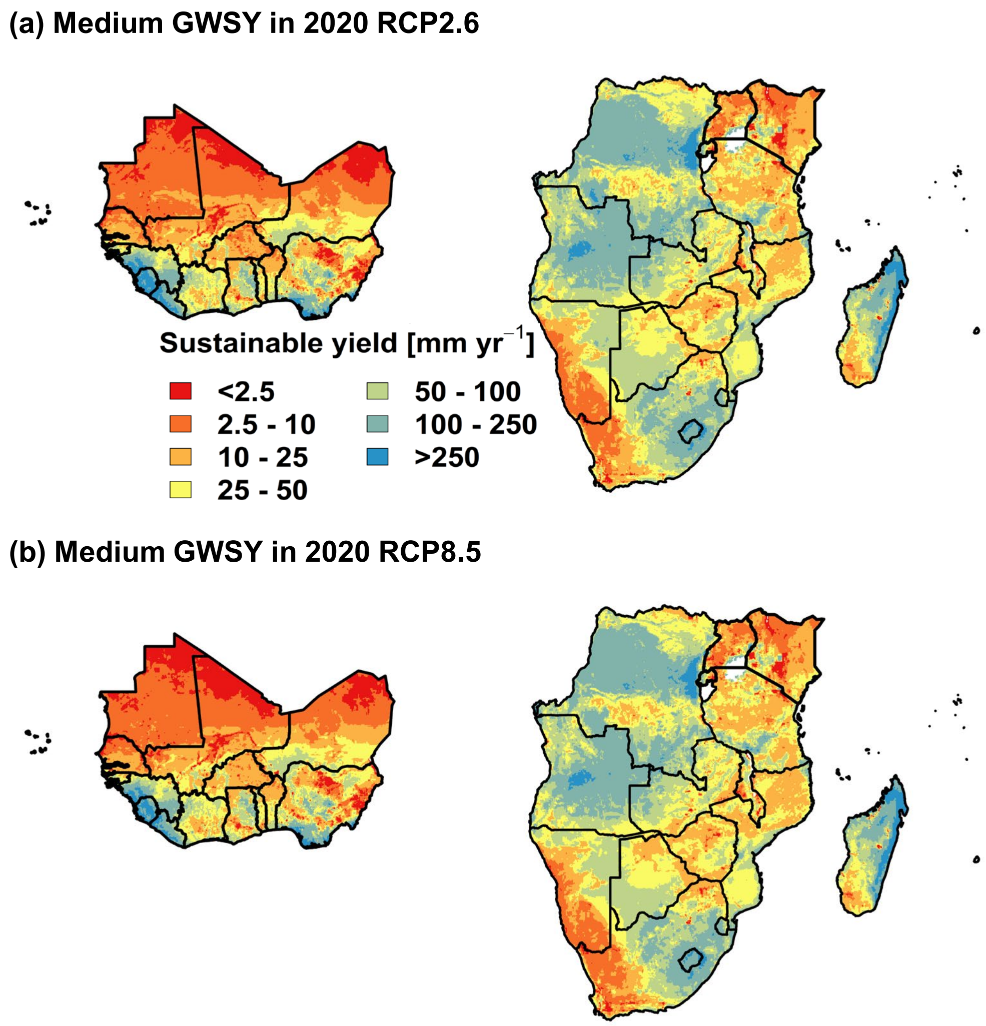


Figure 14. The medium case groundwater sustainable yield for 2020 (the average of 2015 - 2035) under two climate scenarios: RCP2.6 (a) and RCP8.5 (b). [1]

Groundwater sustainable yield in 2030

The long-term average groundwater sustainable yield for the medium scenario, representative of the year 2030, is depicted in Figure 15 for the period 2015 - 2045. Results are provided for both RCP2.6 (Figure 15a) and RCP8.5 (Figure 15b). The analysis for West Africa indicates that the average groundwater sustainable yield in 2030 under RCP2.6 is projected to be 33.3 mm yr^{-1} (Figure 15a). In contrast, under RCP8.5, it is expected to be approximately 31.8 mm yr^{-1} (Figure 15b) for the same scenario. In Southern East Africa, the projected average groundwater sustainable yield for 2030 under RCP2.6 is 73.7 mm yr^{-1}, which is lower than the values observed in 2020 under RCP2.6. Additionally, the region is projected to have an average groundwater sustainable yield of 71.9 mm yr^{-1} under RCP8.5, slightly lower than the 2020 values for RCP8.5.

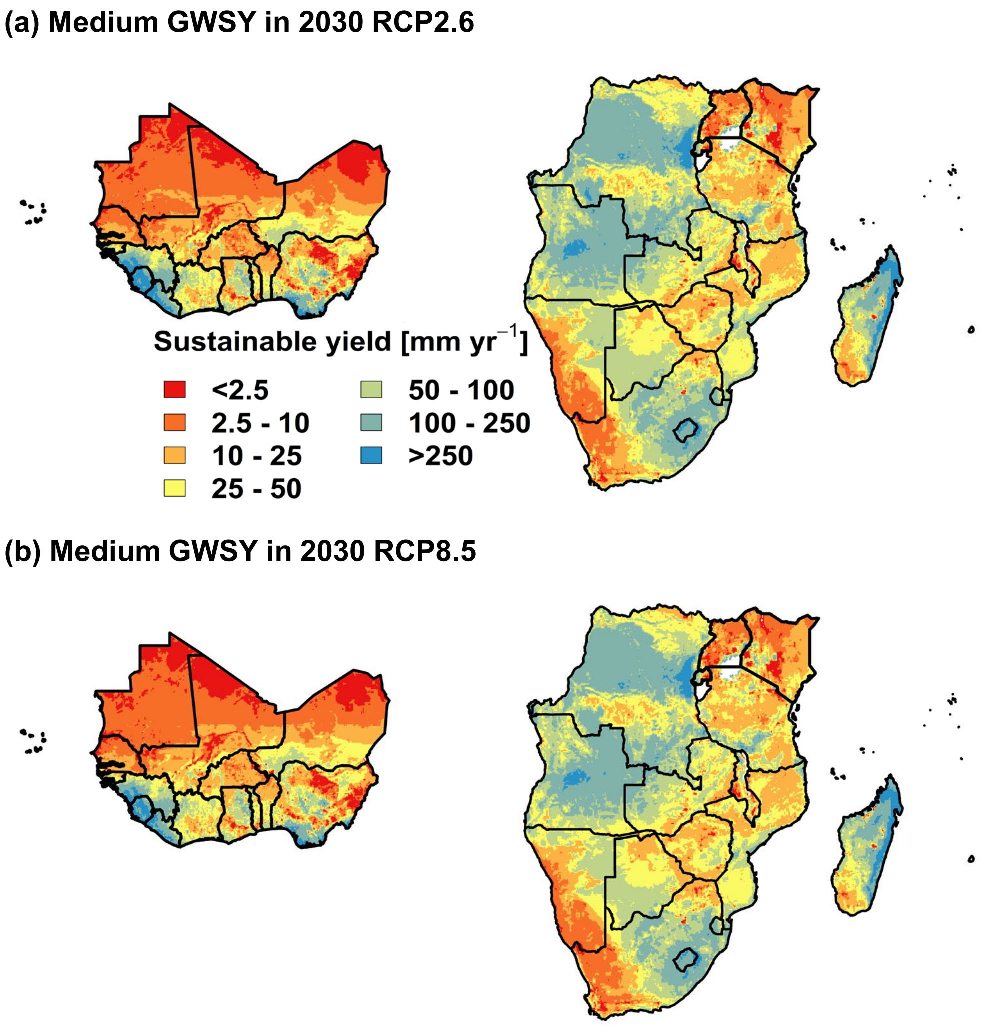


Figure 15 The medium case groundwater sustainable yield for 2030 (the average of 2015 - 2045) under two climate scenarios: RCP2.6 (a) and RCP8.5 (b). [1]

Groundwater sustainable yield in 2050

The long-term average (2036 - 2065) groundwater sustainable yield for the medium case representative for the year 2050 is shown in Figure 16. Results for RCP2.6 (Figure 16a) and RCP8.5 (Figure 16b) are presented. We observe almost an identical spatial distribution of groundwater sustainable yield in 2050 RCP2.6 (Figure 16a) when compared to that of 2020 RCP2.6 (Figure 14a), although with variations in magnitude. The West Africa regional analysis demonstrates that over the entire area average groundwater sustainable yield in 2050 RCP2.6 would be 29.6 mm yr^{-1} for the medium scenario. However, groundwater availability in 2050 RCP8.5 (Figure 16b) is projected to decrease, compared to 2020 RCP8.5 (Figure 14b), particularly over the Northern part of the region. In addition, the results show that the Southern part of the West African region (e.g., Nigeria, Benin, Ghana) consistently will receive less sustainable yield than in 2020 RCP8.5. In 2050 RCP8.5, the West African region is expected to exhibit a mean groundwater sustainable yield value of 27.3 mm yr^{-1}, which is less than in 2020 RCP8.5. In the Southern East Africa region, the results show that although the spatial pattern of groundwater sustainable yield in 2050 under RCP2.6 (Figure 16a) and RCP8.5 (Figure 16b) is similar to the one in 2020, groundwater sustainable yield in 2050 is lower than in 2020 under both RCP2.6 and RCP8.5. Considering 2050 RCP2.6, the average groundwater sustainable yield for the entire region is projected to be 68.6 mm yr^{-1} which is lower than under the RCP2.6 scenario in 2020. Furthermore, the region is projected to show average groundwater sustainable yield values of 67.6 mm yr^{-1} under RCP8.5 which is lower than those observed in 2020 under RCP8.5.

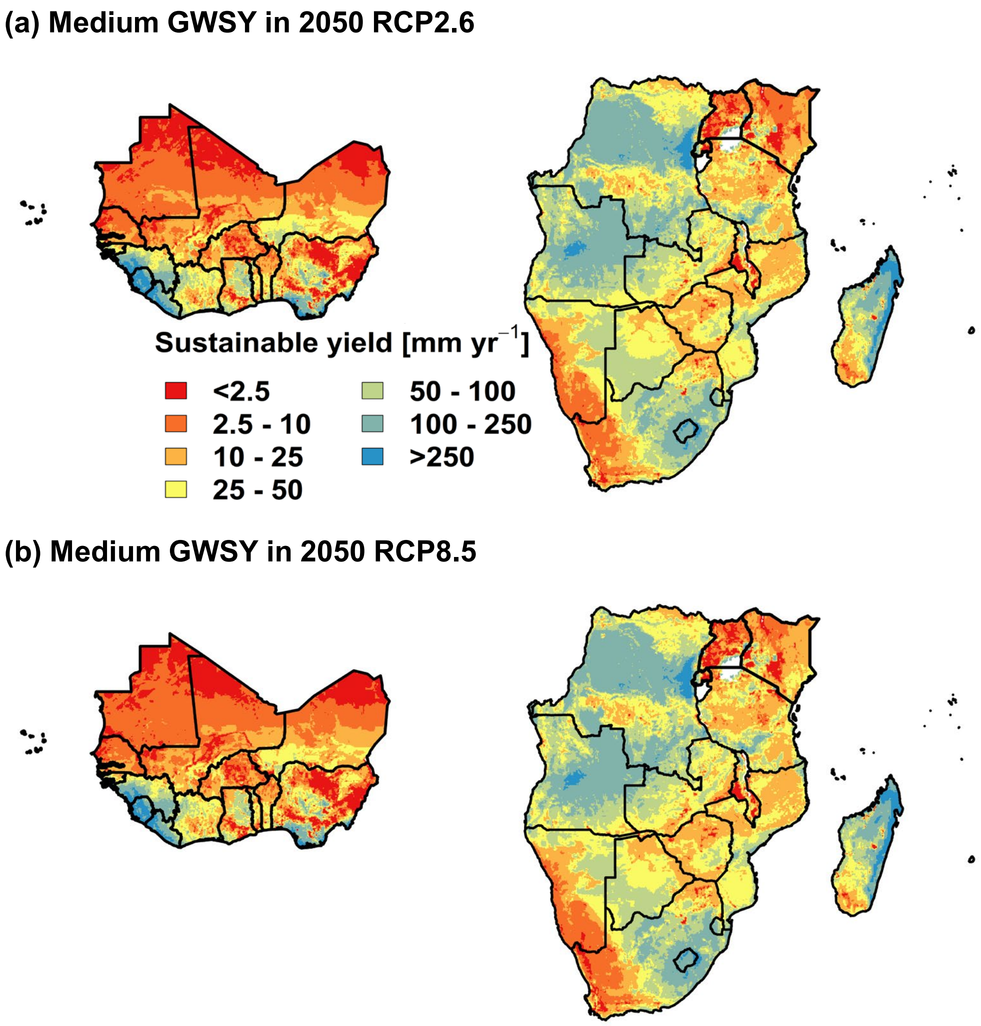


Figure 16 The medium case groundwater sustainable yield for 2050 (the average of 2036 - 2065) under two climate scenarios: RCP2.6 (a) and RCP8.5 (b). [1]

3.5 Socio-political context and development opportunities

The national framework index results based on Lahnaoui et al.[9] and represented in Figure 17 include the total score of three sub-indexes as detailed in the methodology section (Figure 24):

- The Energy Sector Framework and Policies Indicator (ESP) classified from a low score of 0 to a maximum of 1 for green hydrogen project implementation feasibility regarding current energy and power sector performances and future energy policies.
- The Export and Transport Infrastructure Indicator (HFE) classified from a low score of 0 to a maximum of 1 regarding export feasibility based on export, transport and electricity infrastructure performances.
- The Political and Regulatory Framework Indicator (RPF) classified from a low score of 0 to a maximum of 1 regarding security and feasibility of green hydrogen project investment.

Overall, island countries like Cabo Verde, Mauritius, and Seychelles perform well. Among continental countries, those in the Southern and Eastern regions demonstrate better overall results compared to those in the Western region. South Africa, Botswana, and Namibia rank highest, followed by Ghana, Kenya, Rwanda, and Zambia. At the bottom are Guinea-Bissau and the Democratic Republic of Congo. However, the final index ranking incorporates a diverse set of results from all composite indicators. These sub-indicators are crucial for understanding areas that require improvement, the potential for either a more export-oriented or domestic-oriented green hydrogen industry, as well as the potential complementarities and synergies between neighboring countries.

In this regard, Ghana and Kenya stand out for their more attractive energy frameworks and sustainable policies, while island countries excel in regulatory and political frameworks, primarily due to their secure and attractive investment landscapes. Regarding exports, South Africa and Ghana perform higher in the West and South Africa, respectively.

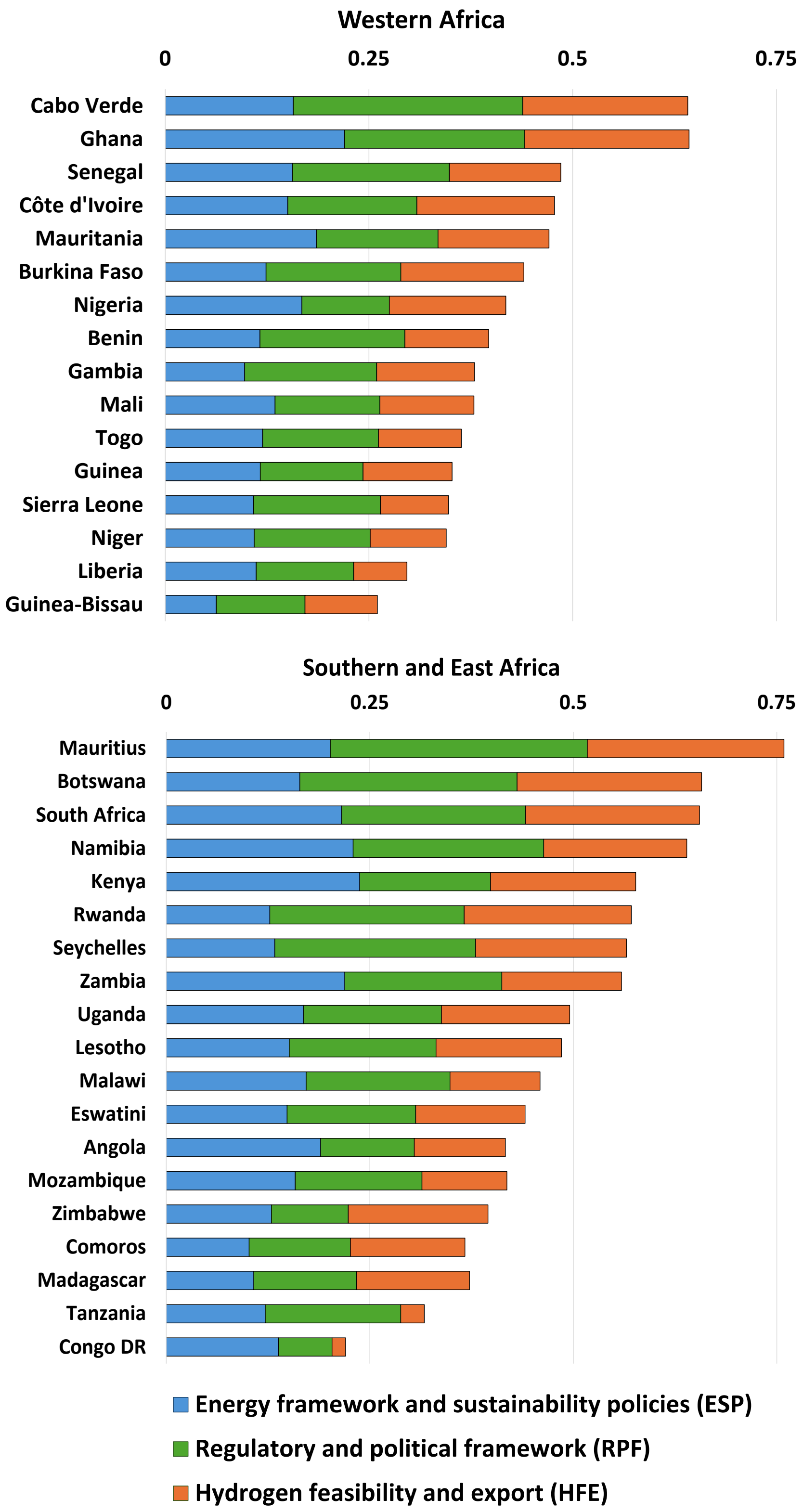


Figure 17 Total index feasibility score for the selected regions. [9]

Regarding the potential local impact of green hydrogen projects, a regional socio-economic composite indicator represented in Figure 18 is represented from low to very high impact on local population. This is calculated based on the sub-indexes detailed in the methodology section (Table 3) including:

- Access to Energy Indicator represented in Figure 19 that accounts for population access to energy per region
- Macroeconomic effect represented in Figure 20 that accounts for labor employment potential per installed capacity and per region

The main local impact in terms of high Socio-economic indicator is notably observed around the African Great Lakes in East Southern Africa such as Lake Malawi, Lake Tanganyika, and Lake Victoria, as well as further inland regions in the Southern and Eastern borders of Democratic Republic of the Congo, northern Tanzania and parts of Mozambique, Zimbabwe and Lesotho. Additionally, in West Africa, the coastal regions of the Upper Guinea, as well as further inland regions encompassing Nigeria and Burkina Faso, exhibit substantial local impacts. This high local impact is mainly due to a combination of access to energy and macroeconomic potential impacts as presented by the two sub-indicators.

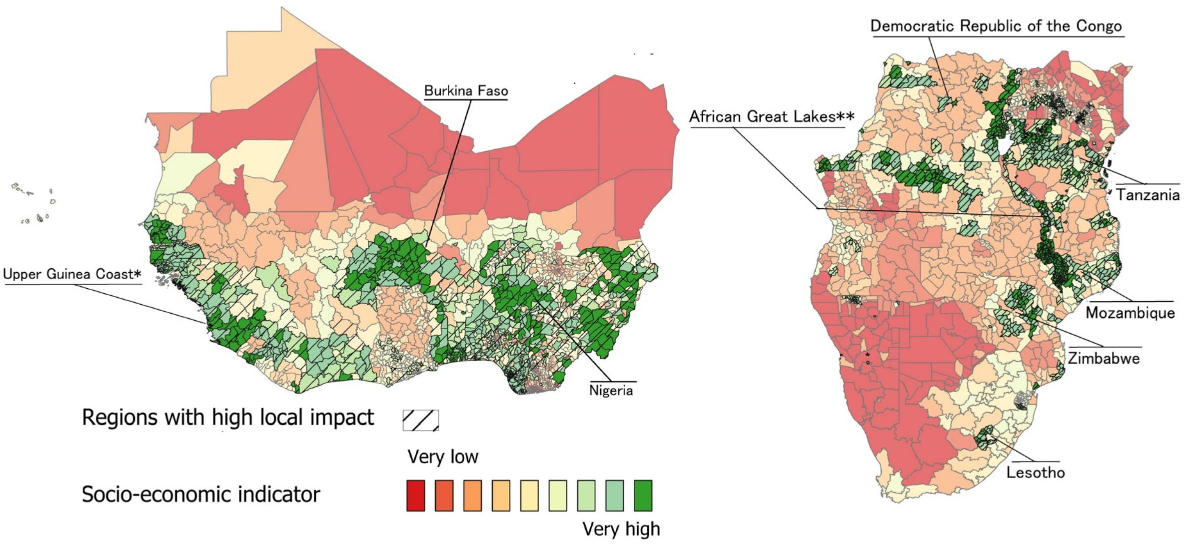


Figure 18 Socio-economic indicator measuring the impact of green hydrogen project. [1]

For the energy access sub-index, the main local impact is observed in Malawi, the northern regions of Tanzania, the southern areas of Mozambique, and western Zimbabwe, as well as the southern part of the Democratic Republic of Congo. In West Africa, this impact extends across the entire southern region, excluding Ghana and Ivory Coast, along with sparsely populated areas in the middle.

High local impact is primarily driven by a combination of factors, including low access to essential services such as electricity and clean fuel. Countries like Burkina Faso, Sierra Leone, and Liberia exhibit particularly low access rates, with electricity access below 30% on average and clean fuel access below 20%. However, the importance of population density is exemplified in the case of Niger, where despite low access to electricity, below 20% on average, access indicators remain relatively low due to sparsely populated or nomadic areas.

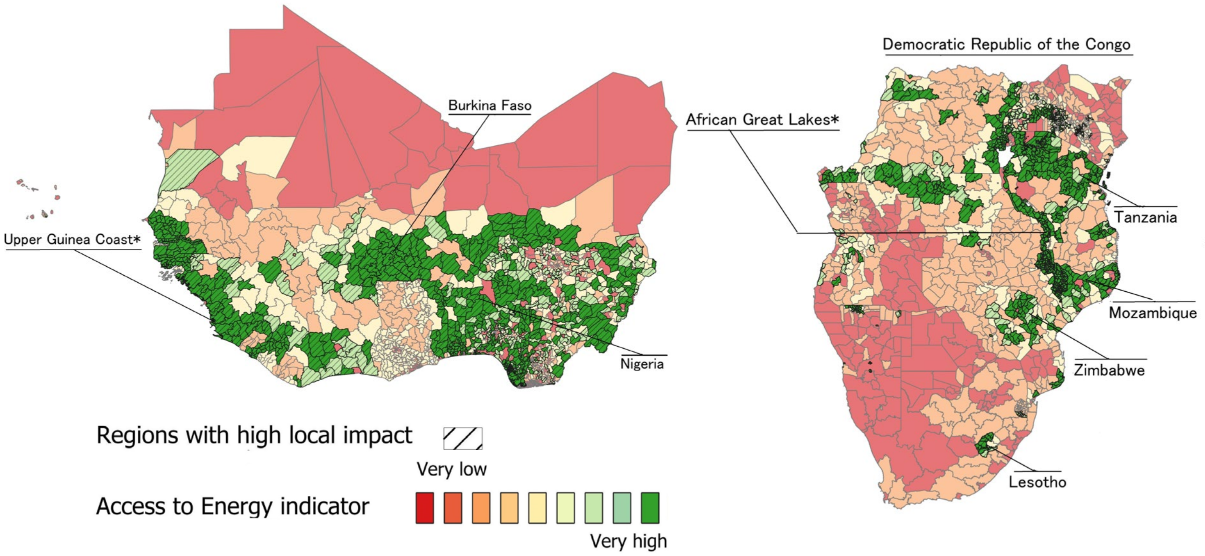


Figure 19 Mapping the energy access indicator. [1]

The macroeconomic effect sub-index is evaluated via regional employment impact, and is characterized by higher impacts in West Africa, particularly Nigeria, Burkina Faso and Cape Verde, along with regions like the Upper Guinea Coast. Similarly, Eswatini, Lesotho, Uganda, and the northwest of South Africa emerge as focal points in the southern African context. Nigeria emerges as a standout with the highest employment impact attributable to its substantial labor force and dispersed and dense population. However, countries like Angola and the Democratic Republic of Congo exhibit lower employment impacts despite comparable labor forces due to energy potential distribution mismatch with population. Notably, Botswana registers the lowest local employment impact due mainly to a sparse labor force, population distribution disparities, and high labor costs.

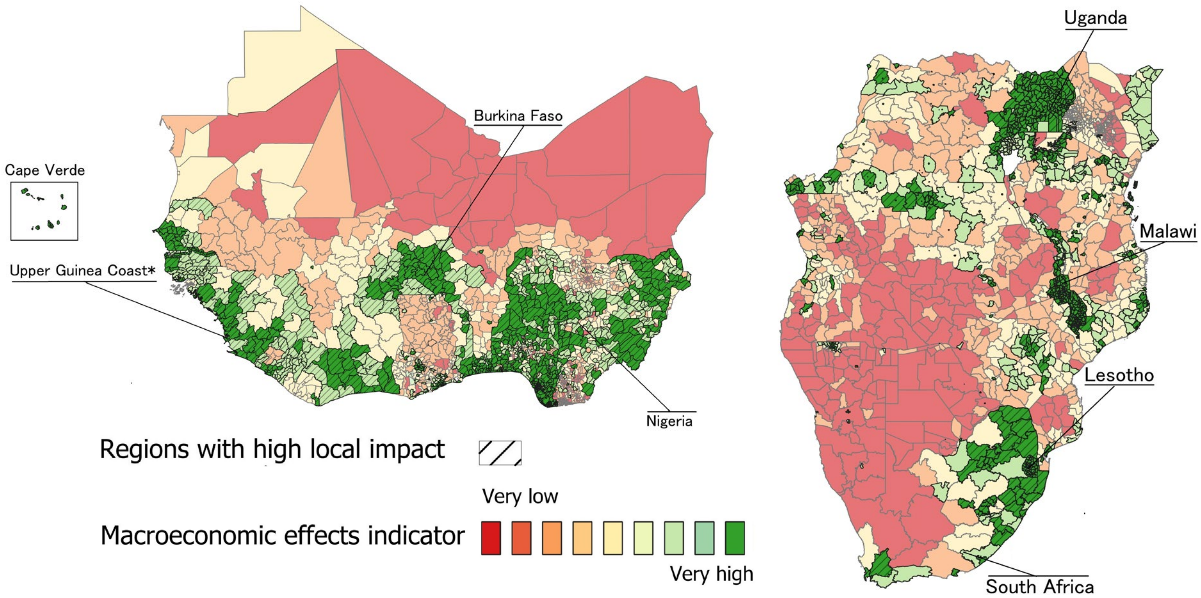


Figure 20 Mapping of the macroeconomic effects indicator. [1]

Part II: Scientific details

The following part is directly taken from Ishmam et al. [2] and Winkler et al. [1] If you intend to refer to content of this part please cite the respective references as given before. This part provides an in-depth description of the underlying methodology and obtained results.

1. Methodology

The description of the methodology is directly taken from Ishmam et al. [2]. If you want to cite this part please use these given references.

1.1 Overview of Methodology

"The underlying methodology of this study consists of several coupled models and integrated data to finally achieve its given goal to serve as decision support shown. The chosen methodology has been already employed in several publications ([12], [13], [14]) and refinements considering preferences of local partners in Africa were included. To illustrate the methodology here a exemplarily region in Sub-Saharan Africa is used. It starts with a dedicated land eligibility analysis which identifies where renewable energy technologies can be placed in accordance with local preferences. Based on those placements each location specific wind turbine and open-field photovoltaic module are simulated to derive their weather dependent hourly electricity generation. In parallel, the availability of sustainable groundwater and the cost for seawater desalination are calculated mostly based on [15]. In a next step, both water supply options together with the time series of renewable energy technologies are fed into an energy system model for each "GID-2" administrative region based on the definition from Global Administrative Areas [16] in the analyzed regions. Each energy system model additionally consists of batteries as potential electricity storage, hydropower plants and electrolysis to supply an exogenously increasing hydrogen demand until the maximum potential is achieved to form a green hydrogen cost-potential curve for each region. In addition to these techno-economic results, the methodology was extended by drawing on previous studies that overlooked aspects related primarily to socio-technical and socio-economic factors. Indeed, since energy projects would provide local added value and could be beneficial in those regions, where the energy supply is not yet fully developed, opportunities for the population should be explored. Together these results are made available via a web-based graphical user interface (GUI) to be accessible for a wide range of decision-makers and stakeholders." [2]

1.2 Land eligibility assessment for open-field photovoltaic and onshore wind turbines

"A land eligibility analysis that yields the overall land area eligible for the placement of renewable plants under specified constraints usually comes before determining the theoretical maximum renewable potential like for onshore wind [17–19]. Typically, the land eligibility analysis takes into account various factors such as topography, land use, environmental constraints, and social and economic considerations [20]. Within the context of this study, the set of land eligibility criteria have been carefully selected from literature sources[20,21] and complemented by feedback received from our local partners. As this study focuses specifically on Sub-Saharan Africa, the inclinations of regional stakeholders, such as community members, governmental bodies, and international institutions are of utmost importance to achieve meaningful results for decision makers. Therefore, deliberate efforts have been made to collect, process, and examine the local preferences aligned with the criteria listed in Table 1 within several workshops. The set of constraints thus obtained are referred to as "local preferences" in the subsequent sections. In cases where it was not possible to receive stakeholder preferences, the median of the local preferences collected was allocated. This has been done for onshore wind turbines and open-field photovoltaics, which are perceived as major building blocks of the global energy transition with comparable low environmental impact [22]. This approach results in 33 criteria and buffer distances for onshore wind and open-field PV each.

The research was conducted using the open-source general-purpose geospatial toolkit GeoKit [23] and the land eligibility model “Geospatial Land Availability for Energy Systems” (GLAES) (GLAES, 2024). GLAES leverages the capabilities of GeoKit to perform all its underlying geospatial operations and is specifically designed for land eligibility analysis. Its design focuses on reducing errors that may arise from geospatial operations commonly needed for land eligibility analysis, being transparent in methodology, scalable for vast geographical regions, and adaptable to standard geospatial data formats. Both GeoKit and GLAES are implemented in the Python 3 programming language and rely on the SciPy [25] ecosystem for general numerical and matrix computations and the Geospatial Data Abstraction Library (GDAL) [26] for geospatial operations, both of which are open-source projects. The computations for the land eligibility analysis were conducted using a custom Lambert azimuthal equal-area projection (LAEA) projection system with a 100 m spatial resolution centered on each region individually, which provide the highest accuracy for the area determination. The exclusion features are the most comprehensive in comparable studies to date. In combination with carefully selected high-resolution geospatial datasets that are particularly suitable for the project region, the resulting land eligibility has an unprecedented degree of reliability. This allows geospatial exclusions even against high resolution satellite imagery. However, it is not able to capture exclusions that are not clearly defined by geospatial properties, such as the objection of landowners or lawsuits due to, for example endangered species that are found in the area only upon local inspection.”

Figure 21“displays an exemplary case of how land exclusions correspond to each criterion in a region in Sub-Saharan Africa. The application of each criterion, with its associated buffers, such as 200 m around primary roadways, 1000 m around settlements, etc., results in the progressive exclusion of more and more land areas. As a result, only a mere 23.8% of the land area is available for this exemplary region.

Based on the collected local preferences, land exclusions were applied for all 33 criteria and eligible areas were computed for each region for both wind turbines and photovoltaic modules. A meticulously curated compilation of the primary open-source geospatial datasets utilized for implementing the exclusions corresponding to the 33 selected criteria is accessible online via the GUI (https://africa.h2atlas.de/). The selection of these datasets is based on the methodology applied by Franzmann et al. [21] and Ryberg et al. [20]. The resulting eligible areas form the basis for the renewable energy potential assessment in Section 2.2 in Ishmam et al. [2]”

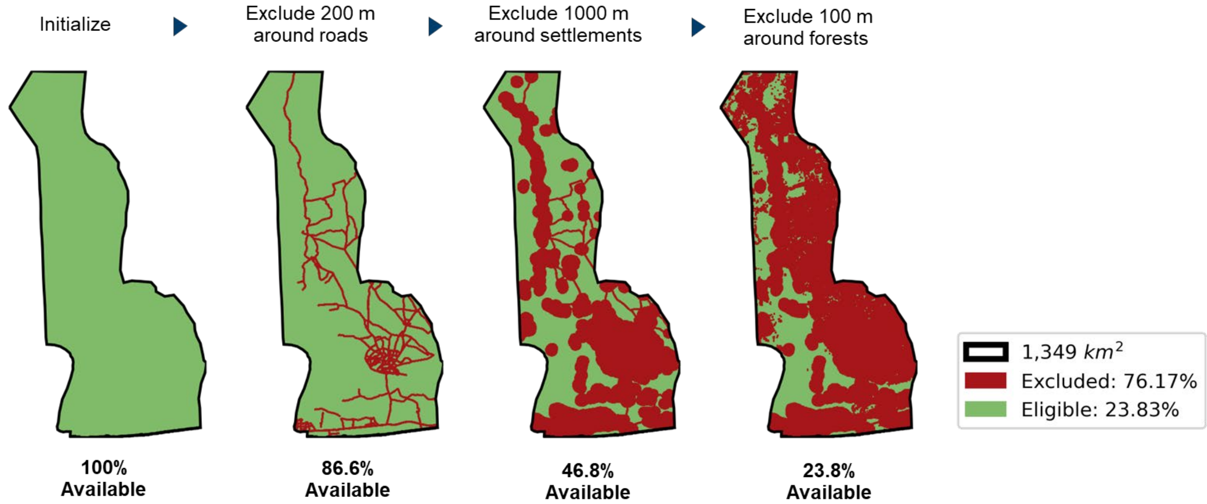


Figure 21 Exemplary exclusion of different criteria for an example region in West Africa (Ouémé in Benin)
[2] ** The buffer distances used here are solely for illustrative purposes.*

Table 1. Selected criteria for land eligibility analysis[2]

Criteria			
1	Settlements (connected)	18	Lakes
2	Settlements (isolated)	19	Creeks
3	Airports	20	Rivers
4	Primary Roadways	21	Coastlines (Ocean, general)
5	Secondary Roadways	22	Woodlands (All Forests)
6	Agricultural Areas	23	(Standard) Wetlands
7	Pasture Areas	24	Specially protected Wetlands
8	Railways	25	Sand Dunes
9	Power Lines	26	Natural Habitats
10	Historical Sites	27	Biospheres
11	Recreational Areas	28	Wildernesses
12	Leisure and Camping	29	Bird Areas
13	Industrial Areas	30	Protected Landscapes
14	Commercial Areas	31	Natural Reserves
15	Mining Sites	32	National Parks, State Parks, etc.
16	Military Areas	33	Natural Monuments
17	National Borders		

1.3 Renewable energy potential assessment

"Subsequently, wind turbines and open-field PV modules are placed on the eligible areas. For this wind turbines are positioned with a distance of 8 times the rotor diameter for the main wind speed direction and 4 times the rotor diameter for the transversal wind speed direction using the placement algorithm in GLAES [27]. The turbines utilized here are specifically designed for future applications and are extensively examined in Ryberg et al. [27], as the applied scenario is specifically framed for the year 2050. The investment cost of each individual turbine is determined through the utilization of a cost model. Hourly simulations are then conducted using the appropriate meteorological data from the ERA5 weather data source [28] for the corresponding year, following the methods outlined in Ryberg et al. based on the open-source tool RESkit [27,29]. The RESKit [29] toolkit not only facilitates high spatiotemporally resolved simulations of solar and wind resources but also allows evaluating the investment cost of each individual solar and wind placement through the utilization of a cost model.

Similarly, simulation sites for open-field PV parks are placed with a minimum distance of 1000 meters between them. When considering PV parks, the area surrounding each placement is an important factor in its potential capacity, as they are much more spread out than wind parks. Eligible area in the case of PV parks is assigned by creating Voronoi polygons [30] at a size of 1000 m around each possible placement location and grouping adjacent and non-contiguous eligible area together. As a last step, the placement locations are updated to correspond to the centroid of each identified area. For this technical potential an open-field coverage of 20 m^2/kW_p and the module Winaico WSx-240P6, as suggested by Ryberg [31] is assumed. Finally, all the locations are simulated for open-field PV systems without single-axis tracking, using the algorithm of RESkit described in [31]. We selected a fixed PV system as it has the lowest investment cost, which is especially relevant for countries potentially facing financing challenges.

The ERA-5 reanalysis dataset has been chosen since several recent studies have evaluated ERA-5 as significantly better for modeling wind and solar resources than other reanalysis datasets such as MERRA-2 [32,33]. Using climate model output datasets such as ERA-5 is the most practical solution due to the large spatial domain, the need for various weather parameters, and the requirement to assess wind generation over multiple years to accurately represent the wide range of potential weather events. Our thorough evaluation process, which takes into account the uncertainties and potential biases associated with using climate model outputs, reassures the validity of our results [34–37].

The hydropower potentials in Africa from Sterl et. al. [38] were utilized to derive the electricity generation time-series available from existing and planned hydropower plants in Africa. The database offers monthly hydropower generation data under three distinct scenarios: "dry," "normal," and "wet" seasons. For this analysis, the "normal" scenario was adopted as it represents a standard performance of the hydropower hydro-fleet according to the author. In addition, its use allows for hydropower production estimation potential under no extreme conditions. Only hydropower plants with a capacity exceeding 1 MW were included in the analysis, encompassing both run-of-river and reservoir hydropower facilities. This makes 394 medium and large hydropower plants total with 84 GW installed capacity for 2050 considered in the assessment. To align with the temporal resolution of wind turbines and PV modules, the monthly generation time series was transformed into an hourly form by linearly projecting the monthly generation into hourly values from one month to the next. The monthly mean values were assigned in the middle of the month. Hydropower costs were taken from the report "Renewable Power Generation Costs in 2019" from IRENA [39].

The geothermal potentials are based on a methodology from Franzmann et al. [40]. Based on the land eligibility results from section 2.1 for geothermal plants, the capacity for enhanced geothermal systems is calculated. The geological temperature is estimated based on an approach from Aghahosseini et al. [41] and heat flow data from Goutorbe et al. [42]. The heat output of the plants is calculated based on Gringartens approach [43,44] applied to location specific plants and the thermal conversion is based on Tester [45]. As geothermal cost is mostly dependent on drilling costs, the medium outlook of geothermal drilling costs is assumed based on NREL [46] for a maximum depth of 7 km [45].

The resulting time series of electricity generation of each wind turbine, open-field PV park and hydropower plants form the supply basis for the subsequent step to derive the green hydrogen potential." [2]

1.4 Sustainable water supply assessment

To evaluate sustainable water supply for green hydrogen production, we consider both groundwater sustainable yield and seawater desalination, along with the associated water transport as follows:

1.4.1 Groundwater analysis

"For the assessment of water availability, we considered sustainable groundwater supply and seawater desalination including water transport. The long-term groundwater sustainable yield has been estimated by integrating detailed land surface hydrology and natural groundwater recharge simulations at 10 km spatial resolution. This analysis was conducted using the Community Land Model [version 5] (CLM5) [47] and supplemented with data on sectoral water usage[62] across Africa. This model-based approach is particularly valuable as it captures spatio-temporal variations, including atmospheric forcings, land cover, and soil texture, thereby providing comprehensive insights into land surface hydrology, such as evapotranspiration and surface runoff. By considering sustainable groundwater supply and seawater desalination options, all regions have a potential source of water supply.

Groundwater recharge

The annual groundwater recharge was determined through simulations using the CLM5 model [47] employing a widely-used water balance method [15,48–50]. Furthermore, to account for anthropogenic water inputs, the water balance integrated irrigation, following CLM simulations [51], as indicated by:

$$R = (P + I) - ET - Q \qquad (1)$$

where R is groundwater recharge [mm yr^{-1}], P is the precipitation (rain and snow) [mm yr^{-1}], I is the simulated irrigation by CLM5 to account for all anthropocentric water supply [mm yr^{-1}], ET is evapotranspiration [mm yr^{-1}], and Q is surface runoff [mm yr^{-1}]. Groundwater recharge was estimated on a yearly basis.

Environmental flow
Environmental flow (Qrest), or the minimum ecological water requirement, represents the essential water volume crucial for sustaining ecosystems and the services they provide. Previous recommendations advocate that the responsible use of water resources should not exceed 10%, 40%, and 70% of the total groundwater recharge, aligning with conservative, medium, and extreme scenarios [52–55]. In accordance with these guidelines, we have adopted three distinct scenarios to allocate environmental flow based on the simulated groundwater recharge: (i) a conservative scenario (90% of recharge), (ii) a medium scenario (60% of recharge), and (iii) an extreme scenario (less conservative with 30% of recharge).

Sustainability analysis
Determining the groundwater sustainable yield involves the application of Eq. (2), which incorporates the concept of the percentage of recharge, as suggested by [48,56], alongside the integration of total sectoral water consumption. This method enables the assessment of the sustainability of groundwater utilization.

$$SY = R - Qrest - SWU \qquad (2)$$

where SY is groundwater sustainable yield, Q_{rest} is environmental flow, and SWU is sectoral water use. The units of all variables in Eq. (2) can be expressed in mm yr^{-1}.
Moreover, we have considered three distinct scenarios for the sustainable yield derived from the three environmental flow scenarios (conservative, medium, and extreme). For groundwater availability analysis, the long-term (2015 - 2100) groundwater sustainable yield has been calculated, and then the average from 2015 – 2035, 2015 – 2045 and 2036 – 2065 are considered representative of 2020, 2030 and 2050. The groundwater recharge is obtained from the CLM5 model [47] simulations at 10 km spatial resolution, forced by the regional climate model runs of CCLM5 [57], REGCM4 [58], and REMO2015 [59], which were driven by the MPI [60] and NOR-ESM [61] General Circulation Models (GCMs). Such regional climate models and GCM simulations from the CORDEX dataset (https://cordex.org/; last accessed: 1 November 2023) are utilized due to their extensive long-term spatial coverage over the targeted regions in Africa. The RCP2.6 (which is considered optimistic indicating low greenhouse gas concentration pathways) and RCP8.5 (which is considered pessimistic indicating high greenhouse gas concentration pathways) scenarios were considered for these simulations. The average groundwater recharge (from six combinations of GCMs and RCMs), and consequently the groundwater sustainable yield, is considered for further use in the green hydrogen project for RCP2.6 (optimistic) and RCP8.5 (pessimistic) scenarios. The environmental flow is calculated from simulated groundwater recharge. The sectoral water use is obtained from literature [62] that takes total water withdrawal for industrial, irrigation, domestic, and livestock into account."

1.4.2 Desalinating seawater and water transport

"The selection of groundwater or desalinated water for hydrogen production depends on the cost incurred. Since groundwater is usually the cheaper option, this means that local groundwater resources are considered first, and desalinated seawater is used once the limits of sustainable groundwater are reached. Regions that do not have sustainable groundwater resources left have to use exclusively desalinated water. After a comparison of published literature on water transport cost, a validated UN cost model [63] based on real data [64] was selected to integrate water supply from seawater desalination in our analysis. This updated model requires the electricity cost for pumping as well as elevation and distance to the shore as an input. This base model was further developed by updating cost values and converting dieselto electricity-powered pumps. Electricity cost was introduced as a variable and set to the average solar photovoltaic levelized cost for 24-hour operation: Exemplary studies in the affected regions revealed that, under the given techno-economic assumptions, the unit cost for constant operation amounts on average to ca. 3x the solar electricity production cost due to the required extra cost for battery storage. Transport distance is then calculated based on distance of the district centroid from the nearest coastline [65] and a detour factor of 1.3 typical for infrastructure routing [66]. Elevation is extracted as the average regional value from OpenTopography [67]. Desalinated water cost is calculated using the cost model of Loutatidou et al. [68], scaled to present day cost, with the previously mentioned PV-based electricity cost and a reference plant size of 367 000 m^3/h, based on Heinrichs et al. [69]." [2]

1.5 Local green hydrogen potential assessment

“In this study the technical hydrogen potential for each "GID_2" region has been evaluated. The "GID_2" regions refer to the administrative divisions of the second level as categorized by the GADM (Database of Global Administrative Areas) [16]. In countries where no “GID_2” level is available, the first level “GID_1” divisions were used. In the following analysis, the simplified term “GID_2 regions” will be used for all regions for improved readability. For each of these GID-2 regions a separate energy system model was defined containing the components shown in“[2] Figure 22.

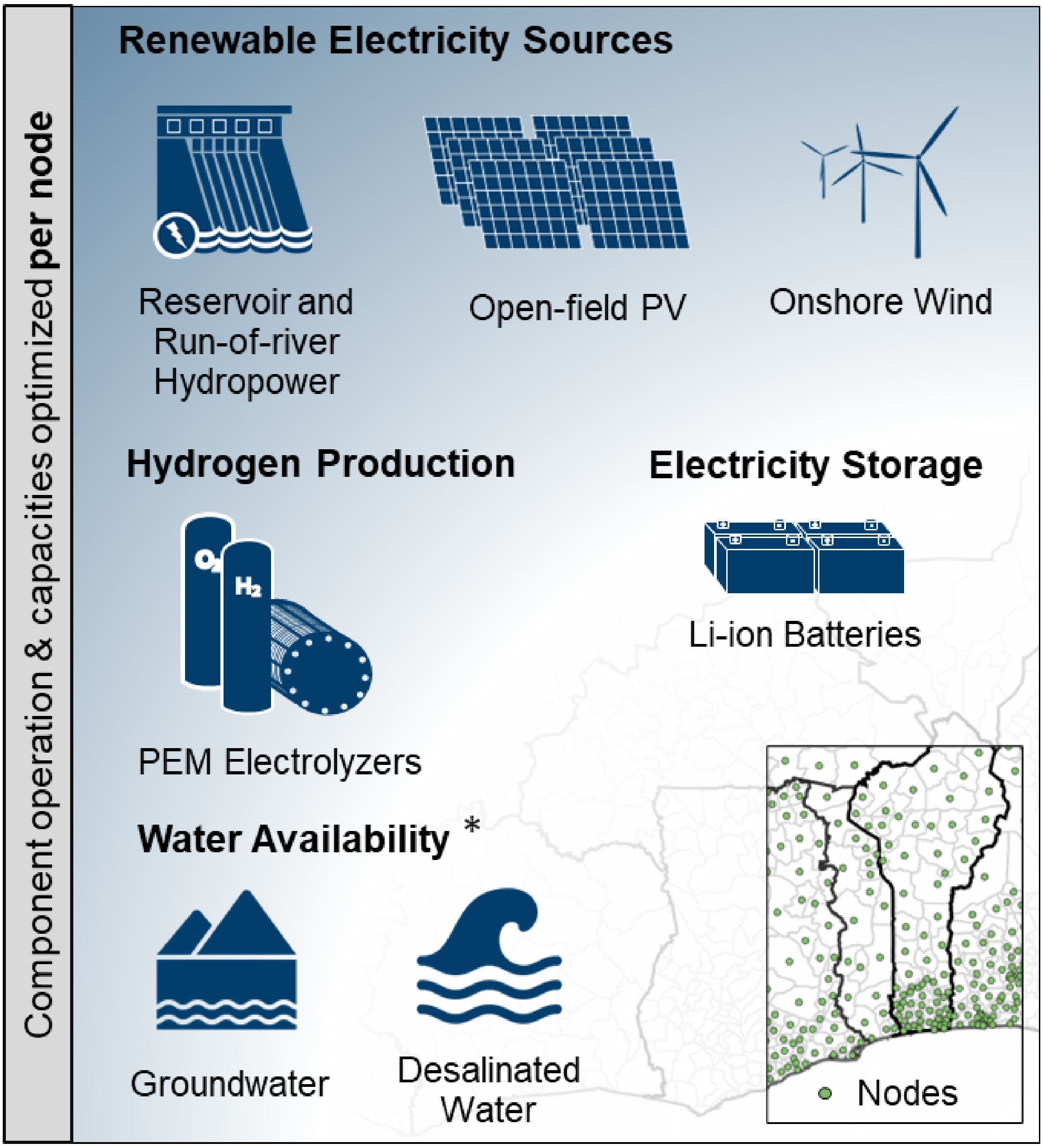


Figure 22 Set of components added to each node of the model.* Icons made by Ayub Irawan and orvipixel from www.flaticon.com

“To determine the maximum amount of hydrogen that may be produced in each GID_2 region and to calculate the related levelized cost of hydrogen (LCOH), an independent energy system model was created for each region and optimized using the ETHOS.FINE (Framework for Integrated Energy System Assessment) optimization framework within the ETHOS model suite. The optimization framework was previously described by Welder et al. [70] and Groß et al. [71] and a publicly accessible version of the framework can be obtained from Github (FINE, 2024).

In the developed ETHOS.FINE model, each region is represented as one node, and an energy system is optimized for each node with several components. Onshore wind turbines, open-field PV parks, and existing hydropower plants were utilized as electricity sources, PEM electrolysis as green hydrogen production technology, and Li-ion batteries for electricity storage. Their assumed techno-economic parameters required for the optimization are listed in Table 2. For all these components the optimal capacity and operation in hourly resolution is optimized, while fulfilling an exogenously assumed gaseous hydrogen demand. The exogenous demand for hydrogen at each node incrementally raised in increments of 6% on average until the node's maximum hydrogen production capacity was depleted. The linear optimization minimized the annual cost of the necessary hydrogen production system and determining the most cost-effective technology portfolio for each node. The renewable energy potential for onshore wind, open-field PV and the existing and planned hydropower capacities were aggregated from individual plant-level time-series to LCOE clusters per each GID_2 region. The LCOE range for wind turbines and PV within each GID_2 region was therefore split into 10 evenly spaced bins for each technology and the capacity-weighted average time series was calculated for each bin. In case of wind, the number of regional LCOE clusters was doubled to account for the high variation of wind potentials within even small geographical extent. As hydropower relies on few locations with possibly very different characteristics, especially when not depending on the same catchment area, the hydropower locations were not further clustered.“[2]

Table 1 Techno-economic assumption parameters for each component [72] [39]

Parameter	**Investment [€/kW] respectively [€/kWh]**				**Fix O&M [% of CAPEX]**	**Variable O&M [€/kWh]**	**Economic Lifetime**
Year	2020	2030	2040	2050	2020 - 2050	2020 - 2050	2020 - 2050
Onshore Wind*	1290	1130	1050	1000	2.5	-	20
Open-field PV**	690	450	370	320	1.7	-	20
Run-of-river Hydropower	1000	1000	1000	1000	2.5	0.005	40
Reservoir Hydropower	1700	1700	1700	1700	2.5	0.005	40
PEM Electrolyzer	800	500	400	350	3	-	10
Li-ion Batteries	311	175	153	131	2.5	-	15

*Onshore wind turbine values correspond to a reference turbine (capacity: 4.2 MW, rotor diameter: 136 m, hub height 120 m, avg. wind speed: 6.7 m/s) forming the basis for the optimized turbine designs

The projected local electricity and hydrogen demand should be prioritized over export countries to ensure local living standards and development as well as the acceptance of potential export schemes beyond local demand62. Therefore, local electricity and hydrogen demand is deducted from national hydrogen potentials in a subsequent step.” 2

1.6 Socio-political context and development opportunities

The socio-political context for green hydrogen feasibility is assessed via vision assessment and composite indicators (Cis) at the national level, while the development opportunities and local impact of green hydrogen deployment is assessed through regional composite indicator (CI).

1.6.1 Socio-political context and vision towards a green hydrogen economy

“The study involved a literature review at the outset to assess the research on visions and expectations and the approaches used to frame the survey of partners and subsequent data analysis. This survey was distributed to the various national teams associated with the two participating African science centers, WASCAL in West Africa and SASSCAL in Southern Africa. In general, the national teams consisted of directors or staff from energy-related ministries or companies, as well as researchers and professors from universities. The survey included seven sets of questions focusing on general expectations and concerns about renewable energy, access to electricity, and hydrogen, with single or multiple-choice questions and space to write answers. Subsequently, the data of the 72 participants was analyzed using qualitative content analysis, inspired by Philip Mayring (2000), and quantitative analysis of the multiple-choice questions. To structure the responses and make them more comparable between the different levels, the study used a categorical approach, with three categories: general, national, and international visions. In this case, 'general' refers to universal application to future possibilities, while 'domestic' refers to expectations for one's own country or region. Additionally, 'out-of-state' visions refer to ideas for what should happen abroad.” [62]

The following Figure 23 illustrates the research approach employed in this study. Firstly, it depicts the literature and methods that were reviewed. Secondly, what research material was at the core of the study, which led to the third part, the visions of the African partners and Germany, which were compared.

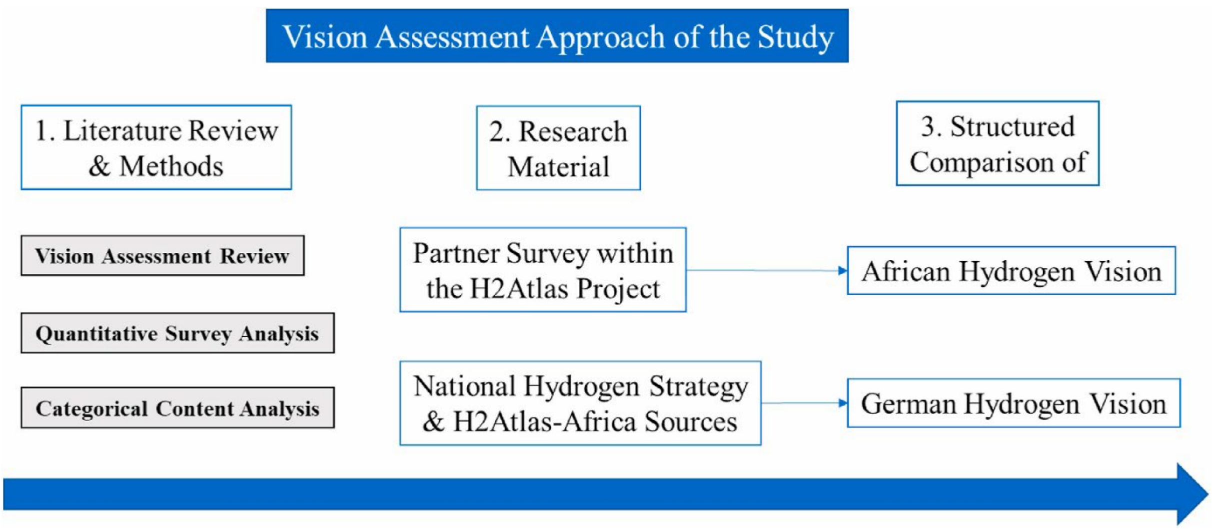


Figure 23 Methodology and conceptual framework for hydrogen visions assessment. [62]

1.6.2 Socio-political framework for green hydrogen feasibility

The feasibility of investment in green hydrogen is performed using an index decomposed on three sub composite indicators (Figure 24).

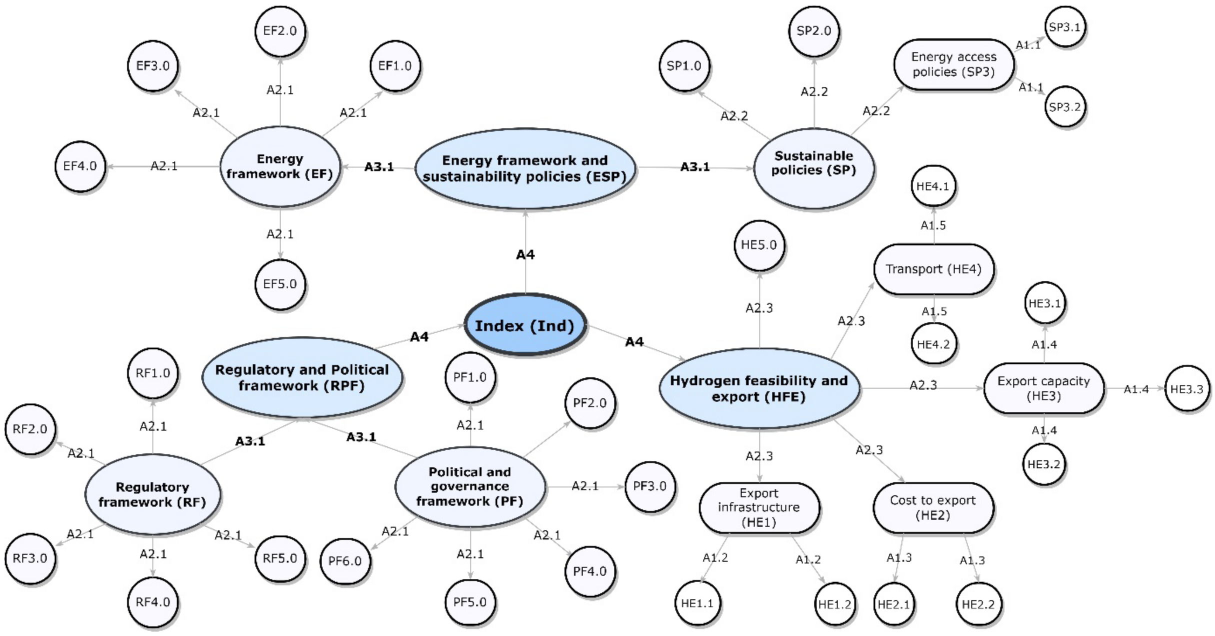


Figure 24 National Framework Index structure. [9]

"The first sub-index Energy framework and sustainability policies (ESP) indicators are presented in Table 3 and analyze current energy framework (EF), and sustainable development goals (SDGs) policies to promote them (SP). The first one (EF) focuses on the performance of energy systems across different countries, considering aspects like energy security, efficiency, intensity, impacts on health, and the role of renewable energy sources. The second one (SP) quantifies the impact of various countries' and regions' policies on promoting renewable energy, mitigating climate change, and promoting energy access.

The second sub-index Hydrogen export feasibility (HEF) indicator quantifies the feasibility of exports, considering aspects such as export and transport. It includes the cost and ease of export as well based on the Doing Business methodology and existing export infrastructure.

Finally, the regulatory and political framework sub-index (RPF) assesses locations highly favorable and secure for green hydrogen project investment. This includes two composites' indexes assessing investment and governance scores based on the Doing Business methodology and the World Governance Index normalized to the region."[9]

Table 2 Dimensions, categories, and indicators of national framework index. [9]

Indicator		Components	Unit	Source
EF1.0	Energy import dependency	Total energy produced / Total energy supply	%	UN
EF2.0	Transformation efficiency	Total final energy demand / Total energy supply	%	UN
EF3.0	Dependency on traditional biomass	Total final energy demand from traditional biomass / Total energy demand	%	UN
EF4.0	Use of renewable energy	Total renewable electricity generation / Total electricity generation	%	IRENA
EF5.0	Investments in renewable	Financial flows for clean and renewable energy production	%	SDG7
EF6.0	Energy intensity per economic activity	Total energy supply / Gross domestic product	kWh/USD	SDG7
SP1.0	Nationally determined contribution	NDCs means (conditional, unconditional) NDCs version (first, updated or second) NDCs scope (Energy, waste, AFOLU, IPPU)	-	IEA
SP2.0	Energy policies	Mention of support to renewable energy	%	[1]
SP3.1	Access to electricity feasibility	Historical 2000-2020 electricity access change Electricity access targeted by national policies	-	SDG7
SP3.2	Level of access	Historical 2000-2020 level of access change Minimum level of access targeted by national policies		[1, 2]
SP3.3	Access to clean fuel feasibility	Historical 2000-2020 electricity access change Electricity access targeted by national policies	-	SDG7 *
HE1.1	Border trade	Trading across neighboring border score		DB
HE1.2	Harbors	Ports organized by size, and numbers		
HE2.1	Border regulation	Time to cost for compliance with customs regulations	USD	DB
HE2.2	Compliance	Time to cost for documentary requirements	USD	DB
HE3.1	Fuel exports	Fuel exports (% of Merchandise exports)	%	DB
HE3.2	Export capacity	Total merchandise export capacity HE3.2		DB
HE3.3	Regional export	Share for export to developing economies	%	DB
HE4.1	Transportation score	Transport composite Index of Africa Infrastructure Development Index (AIDI)		AFDB
HE4.2	Grid score	Electricity composite Index of AIDI		AFDB
HE4.3	Logistic score	Logistic index HE4.2		DB
HE5.0	Security	Security and safety transportation sub–Ibrahim Index	-	IIAG
RF1.0	Registration	Registering property (DB17-20 methodology) - Score	-	DB
RF2.0	Contracts	Enforcing contracts (DB17-20 methodology)	-	DB
RF3.0	Regulation	Regulation (DB17-20 methodology) - Score	-	DB
RF4.0	Permit	Dealing with construction permits (DB16-20 methodology)	-	DB
RF5.0	Investment	security and safety of investment	-	IIAG
PF1.0 **PF2.0** **PF3.0** **PF4.0** **PF5.0** **PF6.0**	WGI sub-index	Control of Corruption: Estimate Government Effectiveness: Estimate Political Stability and Absence of Violence/Terrorism Regulatory Quality Rule of Law: Voice and Accountability: Estimate	-	WGI

[1] Mention of support to renewable energy and level of access are based on partner circulated energy policies
[2] Level of access take into account surveys partners preferences regarding access definition.

1.6.3 Mapping local impact of green hydrogen projects

“This study's research approach was developed using the OECD checklist for the reflective construction of composite indicators (OECD et al., 2008) and its main components are summarized in Table 4. Data sets were selected with a focus on sustainable development, identifying the sustainable development goals (SDGs) most influenced by green hydrogen projects, either directly or indirectly.

Firstly, the more direct impact would be on Goal 7 (affordable and clean energy) and Goal 8 (decent work and economic growth), as an increase in hydrogen projects leads to a concurrent increase in renewable energy capacity. Secondly, green hydrogen projects could indirectly affect goals 1 (no poverty), 2 (zero hunger), 3 (good health and well-being), and 13 (climate action). Economic growth and employment, ideally, could contribute to poverty reduction, enabling more individuals to afford food and healthcare. Additionally, the increase in green energy and clean fuel would have a positive impact on areas affected by indoor pollution and hazardous fossil fuel emissions, aligning with the imperative for climate action.

Further research, complemented by spatial data analysis, was conducted to assess the feasibility of socio-economic indicators in measuring the defined SDGs. The study also incorporated the prioritization of social development goals based on local visions, as revealed in surveys conducted during the project[62].

Table 3. Employed socio-economic composite indicators.

Sub-category	Indicator	Components	Unit
Access to Energy (AE)	Access to electricity	Population without access to electricity per GID 2 region’s area	Capita/km²
Macroeconomic effects (ME)	Direct employment factor	Labour employment potential per installed capacity and per GID 2 region’s area	Jobs/ (Mwp*km²)
Other indirect effects (OE)	Dependence on traditional biomass	Population using traditional biomass per GID 2 region’s area	Capita/km²
	Population living under the poverty line	Share of the population under the poverty line	%

To mitigate concerns about missing or insufficient data during both data selection and subsequent analysis, a robust approach was adopted, involving the collection and cross-checking of data from diverse sources. The selection process encompassed compiling single data points and historical records within the African context to ensure the most reliable data for the chosen indicators.

Mapping Energy Access

The indicator for access to energy began with the recognition that data on energy access is typically available only at the national level for both urban and rural areas [74]. By leveraging population density data, urbanization could be defined. To ascertain the regional distribution of the population without access to energy, a correlation between density and access was established for each ADM-2 region and validated using data from [75]:

$$I_1 = \left(EAu^{ADM-1} * \sum_{ADM-2} PoPu + EAr^{ADM-1} * \sum_{ADM-2} PoPr \right) / Area$$

This distribution was calculated using the urban energy access rate at the ADM-1 level ($\mathrm{EAu}^{\mathrm{ADM-1}}$), the rural energy access rate at the ADM-1 levels ($\mathrm{EAr}^{\mathrm{ADM-1}}$), combined with the total urban and rural population per area at the ADM-2 level (PoPu *and* PoPr *respectively*).

Mapping Local Employment
Employment figures were calculated using regional multipliers for various renewable energy and power-to-hydrogen technologies. The unemployment rate multiplied by the regional labor force available in ADM-2 regions was used to calculate employment for the area, as described by the following equation:

$$\mathrm{I}_2 = \mathrm{RM} * \left(\underset{\mathrm{RES}}{\mathrm{average}}\,\mathrm{EF} + \mathrm{EF}_{\mathrm{PtH}}\right) * \mathrm{UP} * \mathrm{Labor}/\mathrm{Area}$$

Here, RM is the regional multiplier, $\underset{\mathrm{RES}}{\mathrm{average}}\,\mathrm{EF}$ represents the global average employment factor for various renewable energy sources, including wind, solar, and hydro, and *the latter representing the global employment* factor for power-to-hydrogen technologies. The product is then multiplied by UP (unemployment rate) and Labor (total labor force, i.e., the population between the ages of 15 and 64).

Other Impacts
The methodology for calculating the population using traditional biomass mirrored that used for mapping energy access but utilized clean fuel access numbers instead [74]. Regarding the poverty indicator, the share of the population under the poverty line for ADM-2 regions was considered, like ADM-1 regions [76].

Normalization and Weighting
Various normalization techniques, as per OECD guidelines [77], were applied to the set of indicators. Standardization (or z-scores) was found to best reflect the indicator scores. Equal weighting was applied to direct effects, with less importance given to the indirect ones, justified by the absence of other known means of weighting [78]. Arithmetic means were used for aggregating various composite indicators and sub-indexes."[2]

1.7 Result dissemination via web-based geographical user interface

"To ensure widespread accessibility of the study's findings, we developed a user-friendly"[2] geographical user interface "GUI as a webGUI as a web application (Jülich Systems Analysis, 2024). The GUI showcases the obtained results, presenting them on a map through color-coded layers where visualization of various factors influencing the potential of green hydrogen in select regions across Africa is facilitated. Users can also engage with the map interface to delve into the data, enabling them to glean insights that foster comprehension of socio, technical and economic aspects of it. The GUI architecture leverages Docker-based containerization (Docker, 2024), which facilitates a modular and scalable application structure. The frontend employs React (React, 2024) and utilizes the Mapbox API (Mapbox, 2024) to provide dynamic mapping functionalities, allowing users to explore complex geographical data intuitively. The backend integrates Node.js (Node.js, 2024) for server-side operations, paired with a PostgreSQL database enhanced with PostGIS (PostGIS, 2024). This setup effectively manages and queries spatial data, supporting advanced spatial queries essential for the study. A reverse proxy via Nginx (Nginx, 2024) optimizes deployment and enhances performance by managing traffic efficiently. To accurately handle and display geographic data, we employ various software solutions including Geokit (GeoKit, 2024), GeoPandas (Joris Van den Bossche et al., 2024), and QGIS (QGIS.org, 2024). These tools guarantee precise geographic positioning of the data through established standards like EPSG:3857, also referred to as Web Mercator (European Petroleum Survey Group Geodesy, 2020), and EPSG:4326, commonly known as WGS84 (European Petroleum Survey Group Geodesy, 2022). This framework guarantees a functional and user-friendly GUI that maintains precise and informative visualizations. It enables effective communication of complex data, enhancing understanding of green hydrogen potential across regions. Through this advanced GUI, stakeholders access crucial data, aiding decisions on sustainable energy development in Sub-Saharan Africa.“ [2]

2. Results

The following results are directly taken from Winkler et al.[1]. If you want to use them please cite the respective reference.

2.1 Land eligibility

The land eligible for the placement of open-field PV and onshore wind are determined after a careful land eligibility assessment. This entails accounting for all the buffer values and keeping to the local land use preferences as defined by the local authorities.

2.1.1 Land eligibility assessment for open-field photovoltaic and onshore wind turbines

“The local preferences for the set of 33 land eligibility criteria, collected and processed accordingly are shown in Figure 3 with buffer values normalized per criterion. The highest values per criterion are represented by 1 while the lowest are represented by 0. The absolute values of the buffer values received and subsequently applied are listed in the supplementary Table S1 and Table S2. Each gray dot in the figure represents the buffer value received from the countries that responded to the survey. The distribution of local preferences for each criterion highlights the different inclinations of regional stakeholders, including community members, government agencies, and international institutions in each country.

When comparing the buffer values for open-field PV and onshore wind turbines, it is evident that open-field PV has greater variations. In particular, the buffer values for the criteria "Airports", "Historical Sites", "Military Areas", "Natural Habitats", "Biospheres", "Bird Areas", and "Natural Monuments" show the largest distributions. Conversely, the buffer values selected for onshore wind show the largest deviations for the criteria "Military Areas", "Coastline", and "Protected Landscape".” [1]

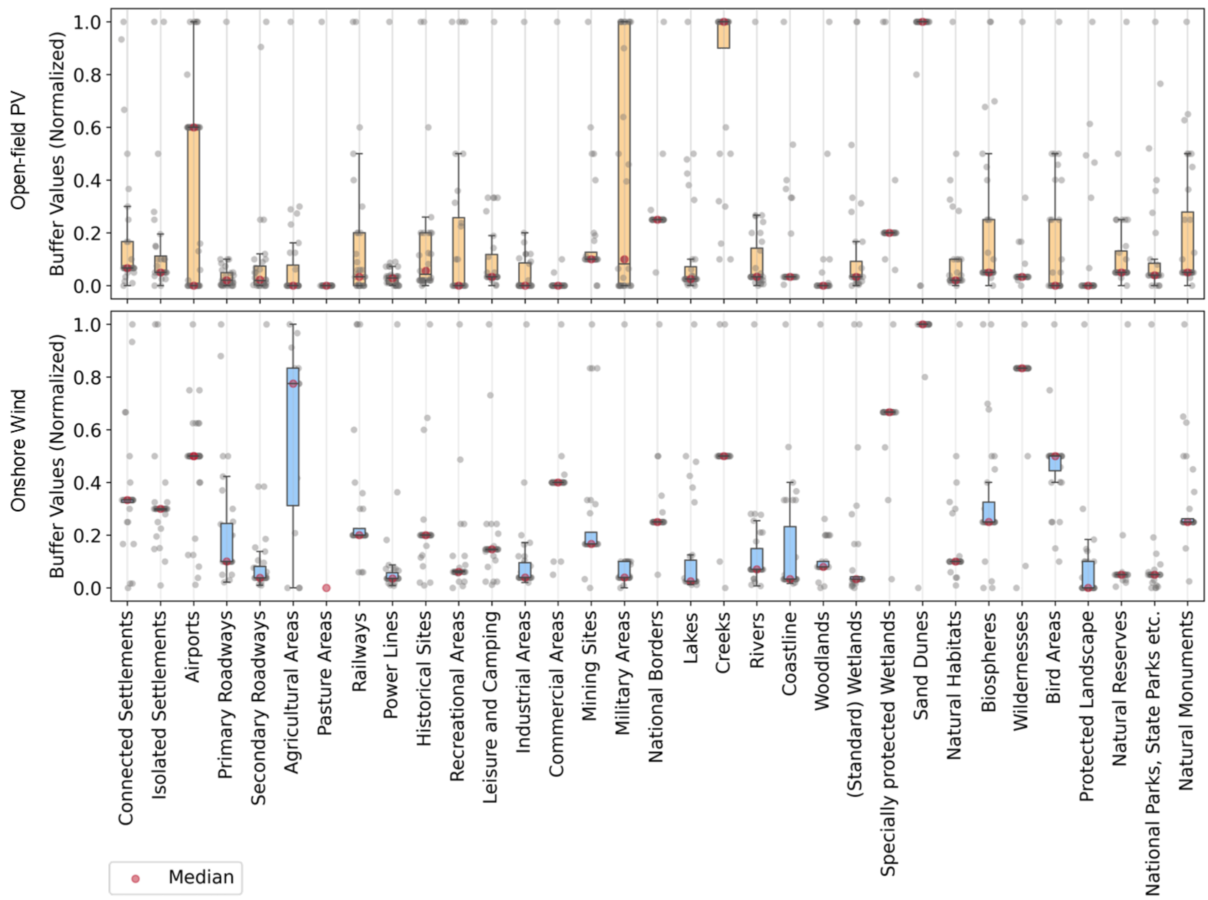


Figure 25 Distribution of buffer values received for each criterion from partner countries and their resulting medians [1]

“In order to gain a comprehensive understanding of the process of determining a country's total land eligibility, it is necessary to examine each individual land exclusion criterion separately. Using this method, it becomes clear that certain criteria, such as "Woodlands", "Isolated Settlements", "Connected Settlements", "Agricultural Areas", and "Pasture Areas", lead to the exclusion of large areas of land (over 40 - 50%) when considering open-field PV” [1] (see Figure *26*). “On the other hand, for onshore wind, the majority of excluded land area (over 40 - 50%) in most countries can be attributed to "Woodlands" and "Isolated Settlements", as illustrated in” [1] Figure 27. “Very low overall eligibilities in countries such as Guinea resulted from the combined high exclusions of land area by criteria such as “Agricultural Areas”, “Pasture Areas“, “Secondary Roadways” and “Woodlands”.[1]

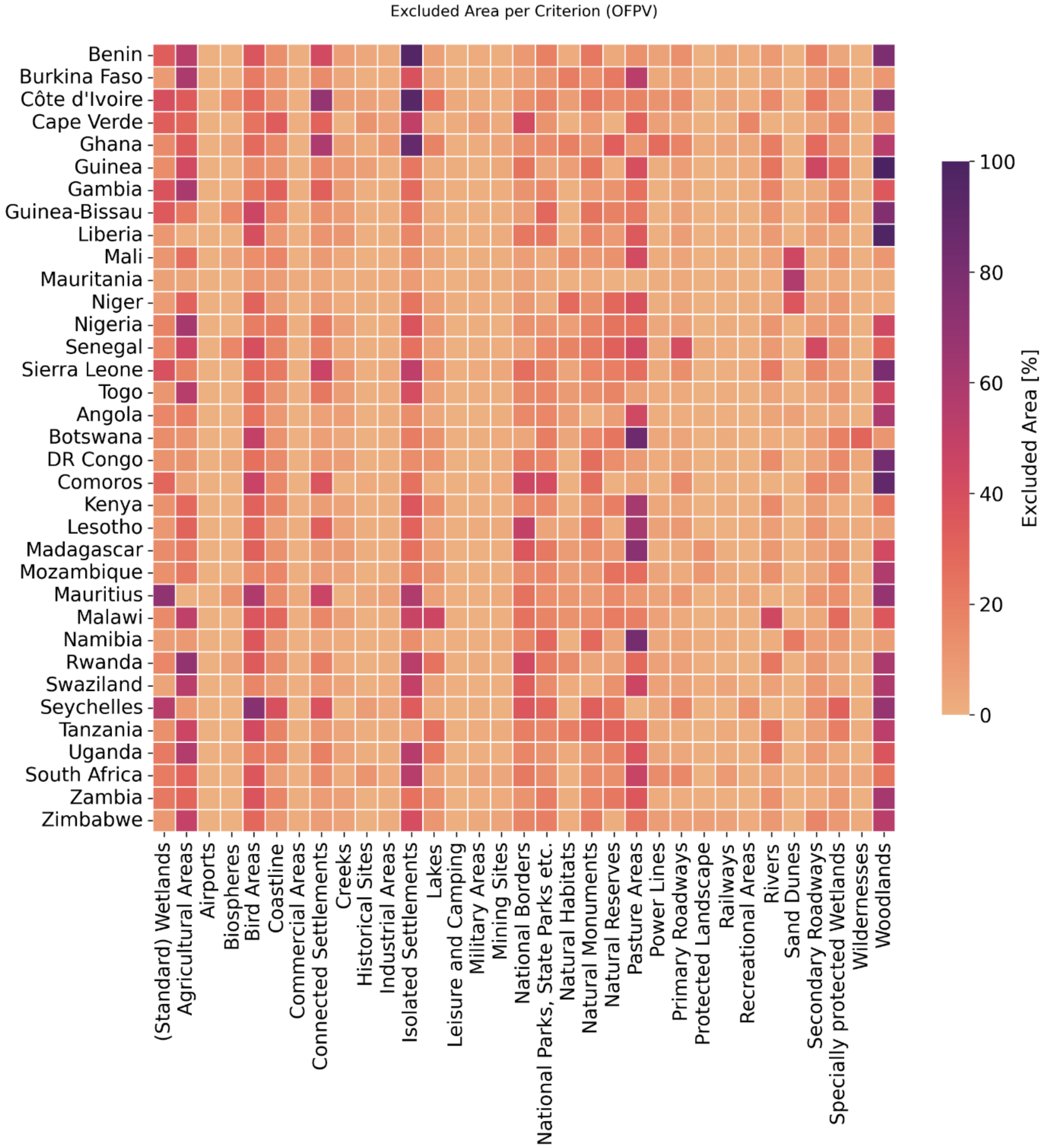


Figure 26 Excluded area per criterion and country in western, southern, and eastern Africa for open-field PV. [1]

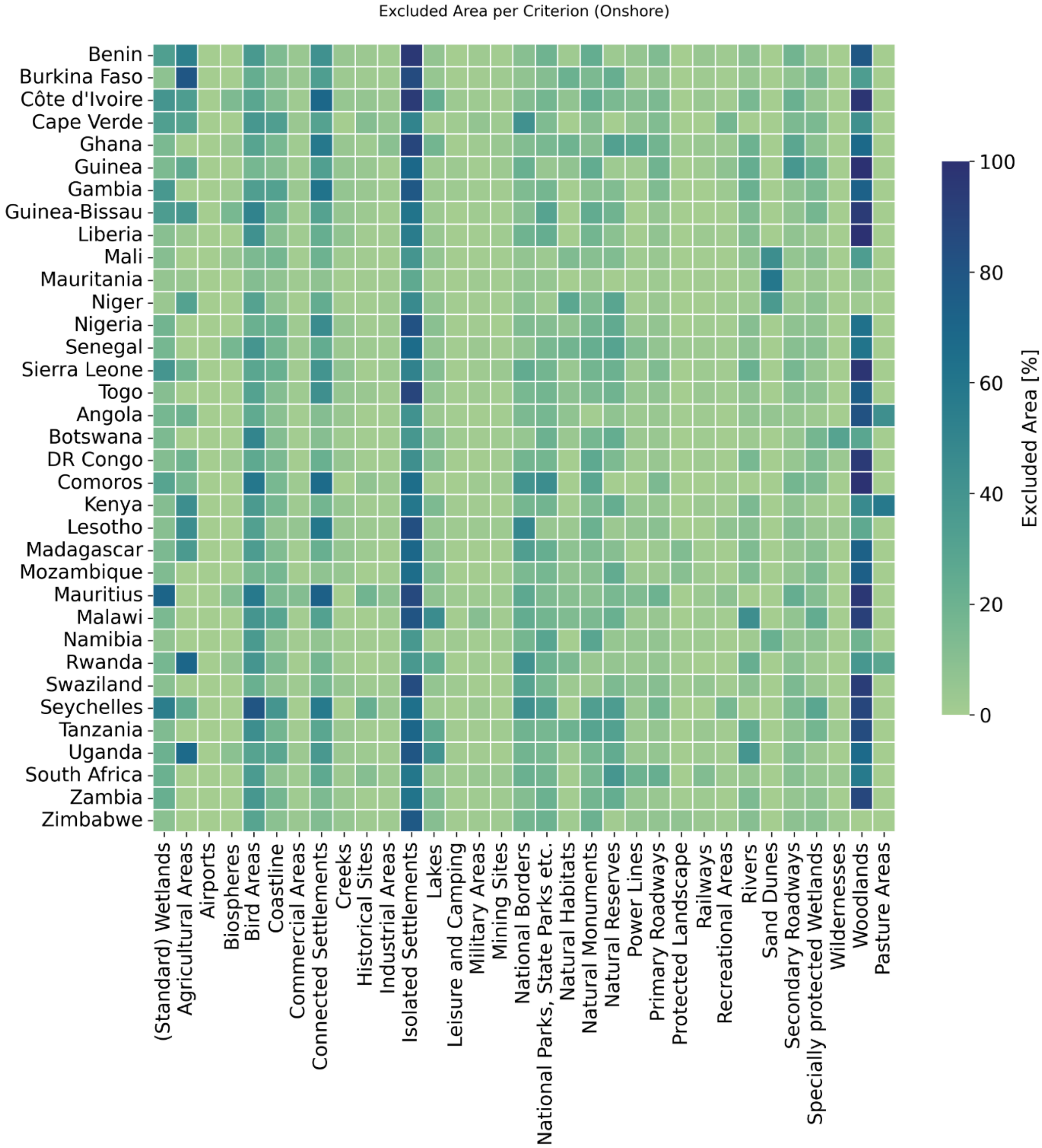
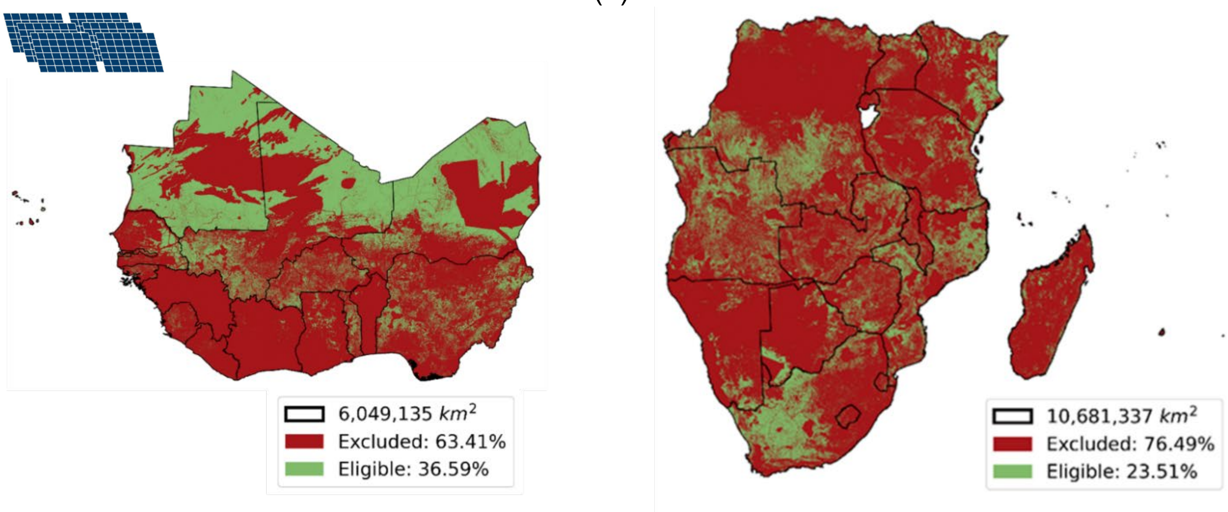


Figure 27 Excluded area per criterion and country in western, southern, and eastern Africa for onshore wind. [1]

Figure 28 (a) "provides an overview of the potential land areas identified as potentially eligible for open-field PV parks in West, Southern and East Africa. In the case of West Africa, approximately 36% of the available land is eligible for open-field PV, with larger eligible areas in the northern part of the region and smaller patches throughout the southern part. Eligibility rates per country vary from ~0.1% in Guinea to around 50% in Niger, Mali, and Mauritania. In Southern and East Africa, larger areas of eligibility are found in the central and southern parts of the region. Approximately 24% of the available land in Southern and East Africa is eligible for open-field PV, with eligibility rates per country ranging from ~0.1% in Seychelles to about 36% in Mozambique. In both regions, protected forests and pastures are a major constraint on eligible land, while sand dunes in West Africa also exclude large areas from eligibility. " [1]

(a)



(b)

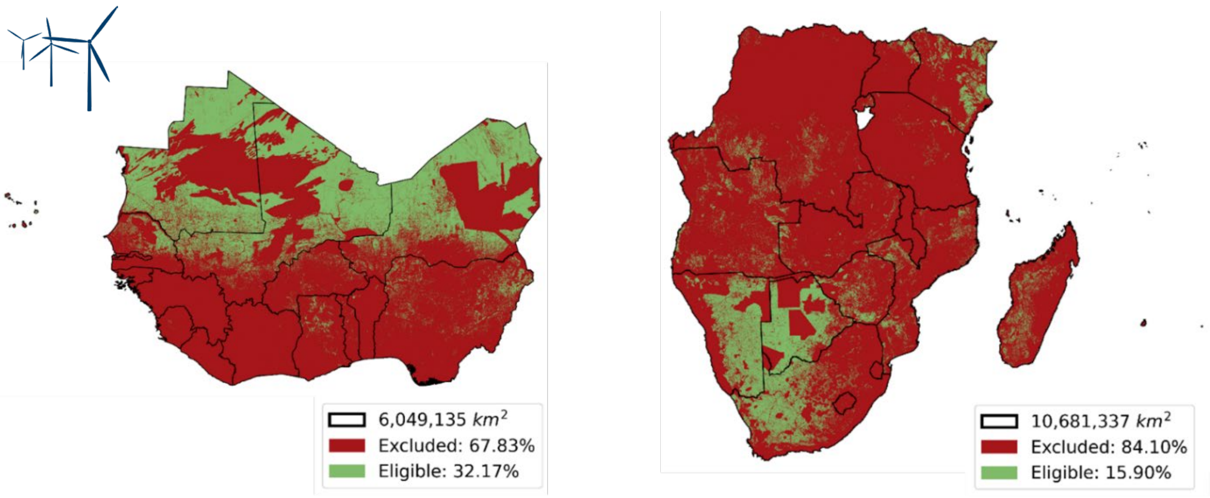


Figure 28 Land eligibility within west (left) and south-eastern Africa (right) according to the local preferences for (a) open-field PV and (b) onshore wind parks [1]

Figure 28 (b) "shows the land area eligible for onshore wind turbines, taking into account local preferences. West Africa has an eligibility rate of 32%, while Southern Africa has an eligibility rate of approximately 16%. Within West Africa, eligibility ranges from 0.06% (in Côte d'Ivoire and Guinea) to about 55% (in Mauritania). In southern and eastern Africa, eligibility rates range from 0% (in the Seychelles) to about 50% (in Botswana), with particularly high eligibility rates in the border region between Namibia, Botswana and South Africa. It's worth noting, however, that in both cases most of the largest land areas are excluded due to isolated and connected settlements, forests, and pastures. Detailed eligibility results per country and per technology are summarized in" [1] Table 5. "These land eligibility results represent potential limited by technical, sociological and environmental criteria, hereafter referred to as "geographic potential". In generally, it is not possible to exploit them to their maximum. It should be noted that economic exclusions were deliberately not considered here, as the economic viability of renewable energy installations depend significantly on the systemic context. A location with a given high energy cost may be uneconomic in a country or region with abundant low-cost resources and low demand, but may be critical in a country with high demand and limited potential and limited cross-border transmission capacity." [1]

Table 4 Overall land eligibility for countries in western, southern and eastern Africa [1]

Country	Onshore Wind Eligi-blity		Open-field PV Eligi-blity	
	%	km^2	%	km^2
Benin	0.7	793	0.7	786
Burkina Faso	6.1	16652	25.5	69790
Cote d'Ivoire	0.1	203	0.8	2515
Cape Verde	22.1	905	21.2	866
Ghana	5.8	13749	6.5	15484
Guinea	0.1	143	0.1	299
Gambia	4.6	493	21.4	2278
Guinea-Bissau	0.2	68	13.2	4471
Liberia	0.002	2	2.2	2084
Mali	50.5	632070	48.7	609590
Niger	48.4	573744	49.9	590072
Nigeria	8.9	81385	22.3	202245
Senegal	18.4	36188	21.7	42787
Sierra Leone	0.5	366	8.1	5849
Togo	2.5	1437	33.5	19099
Mauritania	55.6	579261	63.2	585476
Angola	10.5	131131	33.9	1270166
Botswana	50.4	291008	12.7	220637
DR Congo	3.9	92003	21.0	1465824
Comoros	0.2	3	3.3	164
Lesotho	1.5	457	7.9	7223
Madagascar	13.3	78669	9.2	162343
Mozambique	11.7	92247	35.5	839530
Mauritius	0.2	5	5.9	362
Malawi	0.03	30	14.4	50983
Namibia	44.8	369242	9.1	224865
Swaziland	1.2	209	13.4	7009
Seychelles	0	0	0.1	2
Tanzania	1.7	15544	17.3	488083
South Africa	29.8	363378	34.9	1277897
Zambia	5.2	38755	24.6	553623
Zimbabwe	19.4	75937	23.1	271203
Kenya	20.3	117872	31.2	151617
Rwanda	9.0	2275	6.0	153
Uganda	6.3	14950	23	39149

2.1.2 Land eligibility assessment for geothermal powerplants in Kenya

"Due to the central role of geothermal energy in Kenya's energy strategy [79] the study also assessed the potential for geothermal power. The land eligibility assessment revealed an average eligible land area of 42% across the country. Most of these areas are concentrated in the sparsely populated north and northeast of the country. Exclusions in the southwest and south are mainly due to human settlements, where a relatively large safety distance of 2 km should be maintained to avoid structural damage from reservoir stimulation. The central to western part of the country is also ineligible due to mountain slopes, and throughout the country large contiguous exclusion zones for nature protected areas can be seen" [1] (Figure 29). "Areas with high and extremely high water stress according to the Aqueduct water risk atlas [80] were also excluded due to the water consumption of petrothermal plants during stimulation and water losses during operation [81]." [1]

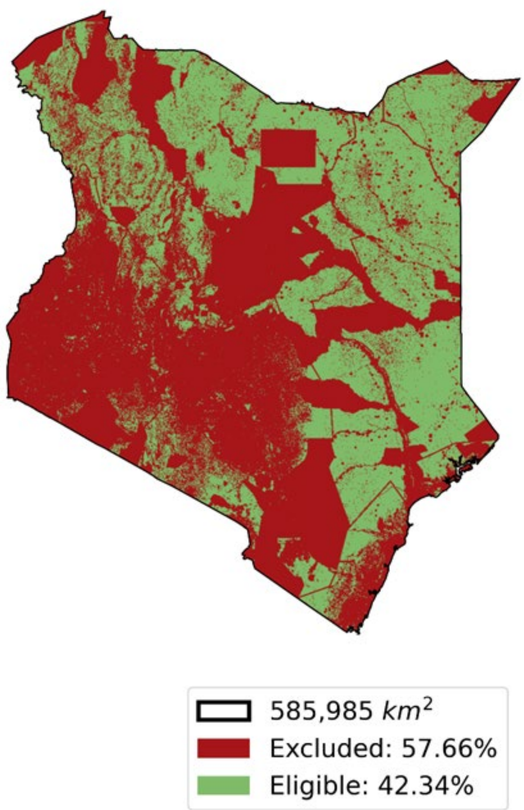


Figure 29: Land eligibility for geothermal power plants in Kenya[1]

2.2 Renewable energy potentials

"The following section discusses the available capacity potential for the major renewable energy sources, namely open-field PV, onshore wind, hydropower, and geothermal. In addition, the levelized cost of electricity patterns are analyzed to shed light on the underlying drivers and connections." [1]

2.2.1 Open-Field Photovoltaics

"The total installable capacity potential of open-field photovoltaics amounts to 107 TW in West Africa and to 123 TW in Southern and East Africa respectively. The pattern in Figure 30 reflects the land eligibility restrictions that were discussed in Section 3.1.1 of Winkler et al[1]. The vast majority of the potential is concentrated in the desert regions of the Sahara and the Nama Karoo in South Africa, extending into Namibia and Botswana. Other notable concentrations of capacity are found in the scrublands and bushlands of Angola, extending into the southern provinces of the Democratic Republic of Congo." [1]

"While there is installable potential in all countries, there are some clear zones of greater installable capacity. For example, West Africa has the greatest accumulation of potential in its northern areas whereas Southern and East Africa have it in the south. Compared to these desert provinces, which reach the terawatt range, the capacity potential in most coastal and equatorial countries is much smaller by comparison. It should be noted, however, that the capacity potential is directly related to the available area of the country, which favors the potential in countries with large areas. In addition, densely populated countries tend to have less areas available for PV installations. These countries tend to be in southern West Africa and many equatorial countries. National aggregated potentials (see Appendix Section 1.A.2 of Winkler et al.[1] or on the online GUI [82]) should therefore always be consulted.

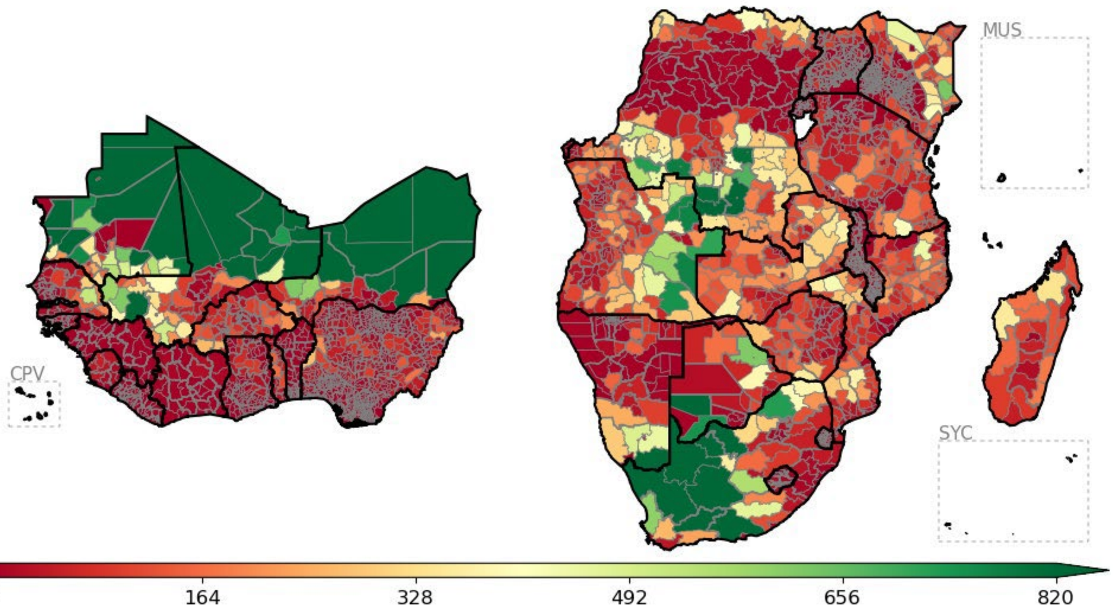


Figure 30 Open-field photovoltaics capacity potential [GW] in West (left) and Southern/East Africa (right). [1]

Based on the solar farm locations determined in the placement-distribution step after the land eligibility assessment, hourly time series and average energy yields were simulated for 20 years, using ERA-5 [28] and Global Solar Atlas[a] [83] weather data input. The average yield was then used together with the techno-economic parameter assumptions to calculate the levelized cost of electricity for each site, once for each reference decade from 2020 to 2050.[1]

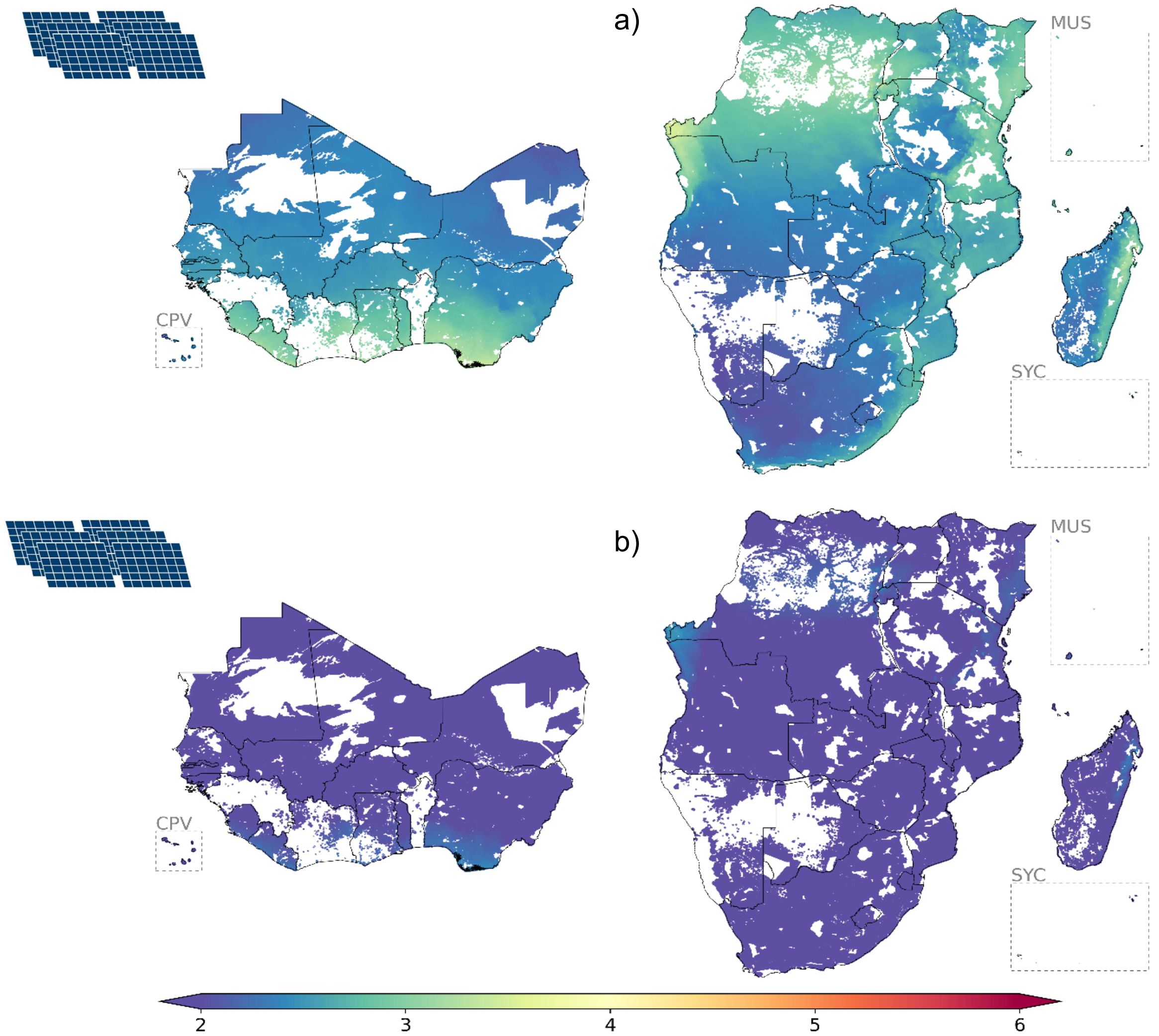


Figure 31 Levelized cost of electricity [Ct€/kWh] from open-field PV for two years: a) 2030 and b) 2050. [1]

“The plant locations in”[1] Figure 31 “clearly reflect the land eligibility patterns in”[1] Figure 28. “The simulation results reveal achievable levelized costs of electricity (LCOE) between 3.5 Ct€/kWh and 2 Ct€/kWh by 2030 in the best locations in the Nama Karoo ecoregion in South Africa and Namibia, extending into Botswana. In West Africa, the cheapest solar power can be produced in the northern desert regions of Niger and Mauritania. Full-load hours in this region can be 50% higher than along the southern coast, where clouds and higher precipitation near the equator are the main reasons for the lower energy yield [84]. The above difference translates into an additional 800 FLH/a or a reduction in levelized cost of up to 1.5 Ct€/kWh. This concentration of large available areas and high full-load hours leads to large-scale and low-cost solar electricity potential in the northern parts of West Africa, whereas the demand is mainly along the southern coast. In Southern and East Africa, reduced full-load hours resulting in higher LCOE can be observed near the equator, such as in the Congo Basin especially along the Congolese and northern Angolan Atlantic coasts. To a lesser extent this can be observed all

[a] “Data obtained from the Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP).”

along the Pacific coast as well. The Congo Basin can be explained by clouds and higher precipitation due to the ITZC[84] while the latter is caused by weather influences due to the Indian Ocean[85].

By 2050, the levelized cost of electricity are expected to decrease further by about 25%, or 0.5-1.0 Ct€/kWh, and then fall below the 2 Ct€/kWh mark in most regions throughout the study area. As a result, the LCOE difference between high- and low-cost regions is narrowed to approximately 1 Ct€/kWh, ultimately causing a progressive but slow reduction in the competitive advantage of the desert regions." [1]

2.2.2 Onshore Wind

"The total installed onshore wind capacity found is 15.4 TW in West Africa and 14.6 TW in Southern and East Africa respectively. Similar to open-field PV, onshore wind turbine capacity is concentrated in the sparsely populated and vegetated desert areas of northern West Africa and the arid border area between South Africa, Namibia and Botswana. Again, the capacity differences between regions are very large. Regions with limited potential, shown in shades of red to orange in "[1] Figure 32 "can reach up to 32 GW, which is a very high absolute value for a district-level region. Such regions exist in most countries, especially in Southern Africa." [1]

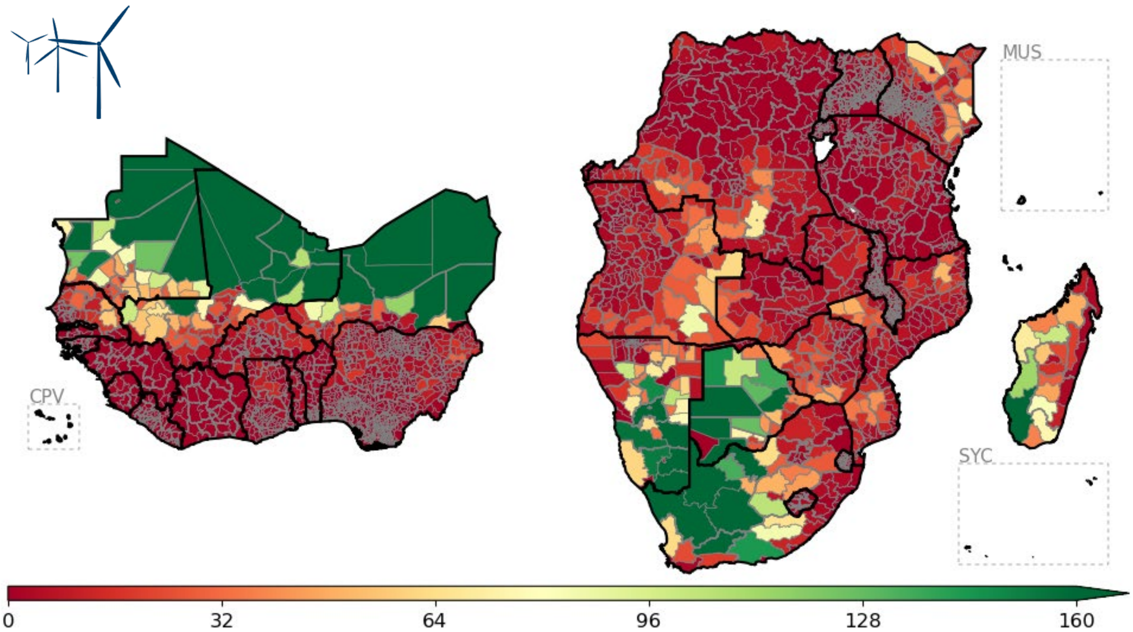


Figure 32 Onshore wind capacity potential [GW] in West (left) and Southern and East Africa (right) [1]

"An analysis of the simulated levelized cost of electricity for onshore wind shows that, on average, the LCOE is significantly higher than for solar PV in the same regions. The amount of onshore wind installations with LCOE in the same range as PV in 2030 (2 Ct€/kWh to 3.5 Ct€/kWh) is about 5% and 9% of the total (71.9 GW in West Africa and 1.3 TW in Southern and East Africa), respectively. In 2050, due to the proportionally larger capacity cost reductions expected for PV, the amount of onshore installations at the corresponding PV LCOE range (1.5 Ct€/kWh to 3 Ct€/kWh) is further reduced to 64.3 GW and 970 GW, respectively. This means that only about 5% or 9% of the regional onshore wind potential has a comparable to

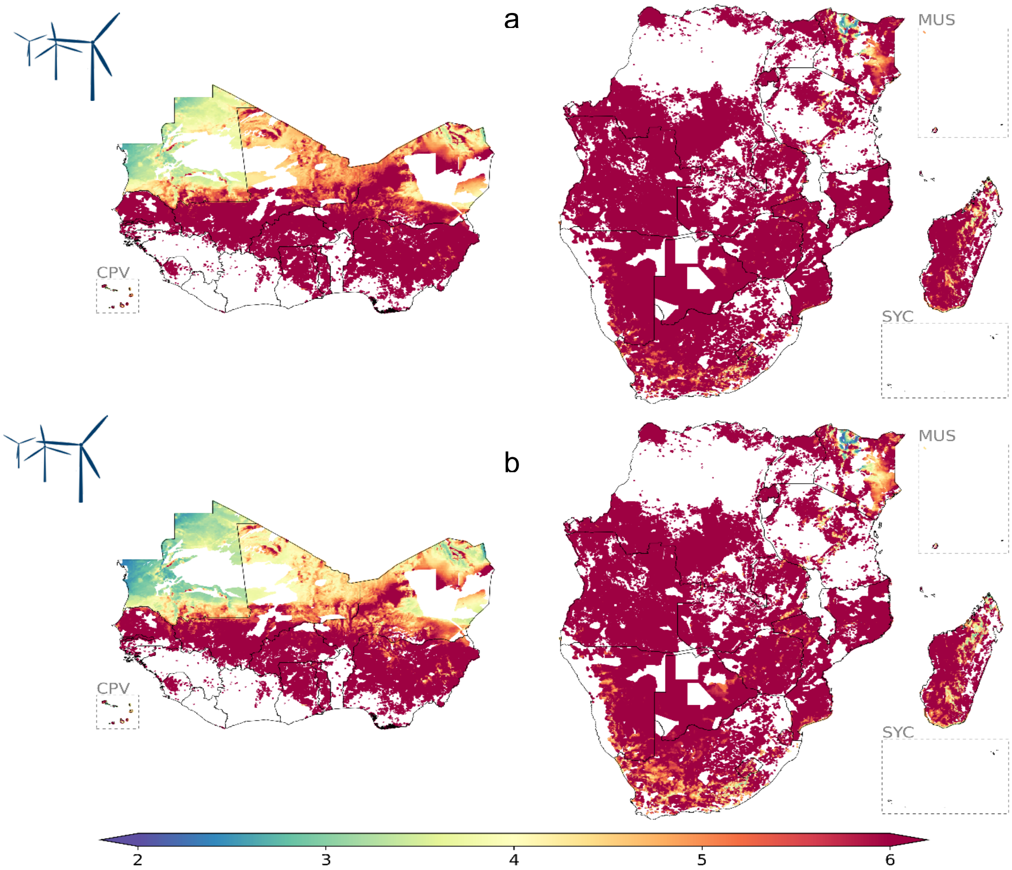


Figure 33 Levelized cost of electricity [Ct€/kWh] from onshore wind for two years: a) 2030 and b) 2050 [2]

PV[b], and its competitiveness is expected to decline over time. A more representative LCOE for onshore wind could be between less than 3 Ct€/kWh and 6 Ct€/kWh, where 10.9 TW can be installed in West Africa and 1.7 TW in Southern and East Africa in 2030. The remaining installations (30% in West Africa and 89% in Southern and East Africa) are located in unfavorable sites, with LCOEs more than doubles those of PV, although the latter is more constant across the study area”[1] (see Figure 33). “Interestingly, the region with the lowest wind power costs coincide in several cases with the best solar locations, most notably the northern West Africa, where large wind potentials meet very low LCOEs. Northwest Mauritania in particular has excellent wind resources, as do some sites in Kenya and Cabo Verde. To a lesser extent, this also applies to the north of Niger and Mali, several locations in South Africa and Madagascar. The subtropical belt along the southern coast of West Africa, similar to the Congo Basin, but also most of the landlocked regions of Southern and East Africa, except for those mentioned above, again has a very low wind energy yield. Towards 2050, the levelized cost of electricity again decreases for wind power plants averaging about -12%, although this is less significant compared to the solar cost reductions discussed above.” [1]

[b] This percentage refers to the for the total potential of the regions (Western and south and eastern Africa respectively) of Wind compared to PV installation capacity (not generation). Individual countries and sub-regions will have their own proportions.

2.2.3 Hydropower

"In contrast to open-field photovoltaics and onshore wind, the hydropower potential is mainly based on an assessment of existing hydropower plants together with locations under construction or in the planning stage[38]. In 2050, 23 GW were found in West Africa and 61 GW in Southern and East Africa. These future potentials represent almost 17 GW and 47 GW additional installations to the current hydropower fleet respectively. The chosen approach takes into account the fact that theoretical and technical assessments of hydropower potential tend to be overly optimistic, and that their realization would lead to significant environmental and social impacts[86]. By relying on practically relevant and hence feasible locations, a tradeoff between sensitive capacity additions and the advantages of hydropower for low-carbon energy generation could be achieved."[1]

Figure 34 "shows in general terms which countries have the most hydropower potential. It shows that countries that were previously less competitive are now the most prominent hydropower locations: DR Congo and Nigeria have the largest feasible capacities at approximately 22 and 10 GW, respectively. This can also be seen when comparing the location of hydropower projects in Figure 35." [1]

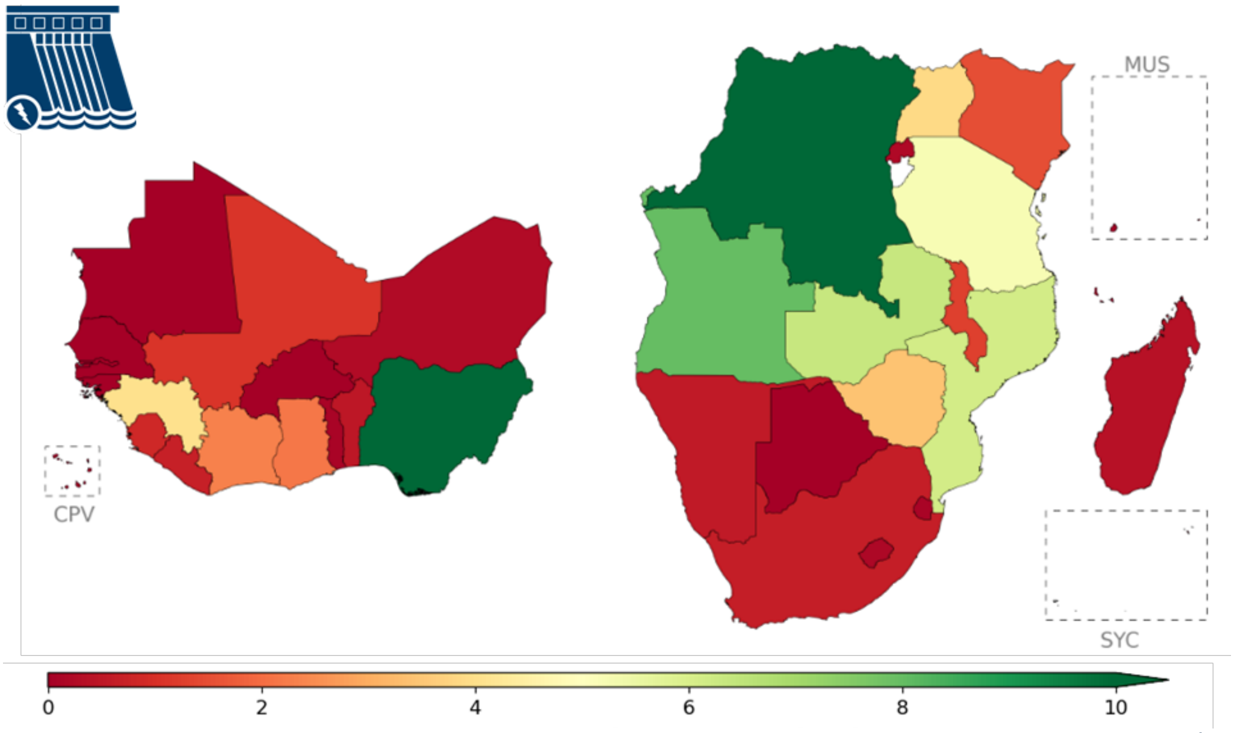


Figure 34 Hydropower capacity potential [GW] in 2030 in West (left) and Southern and East Africa (right) [1]

"Countries such as Angola, Zambia, Mozambique, and to a lesser extent Tanzania and the much smaller Guinea follow suit. While the precipitation surplus along the equatorial belt may be a limiting factor for solar potential [84] it is beneficial for hydropower potentials. Countries such as Ghana, Côte d'Ivoire, Zimbabwe, and Uganda also use of this opportunity. However, hydropower capacity in the previously low-cost regions of the Sahara, the entire southern tip of Africa, and Kenya is now marginal due to the predominantly arid climate in these regions.

Similar patterns emerge when looking at the achievable levelized cost of electricity"[1] (see Figure 35). "Since hydropower costs are assumed to be constant over time, there is no change in LCOE and only 2050, the year with the most locations, is shown in the figure. The lowest cost can be achieved in the Congo Basin, where hydropower is competitive with other renewable energy sources. The main reasons for this are the large discharge quantities in combined with comparatively low seasonality in the rainforest. Especially in the eastern Congo, the mountainous terrain also allows for favorable pressure heads. " [1]

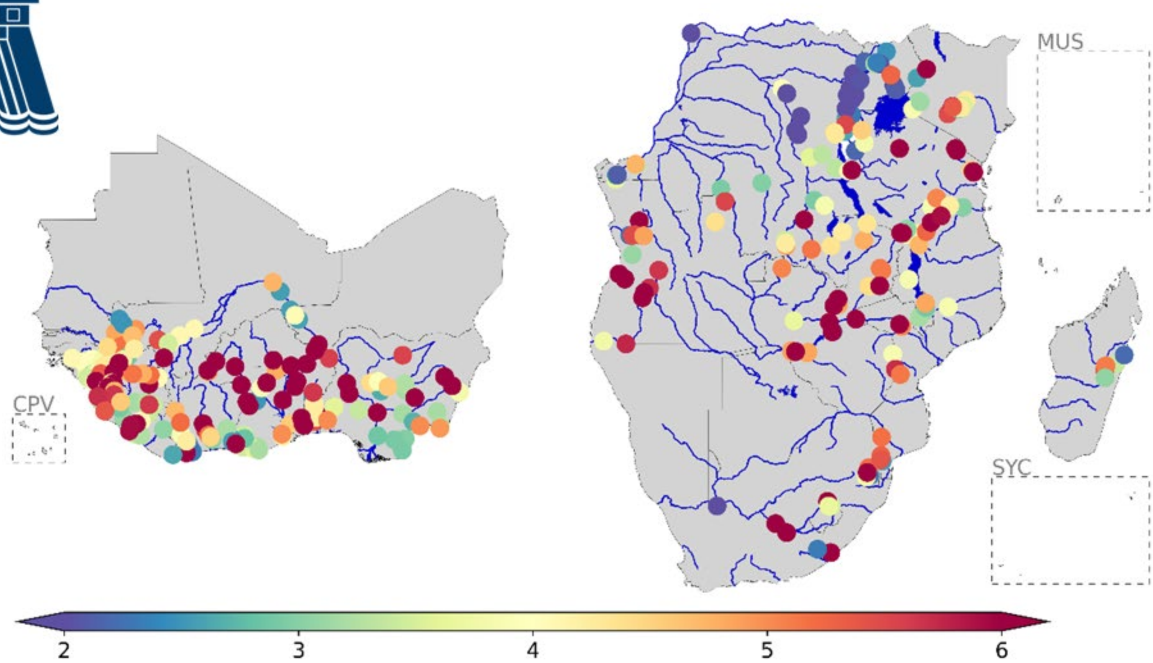


Figure 35 Levelized cost of electricity [Ct€/kWh] from hydropower for the year 2050. [1]

"In regions with higher seasonality hydropower plants cannot operate at full capacity during the dry season, especially if there is no significant reservoir storage available. As a result, annual full load hours are reduced and levelized cost increase. This effect can be seen in the savannas of southern Africa, but also as a south-north gradient in the coastal countries of West African. Several hydropower plants along the Niger river in arid areas of Mali and Niger can serve as an example. The opposite is true for very large rivers where only a minor part of the discharge is required for hydropower plant, for instance those located in the Congo basin and Lake Victoria." [1]

2.2.4 Geothermal Power

"Given the great importance of geothermal energy to Kenya's energy strategy, geothermal power potentials for Kenya were assessed within the scope of the study. The capacity potential is highest in the northern regions"[1] (see Figure 36). "The very low capacities in the southern and southwestern regions of Kenya can be attributed to high population densities and, in the south to the exclusion of protected areas (see Section 2.1.1). The central regions are mainly affected by the exclusion of mountain slope. The total geothermal capacity potential in Kenya amounts to slightly over 187 GW. This capacity potential is about 116 times that of Kenya's hydropower installations (1.6 GW), about 20% of onshore wind (895 GW), or almost 2.5% of PV (7.5 TW)." [1]

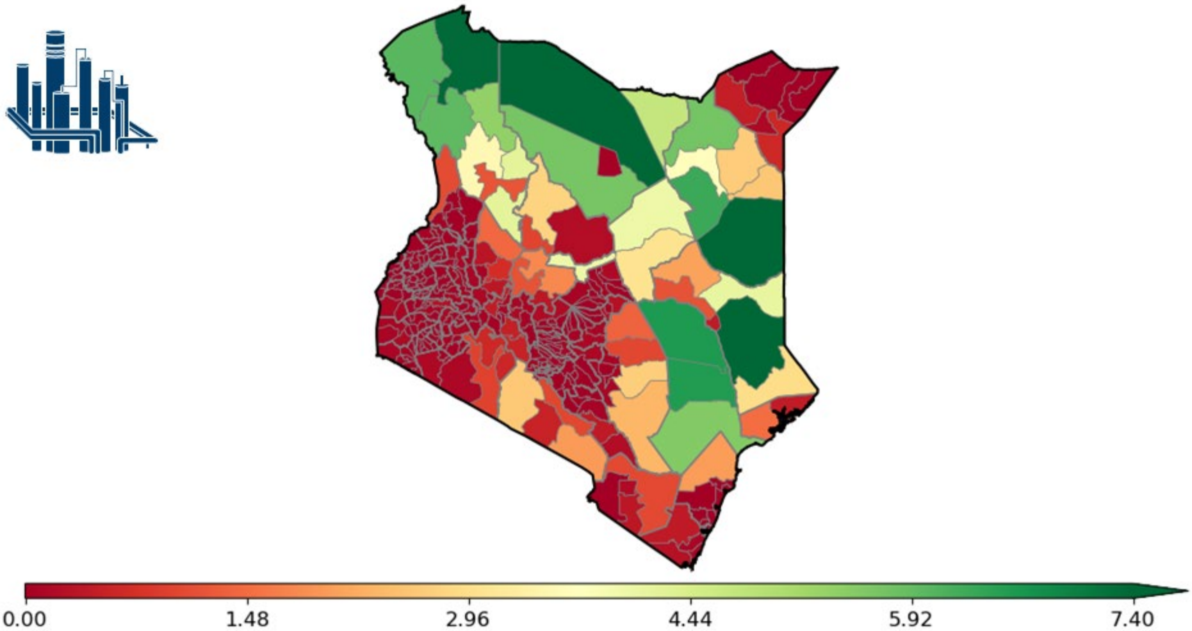


Figure 36: Regional geothermal capacity potentials [GW] in Kenya[1]

"The levelized cost of electricity is lowest in the northeast along the Great Rift Valley starting at ~6.8 Ct€/kWh, but to a lesser extent also east of the central mountain ranges towards the Somali border and partly. As these low cost regions coincide well with the highest capacity potentials, it can be stated that the main geothermal potentials in Kenya are in Turkana and Wajir county, and to a lesser extent also in Garissa and Marsabit. Low cost locations can also be identified in the southern Rift Valley Province, but the capacity potential in this area is comparatively low, with costs between 6.8-15 Ct€/kWh. Beyond these regions, the cost-potential curve rises sharply. In general, geothermal power is more expensive than wind or solar resources in Kenya, but has the advantage of being dispatchable. Subsequent processes can therefore achieve almost ideal utilization rates and therefore low costs. The economic viability of geothermal power for hydrogen production in Kenya therefore depends on the achievable full load hours based on solar and wind power. 70% of the total potential is feasible below 10 Ct€/kWh."[1]

2.3 Water supply for green hydrogen production

"The water availability assessment was conducted by taking into account the average groundwater sustainable yield for the following timeframes: 2020 (2015–2035), 2030 (2015–2045), and 2050 (2036–2065). Additionally, the assessment encompassed the process of seawater desalination, which includes the transportation of water." [1]

Groundwater sustainable yield in 2020

"The long-term average (2015 – 2035) groundwater sustainable yield maps representative for the year 2020 are presented in"[1] Figure 37, "considering two climate scenarios: RCP2.6."[1] (Figure 37a & c & e), "and RCP8.5."[1] (Figure 37b & d & f). "For each climate scenario, three cases are investigated: conservative"[1] (Figure 37a & b), "medium"[1] (Figure 37c & d), "and extreme conditions."[1] (Figure 37e & f), "based on the scenarios described in[2] "[1]. The findings indicate a substantial increase in groundwater sustainable yield from the conservative scenario"[1] (Figure 37a & b) "to the extreme"[1] (Figure 37a & b) "scenario. The medium scenario"[1] (Figure 37c & d) "situated between the conservative and extreme cases could be considered as the most favorable scenario for green hydrogen production. In West Africa, the coastal parts of the region (e.g., Gambia, Guinea, Sierra Leone, Liberia, and Cote d'Ivoire) and those located in the Southern part (e.g., Nigeria, Benin, Ghana) exhibit higher groundwater sustainable yield for RCP2.6 and RCP8.5 and all three cases. The regional analysis"[1] (Table 6) "demonstrates that in the selected West Africa region, the average groundwater sustainable yield for the year 2020 RCP2.6 (RCP8.5) would be 7.4 (6.9) mm yr^{-1} (conservative scenario), 34.9 (33) mm yr^{-1} (medium scenario), and 63 (59.7) mm yr^{-1} (extreme scenario)." [1]

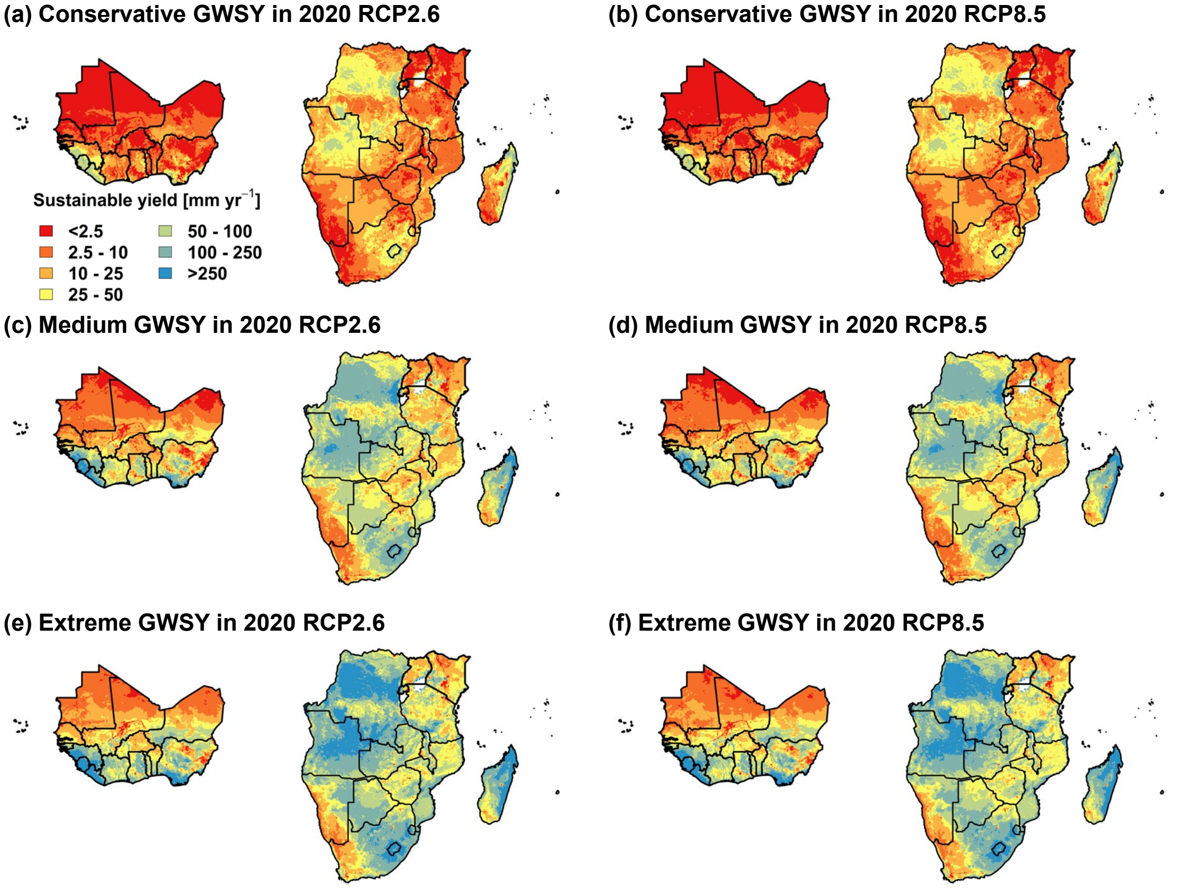


Figure 37. The groundwater sustainable yield for 2020 (the average of 2015 - 2035) under two climate scenarios: RCP2.6 (left panels) and RCP8.5 (right panels). Each scenario considers three cases: conservative (a & b), medium (c & d), and extreme conditions (e & f). [1]

"In Southern East Africa, the results suggest that countries such as Angola, Democratic Republic of Congo, Zambia, Tanzania, and Madagascar consistently exhibit high sustainable yield across all scenarios (Figure 37). Furthermore, the southern part of the region (e.g., South Africa, Lesotho, Namibia, Botswana) demonstrated higher groundwater sustainable yield in 2020 (RCP2.6 and RCP8.5). According to the RCP2.6 (RCP8.5) scenarios, the average groundwater sustainable yield for Southern East Africa (Table 7) would be 17.9 (17.1) mm yr^{-1} (conservative scenario), 75.8 (72.6) mm yr^{-1} (moderate scenario), and 134.2 (128.6) mm yr^{-1} (extreme scenario)." [1]

Groundwater sustainable yield in 2030

"Regarding 2030, the sustainable yield of groundwater based on[2] is averaged over the 2015 – 2045 period and presented in"[1] Figure 38 "under two different climate scenarios: RCP2.6"[1] (Figure *38*a & c & e) "and RCP8.5"[1] (Figure 38b & d & f). "It also illustrates three scenarios: conservative"[1] (Figure 38a & c), "medium"[1] (Figure 38b & d), "and extreme" [1] (Figure 38e & f). "In West Africa, as well the case in 2020, the higher groundwater sustainable yield values are present along the western coastal regions (such as Gambia, Guinea, Sierra Leone, Liberia, and Cote d'Ivoire), as well as in the Southern part (e.g., Nigeria, Benin, Ghana). Our analysis indicates that the average groundwater sustainable yield in 2030 would be slightly lower than the one in 2020 under both RCP2.6 and RCP8.5" [1] (Table 6). "When considering the entire region, our findings highlight the potential for groundwater sustainable yield in West Africa under RCP2.6, with average values of 6.8 mm yr^{-1} (conservative scenario), 33.3 mm yr^{-1} (medium scenario), and 60.6 mm yr^{-1} (extreme scenario). For RCP8.5, the groundwater sustainable yield changed to 6.4 mm yr^{-1} (conservative scenario), 31.8 mm yr^{-1} (medium scenario), and 58 mm yr^{-1} (extreme scenario). Regarding Southern East Africa, as illustrated in Figure 38, the higher sustainable yield values are found in Angola, the Democratic Republic of Congo, Zambia, Tanzania, and Madagascar, particularly in medium and extreme scenarios. Similar to West Africa region, the average groundwater sustainable yield in 2030 under RCP2.6 and RCP8.5 has slightly decreased compared to 2020 RCP2.6 and RCP8.5”[1] (Table 7). “Across the entire Southern African region, we found average rates of 17.3 (16.8) mm yr^{-1} (conservative scenario), 73.7 (71.9) mm yr^{-1} (medium scenario), and 130.8 (127.6) mm yr^{-1} (extreme scenario) under RCP2.6 (RCP8.5).” [1]

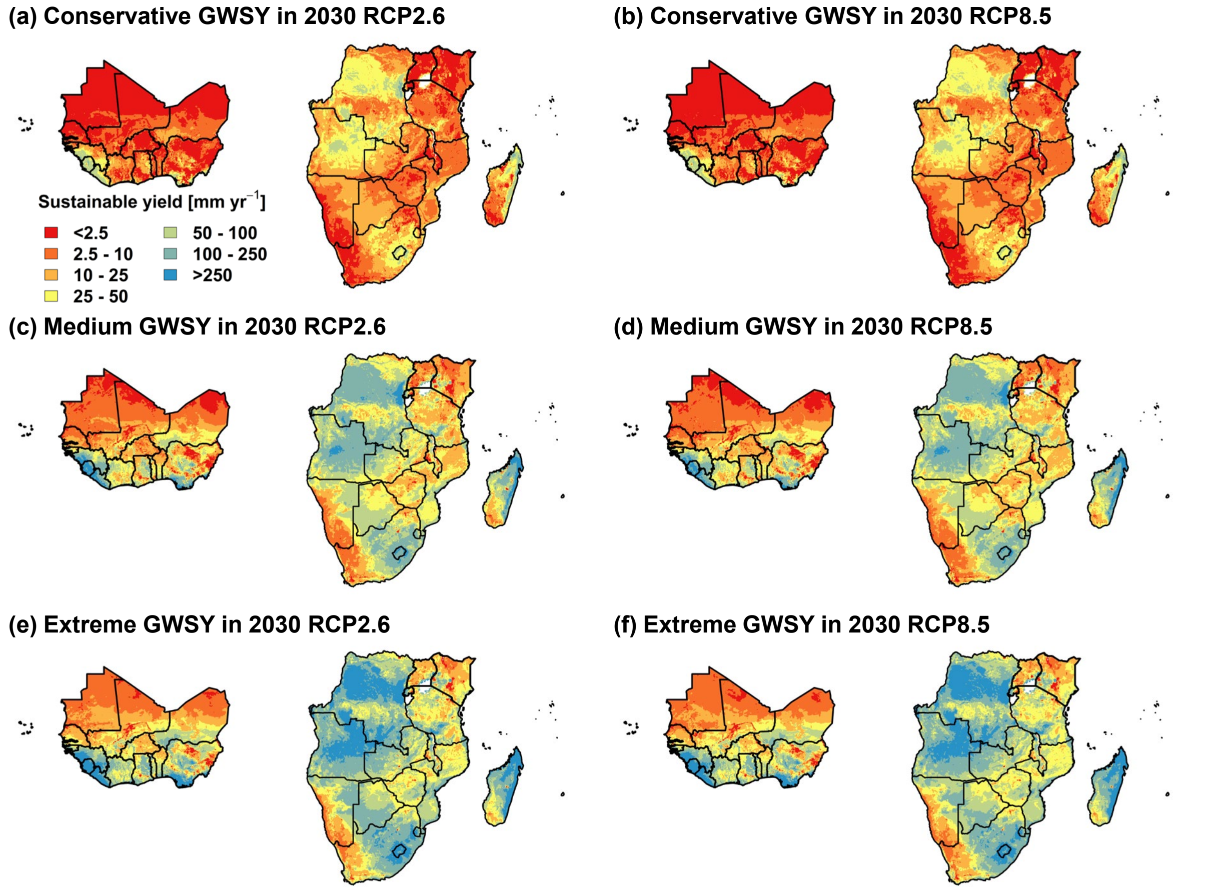


Figure 38. The groundwater sustainable yield for 2030 (the average of 2015 - 2045) under two climate scenarios: RCP2.6 (left panels) and RCP8.5 (right panels). Each scenario considers three cases: conservative (a & b), medium (c & d), and extreme conditions (e & f). [1]

Table 5 The average estimates of groundwater sustainable yield in the West Africa region for 2020 (2015-2035), 2030 (2015-2045), and 2050 (2036-2065) considering two climate scenarios: RCP2.6 and RCP8.5 under conservative, medium, and extreme conditions. [1]

Scenario	West Africa groundwater sustainable yield [mm yr^{-1}]					
	2020		2030		2050	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
Conservative	7.4	6.9	6.8	6.4	5.6	5.1
Medium	34.9	33	33.3	31.8	29.6	27.2
Extreme	63	59.7	60.6	58	55.1	50.9

Table 6 The average estimates of groundwater sustainable yield in the Southern East Africa region for 2020 (2015-2035), 2030 (2015-2045), and 2050 (2036-2065) considering two climate scenarios: RCP2.6 and RCP8.5 under conservative, medium, and extreme condition [1]

Scenario	Southern East Africa groundwater sustainable yield [mm yr^{-1}]					
	2020		2030		2050	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
Conservative	17.9	17.1	17.3	16.8	15.6	15.4
Medium	75.8	72.6	73.7	71.9	68.6	67.8
Extreme	134.2	128.6	130.8	127.6	122.3	121

Groundwater sustainable yield in 2050

" The long-term average (2036-2065) groundwater sustainable yield was calculated as representative for 2050 (Figure 39) for the climate scenarios RCP2.6 (Figure 39a & c & e) and RCP8.5 (Figure 39b & d & f), and for three cases: conservative (Figure 39a & b), moderate (Figure 39c & d), and extreme (Figure 39e & f). The findings indicate that the average groundwater sustainable yield in 2050 is clearly lower than in 2020 under both RCP2.6 and RCP8.5 scenarios, and this is true for all conservative, medium, and extreme cases. The regional analysis (Table *5*) provides an average West Africa groundwater sustainable yield in 2050 under RCP2.6 of 5.6 mm yr^{-1} (conservative scenario), 29.6 mm yr^{-1} (medium scenario), and 55.1 mm yr^{-1} (extreme scenario). Moreover, the groundwater sustainable yield in 2050 for RCP8.5 is lower than for RCP2.6 for all three scenarios, particularly over the Northern part of the region. The results indicate that the Southern part of the region (e.g., Nigeria, Benin, Ghana) consistently receives a lower sustainable yield in all three scenarios (Figure 39b & d & f) than compared to 2020 for RCP8.5. In 2050 for RCP8.5, the region is expected to exhibit average groundwater sustainable yield values of 5.1 mm yr^{-1} (conservative scenario), 27.2 mm yr^{-1} (medium scenario), and 50.9 mm yr^{-1} (extreme scenario), which is less than in 2020 for RCP8.5 (**T**able 6)." [1]

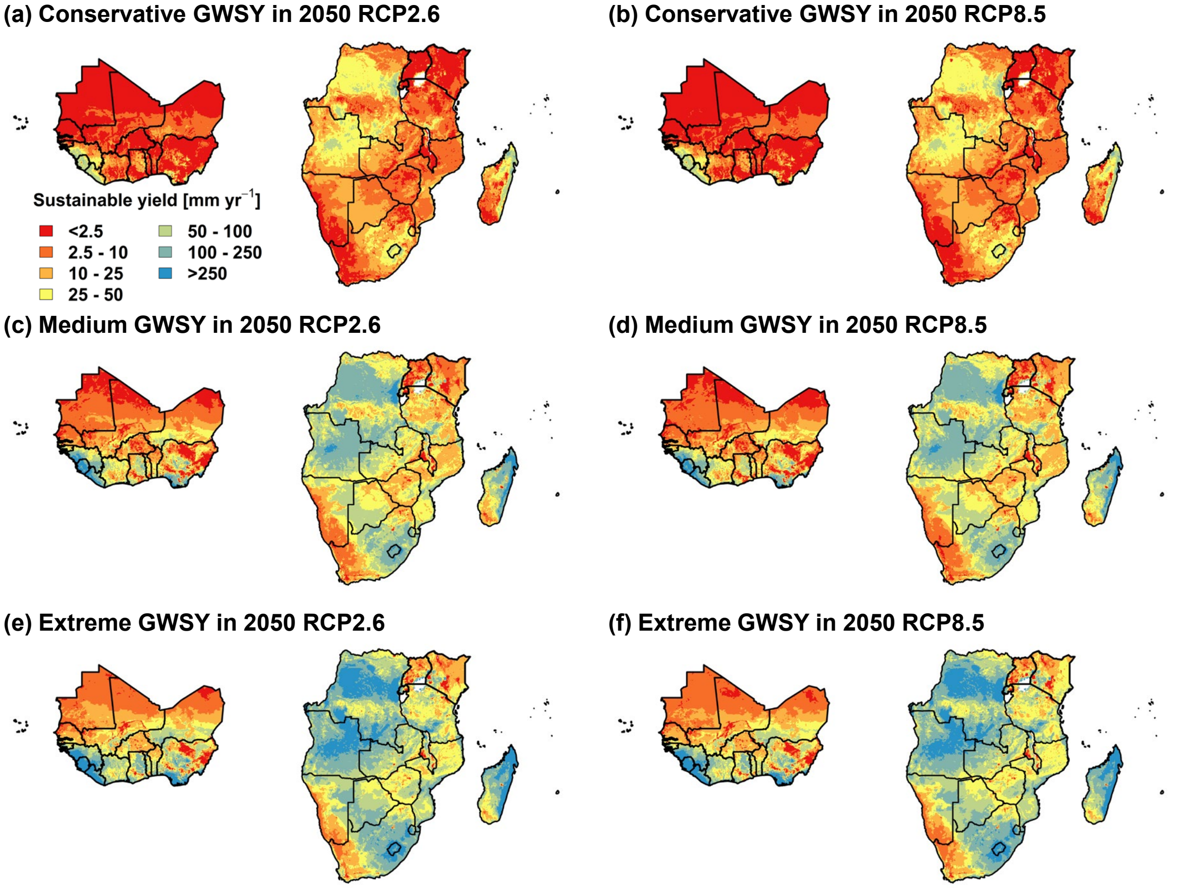


Figure 39: The groundwater sustainable yield for 2050 (the average of 2036 - 2065) under two climate scenarios: RCP2.6 (left panels) and RCP8.5 (right panels). Each scenario considers three cases: conservative (a & b), medium (c & d), and extreme conditions (e & f). [1]

"For Southern East Africa the spatial pattern of groundwater sustainable yield for the three scenarios in 2050 under RCP2.6" [1] (Figure 39a & c & e), "and RCP8.5" [1] (Figure 39b & d & f) "is similar to 2020. However, the absolute amount of sustainable yield is expected to be lower in 2050 than in 2020, both for RCP2.6 and RCP8.5. According to the 2050 RCP2.6, the average groundwater sustainable yield in the Southern East region is projected to be 15.6 mm yr^{-1} (under conservative conditions), 68.6 mm yr^{-1} (under moderate conditions), and 122.3 mm yr^{-1} (under extreme conditions). This is lower than the yield under the RCP2.6 scenario in 2020" [1] (Table 7). "Furthermore, the region is projected to exhibit average groundwater sustainable yield values of 15.4 mm yr^{-1} (conservative scenario), 67.8 mm yr^{-1} (medium scenario), and 121 mm yr^{-1} (extreme scenario) for RCP8.5, all of which are lower than those observed in 2020 under RCP8.5" [1] (Table 7).

2.4 Hydrogen potentials

"In the following, quantitative hydrogen potentials will be analyzed and compared to the amount of hydrogen that can be produced from local sustainable groundwater potentials. The cost of hydrogen and the cost contribution of water will be presented, and the reasons for hydrogen cost differences will be discussed. Further information will be provided by cost-potential curves, which will then be explained in detail based on a n in-depth analysis of the region- and time-dependent optimal system designs for the production of green hydrogen." [1]

2.4.1 Degree of potential expansion and local demands

"For the analysis of the levelized cost of hydrogen (LCOH) and for system design considerations, the dependence of the cost on the degree of potential expansion is first discussed. The lowest cost potentials are exploited first, with costs increasing along the cost-potential curve as the quantity of produced hydrogen is increased. Typically, e.g. for regions with a large quantity of wind turbines, costs start comparatively low and rise sharply at the beginning, with a decreasing slope within the first quartile. The second and third quartiles show very moderate increases, and the last quarter shows a sharp increase towards the end (compare exemplary distribution in Figure 2 of Winkler et al[1]). While very high degrees of expansion at the end of the curve describe economically unrealistic solutions, the very low degrees of expansion describe entry-level costs. These are defined by the most favorable locations and system configurations. Typically, these are also locations that could be occupied by first movers, which may have implications for the economy of scale and learning rate assumptions. However, in an approach with independent regions and high spatial resolution, the economy of scale and learning effects in any given region may depend not only on the region itself, but also on installations in neighboring regions or the entire country. Therefore, it is not possible to reliably quantify the cost effects of first-mover projects in an atlas approach, and costs at very low potential expansion degrees must be interpreted with caution. In addition, renewable energy simulation tools are always subject to statistical errors. While medians and average values are very reliable, potential outliers may further influence the initial costs. For these reasons, the following analysis focuses on a potential expansion rate of 25% when comparing the levelized costs of hydrogen and system designs. Cost in this range are still comparatively low, but very reliable and fairly stable as the production quantity increases." [1]

2.4.2 Quantitative Hydrogen Potentials

"The following quantitative hydrogen potentials were calculated based on the local preference exclusions defined with the national specialists and renewable energy simulations. Subsequently, the hydrogen potentials were determined based on optimal system designs per each district level node. The aggregate maximum hydrogen potential in West Africa, in conjunction with Southern and East Africa, is estimated to exceed 400,000 TWh/a, which is more than double the present global primary energy consumption (165,319 TWh/a in 2021[5]). The cumulative projected local electricity and hydrogen demands in 2050 for the analyzed regions based on the "Net Zero 2050" scenario from the NGFS Climate Scenarios Database [87,88] amount to only 0.5% of the total potentials. The present analysis, therefore, does not concentrate on the total quantitative potential of the entire project region. Rather, it focuses on regional and national potential constraints, as well as available quantities at defined production costs.

The distribution of regional potentials per area is illustrated in"[1] Figure 40 "circumvents the potential distortion of the potential values by the region size and instead reflects the limitations and results described in the land eligibility and renewable energy potentials sections. The analysis indicates that the greatest potential is found in the sparsely populated desert regions of the Sahara and Nama Karoo, yet significant area potential is identified across the entirety of the study area. Notable exceptions to this pattern are the densely populated and forested regions along the Southern coast of West Africa, the Congo basin, and rangeland areas in Southern Africa, which exhibit low wind potentials. It is noteworthy, however, that the requisite area potentials may be minimal, even for industrialized nations such as Germany, where an area potential of less than 6 kWh/m² would suffice to meet the total projected final energy demand of 2164 TWh/a in 2045 [72]. It is notable that approximately 54% of the project regions exceed this threshold." [1]

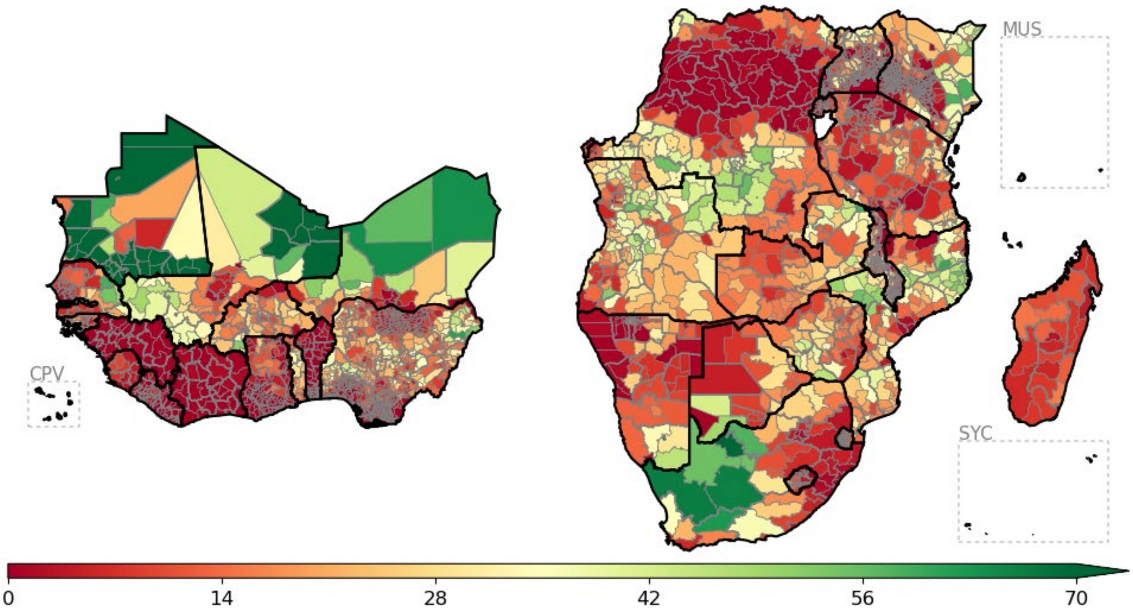


Figure 40 Hydrogen potential per area [kWh/(a*m²)] at district level in 2030, limited only by energy. [1]

"The absolute hydrogen potentials per unit area demonstrate a comparable trend (refer to the GUI[82] for regional values), a phenomenon that is further accentuated by the observation that remote desert regions tend to encompass significantly larger areas." [1]

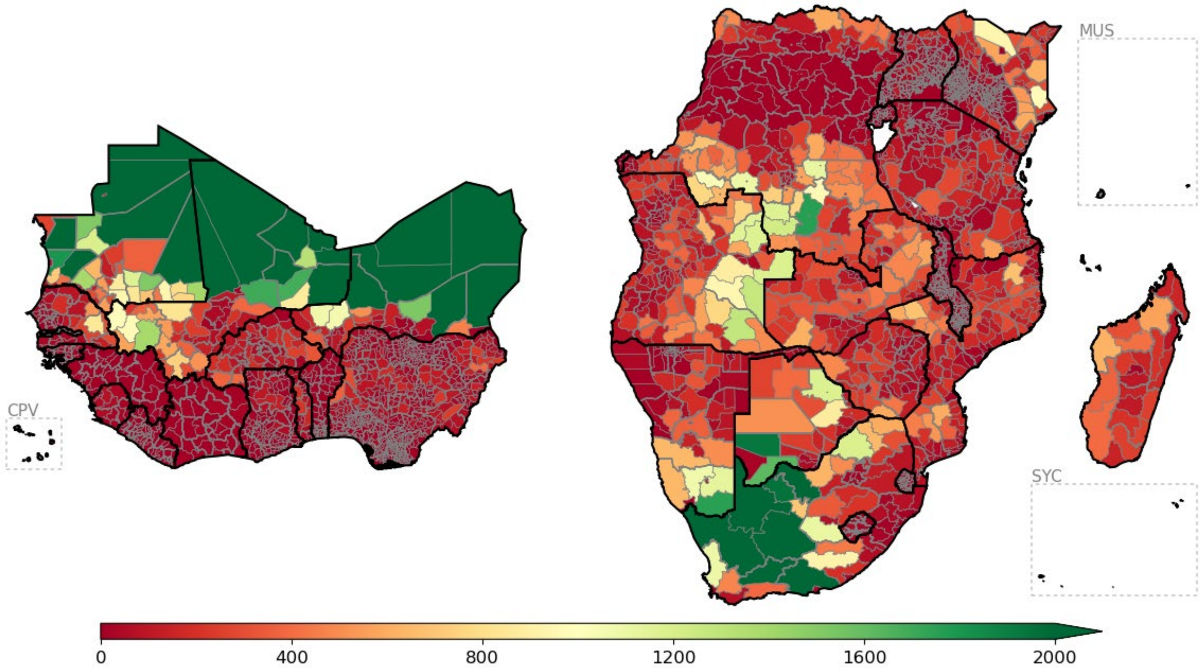


Figure 41 Absolute technical hydrogen potentials [TWh/a] at district level, limited only by energy. [1]

"The national and total potentials were calculated, and local electricity and hydrogen demands were considered as detailed in section 2.4 of Winkler et. al.[1] The national aggregate values are enumerated in the appendix in section 1.A of Winkler et al[1] The analysis revealed that, due to limitations imposed by land eligibility and theoretical energy potential, only three of the thirty-five countries under consideration may experience challenges in meeting their own electricity and hydrogen demands in the year 2050. This is contingent upon maintaining a fifty percent feasibility threshold for the maximum potential. This number is reduced to two out of 35 countries in the unlikely case of a 100% expansion of the potential. However, regulatory decisions may alter this landscape, particularly in regions with minimal overall eligibility, such as island nations like the Seychelles or Mauritius, where such decisions may have a substantial relative impact on potential. For instance, in the Republic of Guinea, the import of energy from neighboring countries would be a viable and efficient solution. The implementation of transmission infrastructure projects within the West African Power Pool (WAPP) framework[89]." [1]

2.5 Sustainable Water Impact on Hydrogen Potentials

"When hydrogen production is based on local sustainable groundwater, the quantitative potential is significantly reduced" [1] (see Figure 42). "A mere 42% of all regions possess sufficient sustainable groundwater to accommodate an expansion degree of 25% of the maximum energetic potential. Notably, regions with both low-cost and high-potential, such as desert areas, are particularly impacted due to their limited precipitation. When the analysis is further restricted to regions with an average LCOH below 2.7 EUR/kg in 2030, the proportion of regions with sufficient groundwater is further diminished to 28%. The hydrogen potential derived from sustainable groundwater is estimated to account for approximately 16% of the total technical hydrogen potential, with energy constraints serving as the primary limiting factor. This percentage may be further diminished if water-intensive cooling methods replace air cooling. The impact of the cooling method on water consumption cannot be quantified in general, since it depends on the specific cooling method and environmental conditions, as well as the reuse options for the cooling water return flow. When assessed based on sustainable water potential, the average levelized cost of hydrogen is 4-5% higher than the overall LCOH without water limitations." [1]

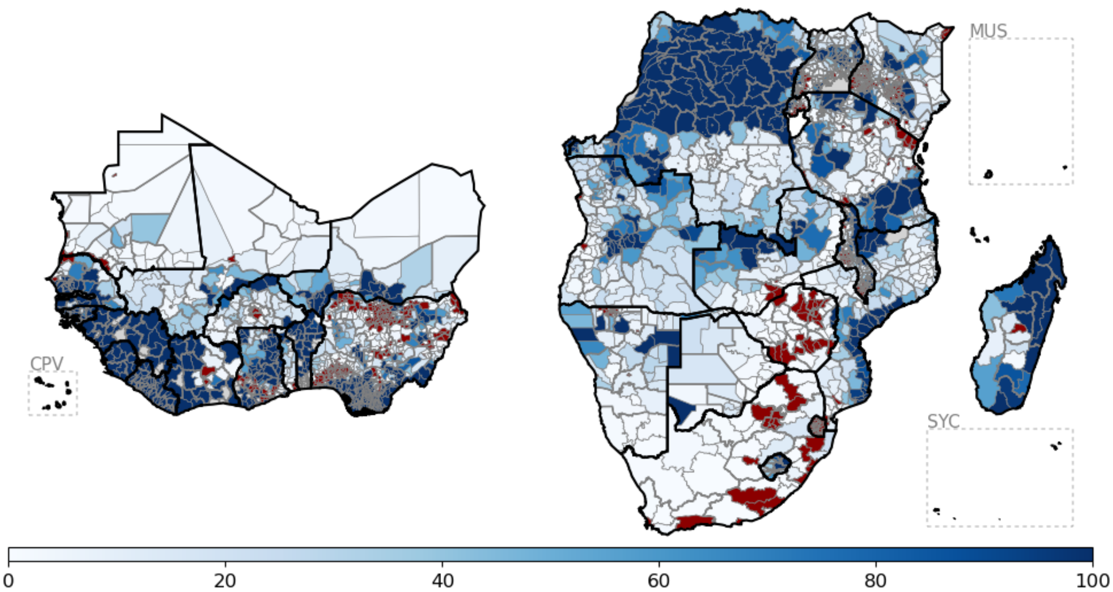


Figure 42 Percentage share of hydrogen [%] producible from local sustainable groundwater. [1]

"However, this does not explicitly imply that sustainable hydrogen production is not feasible beyond the limit of sustainable groundwater potential. In certain instances, surface water can be utilized when it is consistently available throughout the year. However, its sustainability must be evaluated on a case-by-case basis. A particular emphasis should be placed on the seasonality of water availability for hydrogen production in these cases. Water requirements may be particularly pronounced during the dry season in systems with a preponderance of solar photovoltaics (PV). Alternate water sources, such as desalinated seawater, may also be utilized, provided that renewable energy is employed for treatment and transportation, and that water intake and brine outlet are strategically optimized to minimize ecological impact. According to the present assessment, attaining 100% of the overall technical potential would necessitate 84% of the consumed water to be derived from such alternative sources. In the case of desalinated water, this would correspond to the construction of 755 new large-scale desalination plants with a capacity of 367,000 m³/d each, as suggested in Heinrichs et al.[69] or 1,846 plants of the 2020 UAE reference size, as proposed by Eke et al. [90]. The additional cost for water treatment is not significant, given the high value of hydrogen and the relatively low amount of water that is needed to produce it via electrolysis: Even in north-eastern Mali, where the levelized cost of water including pipeline transport reaches nearly 2.50 €/m³ in combination with comparably low LCOH, the share of water cost does not exceed ~1% of the total levelized cost of hydrogen. Consequently, the primary focus should be directed towards assessing the viability of pipeline water transportation over long distances and across national borders, particularly in the context of large-scale sustainable hydrogen production in inland countries such as Niger and Mali, which are characterized by substantial potential. Alternatively, power export from these countries to coastal locations via a power grid in conjunction with electrolysis near the coast would be a viable option. However, the implementation of transnational power lines would necessitate meticulous planning and cooperation, resulting in higher costs compared to pipeline alternatives. Mauritania, South Africa, Namibia, Kenya, Madagascar, and Cabo Verde are notable examples of countries with substantial low-cost potential along the coast, as well as small island nations such as Cabo Verde." [1]

2.6 Levelized Cost of Hydrogen (LCOH)

"First, the levelized cost of hydrogen, which is primarily based on onshore wind, open-field photovoltaics, and geothermal power supply, will be discussed. These represent the large-scale, widely untapped renewable energy resources. Subsequent discourse will address regions characterized by hydropower dominance, which often exhibit cost outliers at the local level.

The analysis indicates that the lowest levelized cost of hydrogen, excluding hydropower contributions, is achieved in Mauritania at 25% of the regional maximum potential, with the cost of production reaching 1.6 €/kg in 2050. If the actual entry level cost is considered, LCOH of approximately 1.8 €/kg in 2030 and 1.5 €/kg in 2050 may be feasible without hydropower, provided that the economy of scale persists. The most economical hydrogen production is located in the Sahara region, particularly towards the Mauritanian coast and in the Nama Karoo region in the border area between Southern Africa, Namibia and Botswana" [1] (see Figure 43), "but also in smaller countries such as Cabo Verde and Lesotho. Additionally, hydrogen can be produced at a lower cost in Kenya and, to a lesser extent, in Madagascar. A cost comparison of the project regions reveals that West Africa has a slight cost advantage (~1.9 €/kg) due to its comparatively large, low-cost potential in the Sahara, as opposed to Southern and East Africa (~2 €/kg), which has higher cost-potentials near the equator. The study's findings indicate that the overall potential-weighted average levelized cost of hydrogen across the entire study area, at 25% of the respective regional technical potential, is estimated to be approximately 2.7 €/kg in 2030 and 1.9 €/kg in 2050." [1]

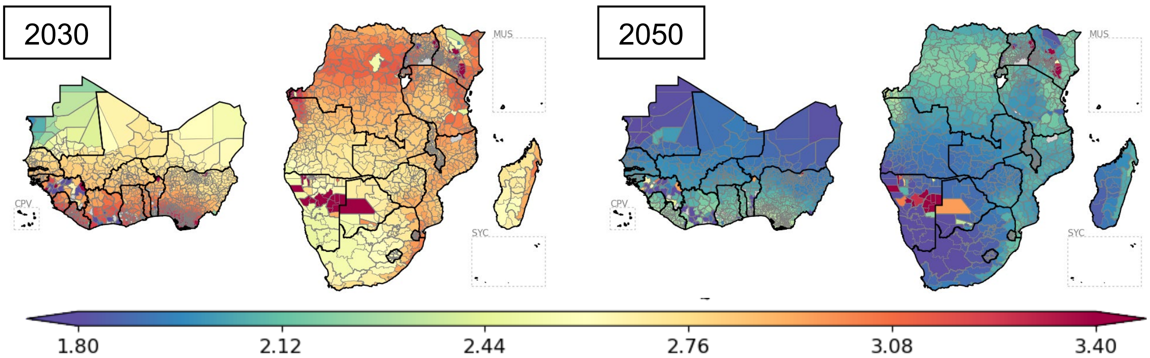


Figure 43 Regional Levelized Cost of Hydrogen [EUR/kg] at 25% potential expansion in the years 2030 (left) and 2050 (right) [1]

"A direct comparison of the levelized cost of hydrogen at 25% expansion between 2030 and 2050 (Figure 44 on the left) demonstrates that the LCOH reduction over the decades is most significant in regions with solar-dominated hydrogen production (see section 3.2.1 of Winkler et al.[1]). However, the majority of the most cost-effective hydrogen regions in 2030 are characterized by a combination of solar and wind generation fleets, and they demonstrate a decline in cost reduction over time. Consequently, alternative solar-driven regions have the potential to achieve cost reductions comparable to those observed in the solar- and wind-mixed regions of North-Eastern Mauritania, which continue to be among the most economical options. The analysis indicates that 64% of the projected cost reductions, as predicted by the techno-economic parameters of the technologies, are to be realized within the initial decade, specifically by the year 2040." [1]

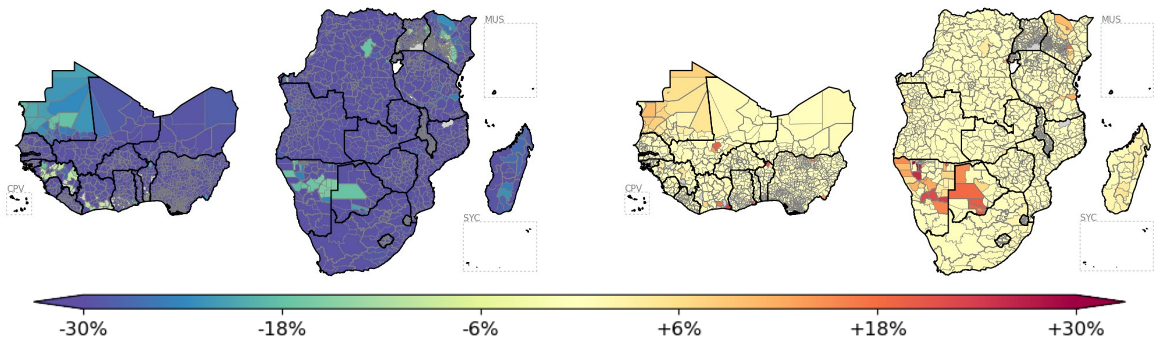


Figure 44 Percentage change [%] of levelized cost between 2030 and 2050 at 25% of technical potential (left) and between 25% and 50% of technical potential in 2030 (right). [1]

"In order to quantify the dependency of the levelized cost of hydrogen on the production quantity, the relative cost increase of the LCOH at 50% potential expansion compared to the standard potential expansion of 25% is analyzed for the year 2030" [1] (see Figure 44 on the right). "The differences are marginally higher yet very similar in 2050. The findings suggest that LCOH in regions dominated by wind power is particularly sensitive to variations in production capacity. In regions predominantly reliant on wind power generation, the levelized cost of hydrogen exhibits a median increase of approximately 6% when production capacity is augmented from 25% to 50% of the technical potential. In contrast, solar-dominated systems exhibit a distinct pattern, with cost exhibiting minimal change with increased production capacity (~0.1% median cost increase). In regions where the capacity limits of the least expensive generation technology are exceeded and more costly alternatives must be used, production quantity increases may also have a significant impact on average LCOH.

An examination of the hydrogen cost map in" [1] Figure 43, "reveals several cost outliers that are worthy of discussion. On the one hand, regions primarily in central Namibia and Botswana, but also isolated cases across the study area, stand out due to their elevated levelized cost of hydrogen. These regions are predominantly situated in areas with minimal wind energy potential and are constrained by limitations on land eligibility that preclude the viability of adequate photovoltaic capacity. In the case of the Kalahari region, which is shared by Namibia and Botswana, the primary factors contributing to this phenomenon are the preservation of rangelands for wildlife and the maintenance of pastures for cattle farming. The latter can be integrated with wind turbines; however, this is not the case with solar open-field photovoltaics. Consequently, elevated combined costs, attributable to high wind shares and high LCOEs in these regions, are observed. A similar scenario may be observed in regions heavily reliant on geothermal energy in Kenya.

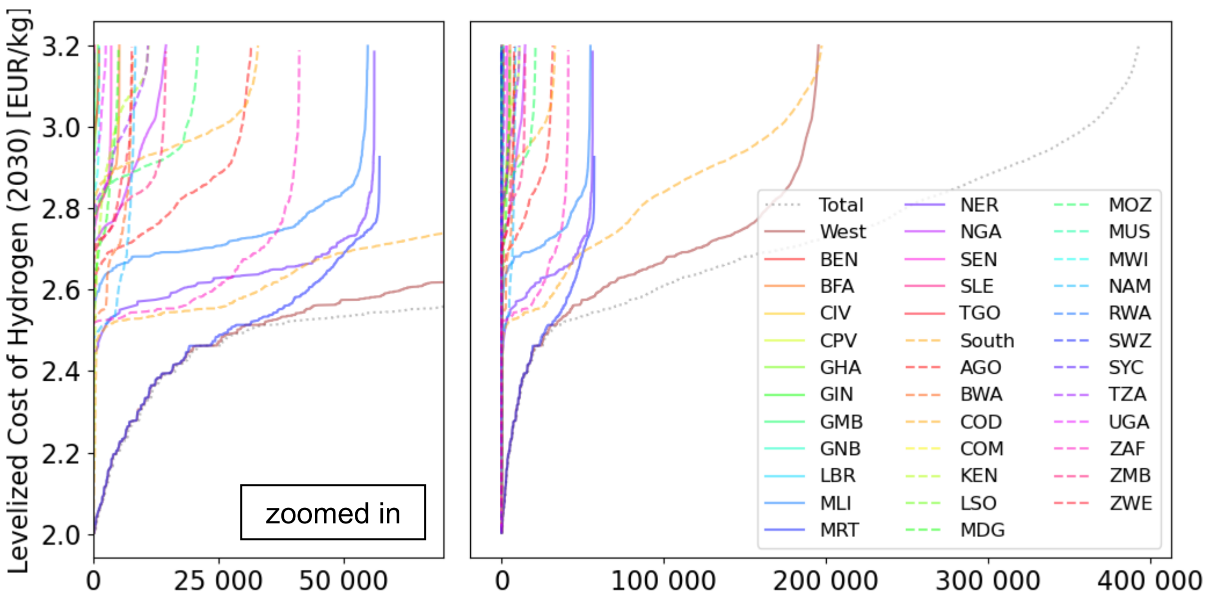
Conversely, there are isolated regions with very low costs that are dispersed throughout the area, particularly in southern West Africa. These regions are characterized by a predominant reliance on hydropower, a strategy that enables the production of hydrogen with a levelized cost that is highly competitive. However, the overall hydrogen potential in southern West Africa is constrained by limited land eligibility and comparatively small region sizes, resulting in a significant reliance on low-cost hydropower, thereby yielding a notably low overall LCOH. The primary benefit of hydrogen derived from hydropower is the high utilization rate of hydropower plants and electrolyzers, particularly at low expansion grades, where the available river discharge remains consistent throughout the year. This results in a cost of electricity and hydrogen that is notably low. In contrast, conventional reservoir hydropower systems can enhance the consistency of their output by storing and releasing excess water, although this approach entails higher investment costs. The lowest entry-level LCOH in 2030 is achieved by run-of-river hydropower at approximately 1.1 EUR/kg in 2030 and 0.9 EUR/kg in 2050. However, it should be noted that this cost is only feasible in the most optimal locations and for projects with limited potential. In most regions and at higher potential expansion degrees, hydrogen derived from run-of-river hydropower is more expensive than reservoir hydropower. In 2030, the cost of hydrogen from run-of-river hydropower was estimated to be approximately 1.5 EUR/kg, while reservoir hydropower was projected to be around 1.3 EUR/kg.

It is imperative to acknowledge that these values should be regarded exclusively as theoretical lower bounds. In reality, reservoir hydropower plants typically play a pivotal role in ensuring grid flexibility, a role that is difficult to substitute. In the majority of cases, hydrogen production is therefore limited to periods of excess electricity, which would significantly reduce electrolysis full load hours. The current cost of electrolysis contributes 25% of LCOH (median value) in low-cost conventional hydropower regions (35% in run-of-river hydropower systems). Consequently, a 50% reduction in electrolyzer utilization rate would result in a 25-35% increase in hydrogen cost. This systemic effect cannot be reflected in an atlas approach, where regions are independent of each other. Consequently, the economic viability and quantitative potential of green hydrogen produced from hydropower must be assessed on a plant-by-plant basis within an (inter-)national energy system model, incorporating temporal demand patterns and other generation capacities within the system." [1]

2.7 Hydrogen Cost-Potential Curves

“The integration of the aforementioned findings on quantitative hydrogen potentials and levelized cost into cost-potential curves facilitates a more profound analysis of quantity-dependent aspects. A comparative analysis of the West, Southern, and East African curves presented in” [1] Figure 45, “reveals that the aggregate hydrogen potentials in the West Africa, and combined potentials in Southern and East Africa project regions are closely analogous, with an approximate value of 200,000 TWh/a. It is important to acknowledge that this is a theoretical estimate, as it is implausible that all renewable energies will be utilized exclusively for hydrogen production. In 2030, West Africa is projected to have a slightly lower levelized cost of hydrogen, primarily due to the substantial areas and conducive energy conditions in Mauritania, with smaller effects observed in Niger and Mali, all exhibiting comparable technical potentials of approximately 56,000 TWh/a. In addition to the countries in the Sahara region and Cabo Verde in West Africa, South Africa, Lesotho, Namibia, and Botswana also exhibit notably low entry-level cost-potential levels, with the most substantial quantities observed in South Africa.

While the cost-potential curves in Niger and Mali exhibit significant similarity, with relatively flat trends across most regions, indicating stability over a wide range of costs, the pattern in Mauritania differs. The cost potential in Mauritania is notably lower, with an entry cost of approximately €2.0/kg by 2030. This suggests the strategic utilization of favorable wind locations during the initial phase of expansion. Conversely, in South Africa, a substantial proportion of the more expensive wind potentials contributes to higher degrees of expansion, resulting in a near-constant solar-driven cost in the initial phase and a steady increase in the cost slope in the subsequent phase.” [1]



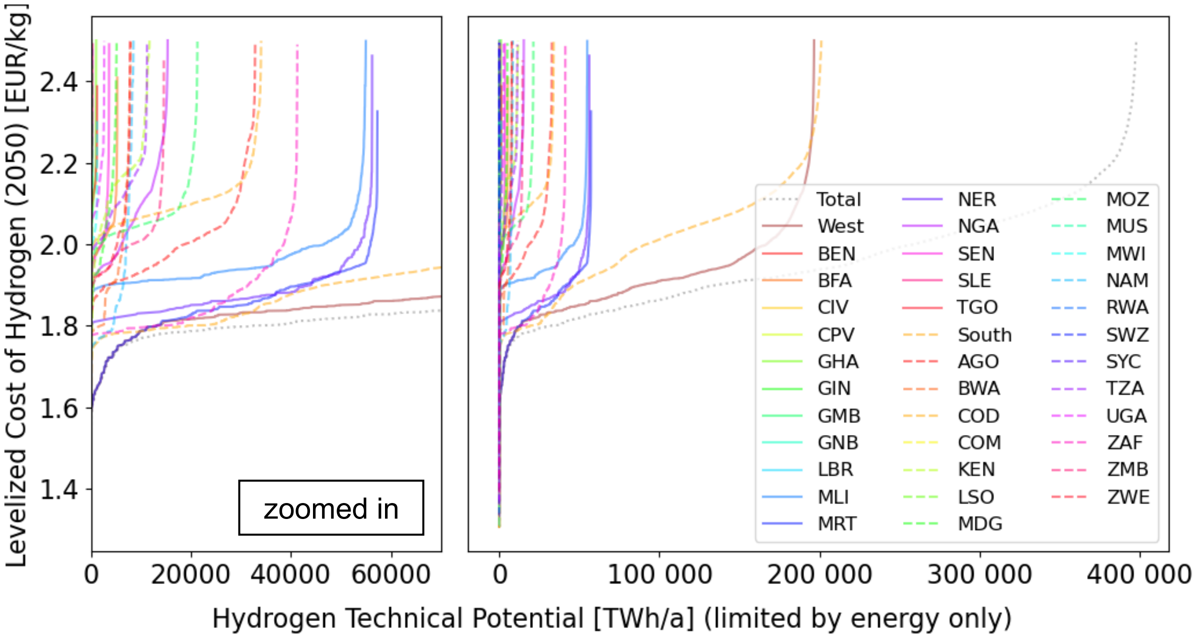


Figure 45 National cost-potential curves for West Africa (continuous) and Southern and East Africa (dashed lines) in the year 2030 (top) and 2050 (bottom), zoom on country level curves on the left. [1]

"A comparison of the 2030 values and the 2050 data presented in" [1] Figure 45, "reveals that the overall cost level is lower in 2050, and the cost differential between entry-level and high-potential expansion degrees has significantly diminished. Consequently, the average cost dependency on production quantity is reduced in 2050. This decline in cost is attributed, in part, to an increase in the adoption of solar power in low-expansion steps, driven by the declining costs of solar photovoltaic (PV) technology over time. When considering only the low-cost technical potentials across the whole project region, the producible green hydrogen under 2.5 €/kg in 2030 amounts to ~31 TWh/a. By 2050, the production capacity is projected to reach nearly 260 TWh/a, with a cost of under 2.0 €/kg." [1]

2.8 Hydrogen Production System Design

"An analysis of the region-specific designs of an optimal hydrogen production system reveals significant differences that explain the cost patterns previously observed. As illustrated in" [1]. Figure 46 "solar photovoltaics are identified as the predominant or exclusive power source in the majority of regions within the study area. Notable exceptions to this predominance include the Sahara region, Madagascar, Northern Kenya, and multiple regions in Southern West Africa, as well as some regions in Namibia and Botswana. The latter can be explained by the lack of photovoltaic potential in the Kalahari region, where either rangeland for the natural fauna or pastures for cattle herding forbid open-field photovoltaics. Instead, onshore wind turbines with a comparatively high Levelized Cost of Electricity (LCOE) are employed, contributing to elevated overall hydrogen costs in these regions. Conversely, regions in southwestern West Africa, characterized by their restricted solar and wind potentials, are well-suited for hydropower, which can contribute significantly to local hydrogen production. In regions where hydropower is also present, this relative share is reduced due to the greater overall potential. Given the significance of geothermal power in Kenya, it was identified as an additional power source for hydrogen production. However, its role remains modest, as it is primarily utilized in regions where solar and wind potentials are limited. Nevertheless, it is anticipated that as the demand for constant hydrogen output increases, geothermal power may become a more cost-effective option, especially when compared to other generation sources that are more susceptible to variability. This is due to the fact that geothermal power does not incur the same additional storage costs that are associated with more variable electricity generation." [1]

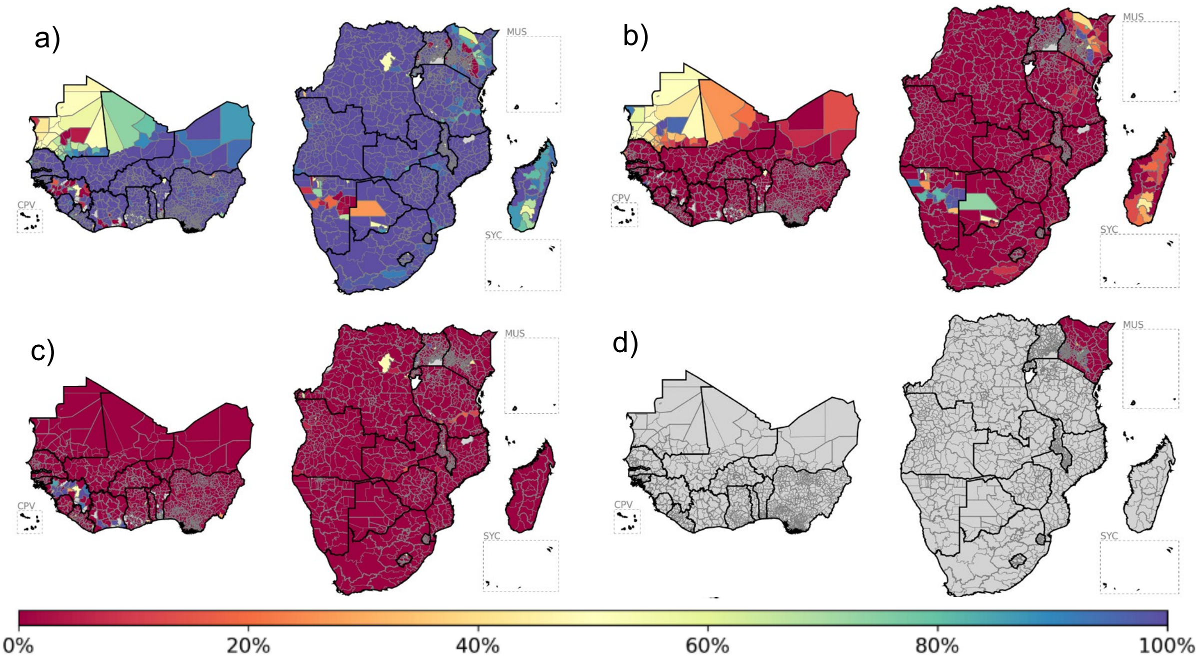


Figure 46 Share of (a) solar photovoltaics, (b) onshore wind, (c) hydropower and (d) geothermal power in [%] of total renewable generation capacity at 25% potential expansion in the year 2030. [1]

"The most salient pattern pertains to the tradeoff between solar photovoltaics and wind energy, driven by cost considerations rather than quantitative potential limits. This phenomenon is most evident in the Sahara region, as well as in Kenya, Madagascar, and with limited presence in South Africa. In these regions, the presence of substantial wind energy resources, particularly during nocturnal hours, enhance the viability of solar power generation. This synergy between wind and solar power results in an increase in the full load hours of the electrolyzer leading to a reduction in the necessary investment for electrolysis. In conjunction with elevated full load hours of wind farms in these regions, this synergy equalizes the higher investment for wind farms and consequently reduces the levelized cost of hydrogen. The most cost-effective hydrogen is produced in regions with wind capacity shares ranging from 70% to 95%. This trend is most evident in Mauritania along the northern coastline and on the central Tagant plateau, owing to the exceptionally high local wind speeds, but is also discernible in Southern Madagascar and in northern and central Kenya. The impact on electrolysis full load hours is substantial, as illustrated in" [1], as Figure 47 shows, "on the left. Regions with high wind shares exhibit electrolysis full load hours that exceed those of the best solar-only regions by up to 60%. A similar high full load hours are achieved in regions dominated by reservoir hydropower plants, which can flexibly shift or smoothen generation peaks." [1]

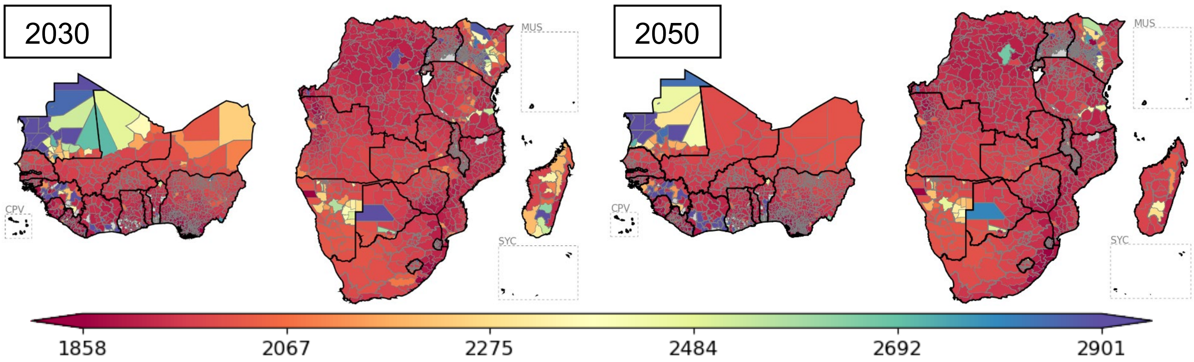


Figure 47 Electrolysis full load hours [h/a] in the years 2030 (left) and 2050 (right) in comparison. [1]

“However, as illustrated in the right-hand side of ” [1] Figure 47 “a decline in electrolysis full-load hours towards 2050 is projected for many of the wind regions discussed above. This decline is attributed to a shift in energy supply toward solar photovoltaics, as evidenced by the optimal system designs projected for the year 2050” [1] (Figure 48). “With the exception of wind capacities in the Kalahari region, which are attributable to limitations in suitable land for open-field photovoltaics, wind will play a significant role by 2050 only in Mauritania, Kenya, and two central regions of Madagascar. In Mali and Niger, for instance, wind power has been entirely superseded by open-field photovoltaics by the year 2050. In Kenya and central Madagascar, as well as in several regions of Mauritania, the share of wind has been reduced to a significant extent. This transition is primarily driven by the substantial cost reductions witnessed in photovoltaic technology between 2030 and 2050, when compared to the already mature wind turbine sector. This shift has implications for electrolysis full load hours, which decline in tandem with the wind share compared to 2030 levels. The cost advantage of photovoltaics, when considered in conjunction with the reduced capital expenditures (CAPEX) for electrolysis in 2050 as compared to 2030, results in a net benefit that outweighs the additional capacity required for electrolysis.” [1]

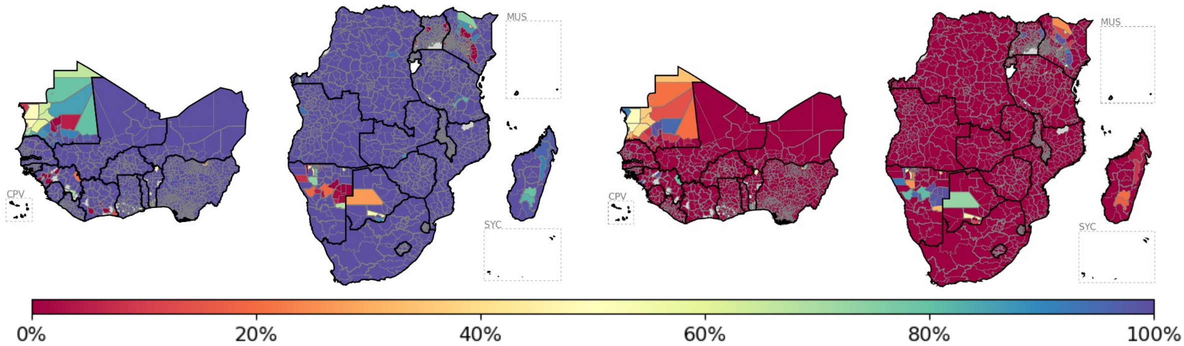


Figure 48: Share of solar photovoltaics (left) and onshore wind (right) in [%] of total renewable generation capacity at 25% potential expansion in the year 2050. [1]

"It is important to acknowledge the proposal of lithium-ion batteries as a system component. However, it should be noted that this is not the most optimal solution. When considering the cost assumptions for the coming decades and the local generation profiles, it is more economical to overbuild generation capacities and/or operate electrolysis at reduced utilization rates. This approach is predicated on the assumption of a time-independent, lowest-cost hydrogen generation process; however, it is acknowledged that this may be subject to modification as specific demand profiles of electricity or hydrogen must be met." [1]

2.9 Socio-political context and development opportunities

The socio-political context for green hydrogen feasibility is assessed via CIs results at the national level, while the development opportunities and local impact of green hydrogen deployment is assessed through regional CI results.

2.9.1 Socio-political framework for green hydrogen feasibility

"The index results are detailed inTable 8, including the total score (Ind) and country rankings (Rank). Overall, island countries like Cabo Verde, Mauritius, and Seychelles perform well. Among continental countries, those in the Southern and Eastern regions demonstrate better overall results compared to those in the Western region. South Africa, Botswana, and Namibia rank highest, followed by Ghana, Kenya, Rwanda, and Zambia. At the bottom are Guinea-Bissau and the Democratic Republic of the Congo. However, the final index ranking incorporates a diverse set of results from all composite indicators. These sub-indicators are crucial for understanding areas that require improvement, the potential for either a more export-oriented or domestic-oriented green hydrogen industry, as well as the potential complementarities and synergies between neighboring countries.

In this regard, Ghana and Kenya stand out for their more attractive energy frameworks (EF) and sustainable policies (SP), while island countries excel in regulatory (RF) and political frameworks (PF), primarily due to their secure and attractive investment landscapes. Regarding exports (HEF), South Africa and Ghana perform higher in the West and South Africa, respectively."[9]

Table 7 Total index feasibility score for the selected regions based on index structure (Figure 24) .[9]

Aggregation level				A4	A3			A2			
Country	**CN**	**Region**	**Rank**	**Ind**	**ESP**	**HEF**	**RPF**	**EF**	**SP**	**PF**	**RF**
Mauritius	MUS	S-E	1	0.68	0.60	0.50	0.95	0.5	0.66	0.94	0.95
Botswana	BWA	S-E	2	0.66	0.49	0.68	0.80	0.4	0.59	0.88	0.72
South Africa	ZAF	S-E	2	0.66	0.65	0.64	0.68	0.5	0.83	0.71	0.64
Namibia	NAM	S-E	4	0.64	0.69	0.53	0.70	0.8	0.56	0.75	0.65
Cabo Verde	CPV	W	4	0.64	0.47	0.61	0.84	0.3	0.62	0.85	0.84
Ghana	GHA	W	4	0.64	0.66	0.60	0.66	0.6	0.73	0.65	0.67
Kenya	KEN	S-E	7	0.58	0.71	0.53	0.48	0.65	0.78	0.34	0.63
Rwanda	RWA	S-E	8	0.57	0.38	0.62	0.72	0.35	0.42	0.58	0.85
Seychelles	SYC	S-E	8	0.57	0.40	0.56	0.74	0.2	0.60	0.75	0.73
Zambia	ZMB	S-E	10	0.56	0.66	0.44	0.58	0.7	0.58	0.48	0.68
Uganda	UGA	S-E	11	0.50	0.51	0.47	0.51	0.46	0.55	0.36	0.66
Lesotho	LSO	S-E	12	0.49	0.45	0.46	0.54	0.3	0.62	0.52	0.56
Senegal	SEN	W	12	0.49	0.47	0.41	0.58	0.4	0.58	0.59	0.57
Côte d'Ivoire	CIV	W	14	0.48	0.45	0.51	0.48	0.4	0.48	0.36	0.60
Mauritania	MRT	W	15	0.47	0.56	0.41	0.45	0.51	0.61	0.33	0.56
Malawi	MWI	S-E	16	0.46	0.52	0.33	0.53	0.5	0.52	0.45	0.61
Eswatini	SWZ	S-E	17	0.44	0.45	0.40	0.47	0.4	0.46	0.37	0.57
Burkina Faso	BFA	W	17	0.44	0.37	0.45	0.50	0.3	0.43	0.46	0.53
Angola	AGO	S-E	19	0.42	0.57	0.34	0.34	0.6	0.53	0.23	0.46
Mozambique	MOZ	S-E	19	0.42	0.48	0.31	0.47	0.5	0.44	0.37	0.57
Nigeria	NGA	W	19	0.42	0.50	0.43	0.32	0.3	0.71	0.21	0.43
Zimbabwe	ZWE	S-E	22	0.40	0.39	0.51	0.28	0.4	0.36	0.11	0.46
Benin	BEN	W	22	0.40	0.35	0.31	0.53	0.16	0.54	0.50	0.57
Gambia	GMB	W	24	0.38	0.29	0.36	0.49	0.1	0.45	0.43	0.54
Mali	MLI	W	24	0.38	0.40	0.35	0.39	0.3	0.48	0.33	0.45
Comoros	COM	S-E	26	0.37	0.31	0.42	0.37	0.2	0.43	0.26	0.48
Togo	TGO	W	28	0.36	0.36	0.31	0.43	0.2	0.54	0.31	0.55
Guinea	GIN	W	29	0.35	0.35	0.33	0.38	0.2	0.50	0.22	0.53
Sierra Leone	SLE	W	29	0.35	0.33	0.25	0.47	0.5	0.19	0.37	0.57
Niger	NER	W	31	0.34	0.33	0.28	0.43	0.3	0.35	0.35	0.50
Tanzania	TZA	S-E	32	0.32	0.36	0.09	0.50	0.3	0.44	0.43	0.57
Liberia	LBR	W	33	0.30	0.33	0.20	0.36	0.3	0.34	0.32	0.40
Guinea-Bissau	GNB	W	34	0.26	0.19	0.27	0.33	0.1	0.31	0.17	0.48
Congo DR	COD	S-E	35	0.22	0.41	0.05	0.20	0.5	0.35	0.17	0.22

“The detailed disaggregation of the scores is reported inTable 8. In the Western region, Ghana stands out with an overall Energy framework and sustainability policies (ESP) score of 0.66, followed by Mauritania (0.56). Gambia and Guinea-Bissau, perform very poorly in terms of this sub-index with scores of 0.29 and 0.19, respectively. When looking into the sub-components of ESP, Ghana confirms its first position concerning both energy framework (EF) and sustainable policies (SP) with a score of 0.6 and 0.73, respectively. While a moderate correlation between the EF and SP indicators can be noticed, EF and SP indicators do not necessarily go hand in hand: e.g., Togo has the worst performance in terms of EF (0.20) but an above-average score in SP (0.54). Mainly energy security has the most positive impact on the final index score, with Cape Verde, Gambia, and Benin ranking low in terms of energy security.

In the Southern and East region, Kenya performs best in terms of ESP with a score of 0.71, followed by Namibia (0.69). In contrast, Comoros (0.31) has the lowest scores in the region. Concerning the energy framework, Namibia (0.8) and Zambia (0.70) hold the top positions. Regarding sustainable policies, South Africa ranks first with a score of 0.83, followed by Kenya (0.78).

Overall, both regions appear to have a few countries performing significantly better than the rest, especially Ghana and Kenya which combine both the implementation of sustainability-oriented policies and a good energy framework and infrastructure.

Regarding Hydrogen export feasibility (HEF Cabo Verde (0.61), Ghana (0.60), and Côte d'Ivoire (0.51) perform best. Weaknesses common to Cabo Verde, Guines-Bissau, and Gambia are export capacity, fuel exports, and regional exports indicators. Burkina Faso, Niger, and Sierra Leone rank low in terms of risk and security. In the Southern and East region, Table 8shows that South Africa stands out with a score of 0.64 in terms of HIE. The infrastructure score is a main weakness for both Mozambique and Madagascar. Mauritius ranks low on fuel exports and regional exports, whereas Malawi and Botswana underperform in terms of documentary compliance and logistic score.

Finally, regarding Regulatory and Political framework (RPF), island countries performed well with a score of 0.95 for Mauritius, 0.84 for Cabo Verde, and 0.74 for Seychelles. Regarding political framework, additional continental countries that perform well are Botswana (0.88) and Ghana (0.65). For Regulatory framework (RF), besides island countries, Rwanda has a high score as well of 0.85."[9]

2.9.2 Mapping local impact of green hydrogen projects

For this analysis of socio-economic development in Africa, the Socio-economic indicator (Figure 49) provides a comprehensive overview of the composite indicator research, with high results indicating potential areas of interest for further green hydrogen and renewable energy projects.

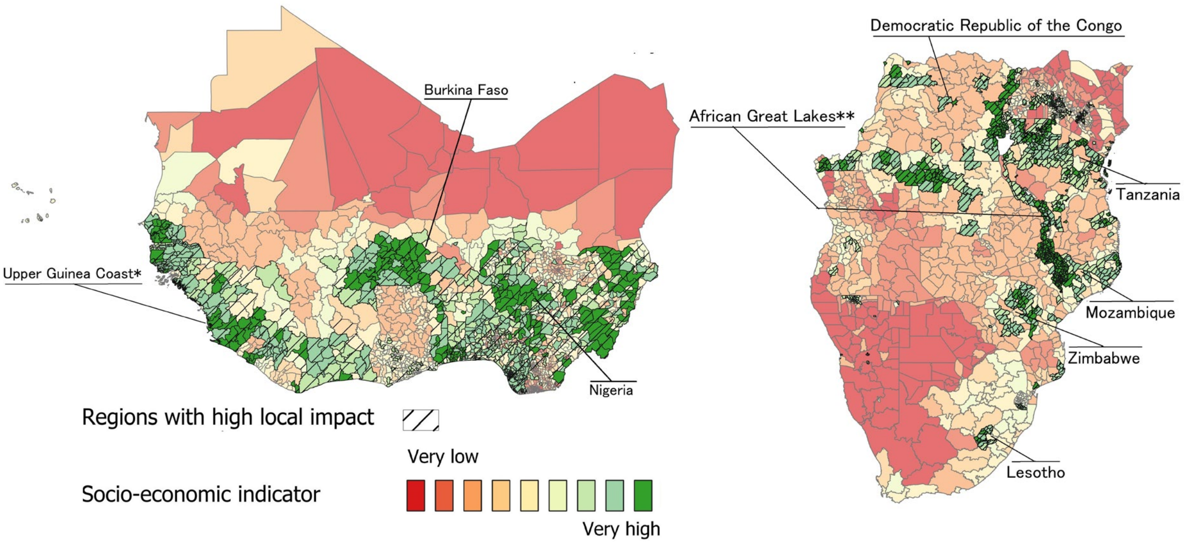


Figure 49 Socio-economic indicator measuring the impact of green hydrogen project.[1]

As demonstrated in Figure 49, the most significant local impact (highest values) of such projects is evident around the African Great Lakes region of East Southern Africa, including Lake Malawi, Lake Tanganyika, and Lake Victoria. Similar results can be identified in inland regions near the southern and eastern borders of the Democratic Republic of the Congo, northern

Tanzania, and parts of Mozambique, Zimbabwe, and Lesotho. For Western Africa, the coastal regions of Upper Guinea and the inland regions encompassing Nigeria and Burkina Faso demonstrate a notable local impact. This high local impact in the described regions is primarily attributable to a combination of factors, including access to energy and macroeconomic potential impacts, as illustrated by the following two sub-indicators:

The impact of the projects in terms of the Socio-economic indicator is reflected in the composition of AE, which depicts the energy access indicator in capita/km²; ME, which highlights the macroeconomic effect in Jobs/ (Mwp*km²); and OE, which summarizes the score of the other effect. The underlying indicator results for AE and ME for the two regions are presented in the form of normalized score maps and statistical summaries in the subsections below.

Energy Access indicator (AE)

The energy access sub-index considers a combination of regional access to energy, and the access density. A combination of factors, mainly low access to essential services such as electricity and clean fuel, contributes to a high local impact value. The regional distribution is shown in Figure 50, along with the indicator statistics, energy access, and population density average at the national level.

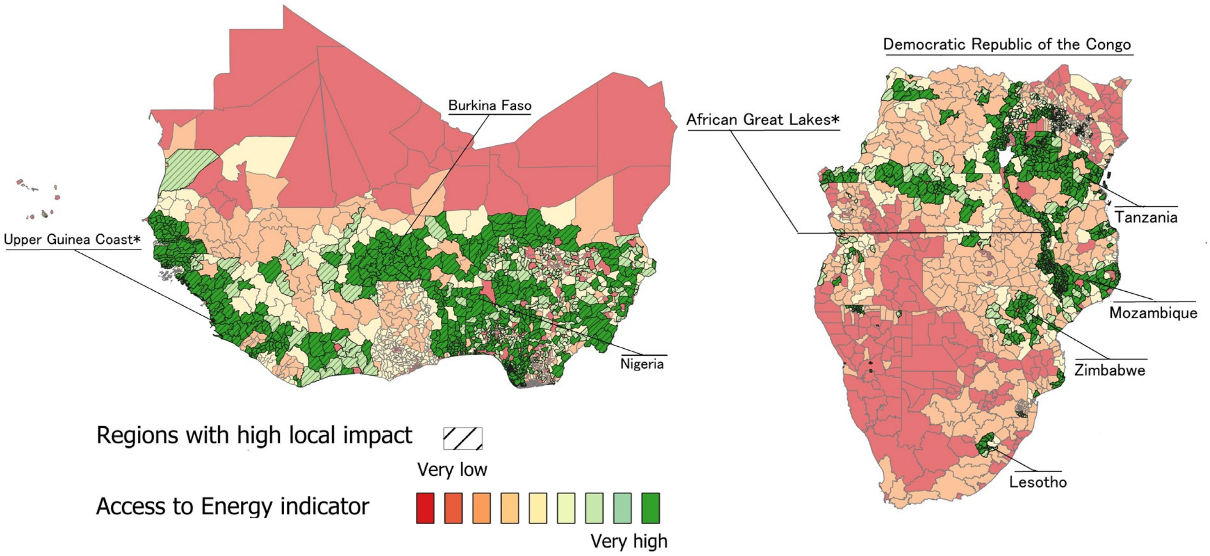


Figure 50 Mapping the energy access indicator.[1]

“Malawi, the northern regions of Tanzania, the southern areas of Mozambique, and western Zimbabwe, as well as the southern part of the Democratic Republic of Congo, exhibit a significant local impact in this regard. For West Africa, the impact extends to the entire southern region, except Ghana, the Ivory Coast, and sparsely populated areas in the central region”[1] (Figure 50). ”Notably, countries such as Burkina Faso, Sierra Leone, and Liberia are showing particularly low access rates, with an average of less than 30% access to electricity and less than 20% access to clean fuels. Nevertheless, the significance of considering the population density is exemplified by the case of Niger. In this instance, despite the low access to electricity, which is below 20% on average, the sub-index value remains relatively low for Niger due to the sparsely populated or nomadic areas.

A comparison of the AE indicator statistics at the national level”[1] (Table 9) “reveals that in the Western region Nigeria, Gambia, and Sierra Leone, followed by Benin and Burkina Faso, have the greatest potential impact. This impact arises primarily from two factors: the high population density in the first two countries and the low levels of energy access for the remaining. It is also relevant to highlight that the interquartile range (IQR) for Gambia and Nigeria is higher than that of other countries due to regional inequalities in terms of electrification and population distribution, which is particularly evident in the case of Nigeria. Accordingly, it can be argued that these countries would greatly benefit from the implementation of projects that aim to enhance renewable energy potential. Conversely, some countries will not benefit from similar energy capacity projects, such as Cape Verde and Ghana, as they already have high levels of energy access.

In the depicted Southern and East regions"[1] (Table 9), "due to a combination of low average access to electricity and high population density, Malawi, Rwanda, and Uganda report the highest averages, followed by Tanzania. By contrast, countries such as Botswana and South Africa show lower values due to their high electrification rates."[1]

Table 8 Energy access indicator statistics results along national energy access averages for West (W), East and Southern (S-E) regions. [1]

Country	CN	Region	AE indicator statistics				Energy access	Density
			Median	Q25	Q75	IQR	Average in %	Average in c/km2
Benin	BEN	W	48.3	31.8	79.4	47.7	42.0	110.0
Burkina Faso	BFA	W	45.4	33.5	74.7	41.2	19.0	79.0
Cabo Verde	CPV	W	5.0	3.0	9.7	6.7	95.5	139.0
Côte d'Ivoire	CIV	W	26.0	16.4	30.7	14.3	71.1	85.0
Gambia	GMB	W	130.1	23.4	194.0	170.6	63.7	246.0
Ghana	GHA	W	19.7	7.9	24.0	16.2	86.3	139.0
Guinea	GIN	W	32.2	24.0	40.4	16.4	46.8	55.0
Guinea-Bissau	GNB	W	40.8	28.0	49.8	21.8	35.8	72.0
Liberia	LBR	W	22.0	12.2	35.2	23.1	29.8	54.0
Mali	MLI	W	14.2	5.2	23.8	18.5	53.4	17.0
Mauritania	MRT	W	0.7	0.3	6.9	6.6	47.7	5.0
Niger	NER	W	38.4	15.6	63.7	48.1	18.6	20.0
Nigeria	NGA	W	126.1	54.8	268.9	214.1	59.5	232.0
Senegal	SEN	W	39.8	12.7	54.6	41.9	68.0	89.0
Sierra Leone	SLE	W	68.5	46.8	73.3	26.5	27.5	113.0
Togo	TGO	W	43.0	34.3	49.7	15.4	55.7	156.0
Angola	AGO	S-E	6.8	1.7	17.7	16.0	48.2	27.0
Botswana	BWA	S-E	0.2	0.0	1.5	1.5	73.3	4.0
Congo DR	COD	S-E	14.5	0.1	30.5	30.4	20.8	41.0
Eswatini	SWZ	S-E	15.0	13.5	21.7	8.1	82.9	68.0
Kenya	KEN	S-E	36.0	21.2	56.8	35.6	76.5	97.0
Lesotho	LSO	S-E	37.8	27.2	44.4	17.2	50.4	71.0
Malawi	MWI	S-E	149.4	101.1	254.6	153.5	14.2	208.0
Mozambique	MOZ	S-E	20.0	8.6	31.0	22.3	31.5	41.0
Namibia	NAM	S-E	5.8	1.0	47.5	46.5	55.2	3.0
Rwanda	RWA	S-E	397.6	256.2	465.2	209.0	48.7	538.0
South Africa	ZAF	S-E	2.5	0.0	5.2	5.1	89.3	49.0
Tanzania	TZA	S-E	55.0	26.6	90.8	64.1	42.7	69.0
Uganda	UGA	S-E	140.0	64.5	240.1	175.5	45.2	235.0
Zambia	ZMB	S-E	11.0	7.8	15.4	7.6	46.7	25.0
Zimbabwe	ZWE	S-E	27.4	15.0	37.1	22.2	49.0	39.0

Macroeconomic Effects indicator (ME):

“The macroeconomic effect sub-index is evaluated in terms of the regional impact on employment, with unemployment data serving as one of the main indicators”[1] (Figure 51). “This index demonstrates that the most significant possible macroeconomic developments in West Africa are possible in Nigeria, Burkina Faso, and Cape Verde, as well as in regions such as the Upper Guinea Coast. Similarly, Eswatini, Lesotho, Malawi, Uganda, and the north-west of South Africa emerge as key areas in the Southern African context. Nigeria stands out as a state with the highest employment impact, due to its large labor force and dispersed but dense population. Nevertheless, countries such as Angola and the Democratic Republic of Congo exhibit a lower impact on employment levels despite comparable labor forces. This disparity occurs because of a mismatch between the distribution of energy potential and the population. It should be noted that Botswana has the lowest local employment impact, which is largely attributable to a sparse labor force, population distribution disparities, and high labor costs.”[1]

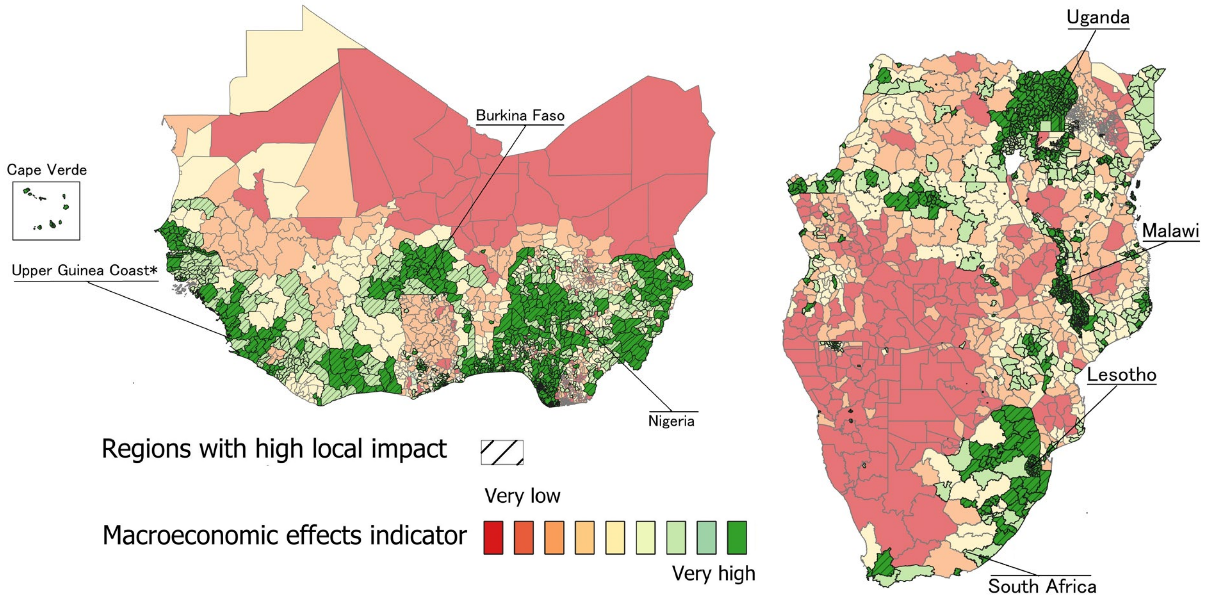


Figure 51 Mapping of the macroeconomic effects indicator.[1]

“At the national level, the ME indicator statistics”[1] *(*Table 10*)* “demonstrate that in the Western region, the macroeconomic effect values are primarily related to the employment factor of increased electrical power and their potential for job creation. Burkina Faso, Gambia, Ghana, Nigeria, and Togo are notable countries in this region. Cabo Verde, despite having good energy access, exhibits a high macroeconomic effect value due to its high unemployment rate (13.3%). The results indicate that Kenya, Eswatini, Lesotho, Malawi, and Rwanda have a noteworthy potential for job creation from renewable energy projects (high macroeconomic effect). In this regard, for South Africa, it is mainly the unemployment rate that could be tackled with such development projects. In contrast, to other countries, the macroeconomic effect is attributable to the employment factor here in terms of potential job creation per megawatt-peak in these countries higher than 5.8 job/Mwp.

For this analysis, the focus is on the local labor forces in construction or operations and maintenance (OM), with manufacturing jobs being excluded. Nevertheless, the potential for competitive regional solar and wind industries to create an additional 30% and 11% of jobs, respectively, represents a significant opportunity for economic growth. Furthermore, due to data constraints and the fact that the analysis is conducted using local employment factors, indirect and induced jobs are not accounted for. This limitation analysis does not conflict with a local impact indicator that aims to analyze direct local jobs without population displacement.

Whereas Nigeria's potential stems primarily from its large workforce, West Africa's potential stems from its comparatively lower labor costs. Thus, for instance, green hydrogen production from wind, even with a lower employment impact than solar hydrogen production, still generates up to 11 times more jobs per megawatt peak than in the EU. In contrast, countries in Southern Africa, such as South Africa, Botswana, and Namibia, have labor costs that are on average only two to three times higher than in the European Union. Nevertheless, even in these countries, particularly in the northwestern region of South Africa with a high population density, the high labor cost is offset by soaring unemployment rates exceeding 20% over the past two decades. This highlights the necessity for strategic interventions to leverage green hydrogen and renewable energy deployment as a potential employment catalyst."[1]

Table 9 Macroeconomic indicator statistics results along employment national indicators for West (W), East and Southern (S-E) regions. [1]

			ME indicator statistics				Unemployment	Employment Factor
Country	CN	Region	Median	Q25	Q75	IQR	Average in %	Average in job/MWp
Benin	BEN	W	6.4	2.0	14.6	12.6	1.6	5.9
Burkina Faso	BFA	W	6.7	4.8	10.8	6.0	5.0	6.0
Cabo Verde	CPV	W	26.2	15.4	53.9	38.5	13.3	4.5
Côte d'Ivoire	CIV	W	5.6	3.2	8.0	4.9	2.7	5.8
Gambia	GMB	W	16.3	13.2	27.4	14.2	4.6	5.9
Ghana	GHA	W	13.7	8.2	36.1	28.0	3.7	5.8
Guinea	GIN	W	6.0	4.1	9.0	4.9	5.5	5.8
Guinea-Bissau	GNB	W	5.4	3.7	6.1	2.4	3.5	6.0
Liberia	LBR	W	4.1	2.0	6.1	4.0	3.4	5.7
Mali	MLI	W	1.0	0.4	1.9	1.5	2.4	5.9
Mauritania	MRT	W	1.5	0.3	3.3	2.9	10.9	5.8
Niger	NER	W	0.6	0.2	1.1	0.9	0.6	6.0
Nigeria	NGA	W	29.1	13.3	81.9	68.6	5.6	5.4
Senegal	SEN	W	3.8	2.9	14.2	11.3	3.4	5.6
Sierra Leone	SLE	W	11.3	7.1	12.9	5.8	3.5	5.7
Togo	TGO	W	7.7	5.8	14.3	8.5	3.9	5.9
Angola	AGO	S-E	1.0	0.4	2.2	1.8	10.0	1.8
Botswana	BWA	S-E	0.2	0.0	22.1	22.1	20.6	0.3
Congo DR	COD	S-E	3.8	1.5	26.8	25.2	4.8	5.9
Eswatini	SWZ	S-E	29.4	18.7	30.7	12.0	23.9	3.1
Kenya	KEN	S-E	17.0	7.8	36.0	28.1	5.2	5.8
Lesotho	LSO	S-E	6.3	4.0	12.8	8.8	17.7	2.3
Malawi	MWI	S-E	22.1	14.3	45.8	31.4	5.4	5.9
Mozambique	MOZ	S-E	2.4	1.1	4.2	3.1	3.7	5.9
Namibia	NAM	S-E	0.7	0.1	4.7	4.6	20.6	1.4
Rwanda	RWA	S-E	162.4	121.4	189.1	67.8	12.8	5.9
South Africa	ZAF	S-E	7.8	4.1	16.7	12.6	26.5	1.4
Tanzania	TZA	S-E	5.1	2.2	11.5	9.3	2.5	5.9
Uganda	UGA	S-E	16.4	7.8	25.9	18.1	4.0	5.8
Zambia	ZMB	S-E	0.6	0.3	1.2	1.0	5.8	1.6
Zimbabwe	ZWE	S-E	3.9	1.9	6.2	4.3	7.6	4.2

3. Conclusion

“In the domain of energy supply, the competition for land between electricity and hydrogen has garnered attention due to the substantial potential for both. In photovoltaic (PV) dominated systems, the costs are less impacted by the expansion rate, creating opportunities for regions with abundant resources. The identification of regions with inexpensive potential that exceeds their own demand creates the potential for these regions to become exporters within and outside of Africa. The hydrogen cost patterns observed in this study, generally align with those reported in other studies that evaluated LCOH in African countries. In comparison to the findings of Gado et al. [91], the utilization of a co-optimized PV and wind hybrid system across the considered countries can reduce the reported LCOH can be lowered by 2 - 3 EUR/kg in 2030.

“However, it is crucial to note that excessive exploitation of groundwater resources in coastal regions can significantly exacerbate the risks of saltwater intrusion and land subsidence [92,93]. This is in addition to the environmental concerns discussed by Bierkens and Wada [94]. It is therefore imperative to strike a balance between desalination of seawater and groundwater extraction, particularly in coastal areas. It is crucial to exercise prudence in the planning of groundwater exploitation, even when cost-effective solutions appear viable. Prioritizing desalination over extensive groundwater extraction is instrumental in safeguarding these vital freshwater reserves and ensuring a more sustainable and resilient water supply. Desalination mitigates risks such as land subsidence and long-term aquifer depletion, which can have significant environmental and economic consequences. Consequently, the incorporation of desalination into comprehensive water resource management strategies is essential to maintain the integrity of coastal water supplies. Beyond its application in hydrogen production, a reasonable oversizing of the desalination and water transportation infrastructure could enhance local access to affordable and clean water.

“The impact of groundwater availability is a salient factor in this regard. In addition, the overall green hydrogen cost potential is driven by the local land eligibility constraints which are tied to the local prevailing policies or regulations. For countries with similar land area, the eligibility of such land for green hydrogen production can vary substantially, resulting in significant differences in the levelized cost of hydrogen among countries, as illustrated.

“Notably, the coastal regions of Western Africa and Northeastern Africa are identified as promising hubs for hydrogen production, offering not only significant potential for generating green energy but also for delivering substantial local economic benefits. These regions possess abundant natural resources, which, when combined with their strategic geographic locations, make them ideal candidates for large-scale hydrogen production and export. The region’s rapidly expanding population and the sizeable labor force present a distinctive advantage, particularly in the early stages of hydrogen economy development, where there will be a significant demand for construction, installation, operation, and maintenance jobs. However, to capitalize on the full potential of this emerging technology, it is imperative to allocate resources toward capacity building to further develop a local manufacturing industry. In the long term, this development could be driven by the competitive costs of African technologies could be driven by the African Continental Free Trade Agreement (AfCFTA),which is expected to enhance cross-border trade and investment in the renewable energy sector.

“The current inadequate energy access levels in many African regions could pose challenges such as increasing the risk of energy supply insecurity for hydrogen production and the potential for energy-related conflicts. The developed approach underscores the potential of green hydrogen projects to enhance energy security and broaden electricity access, thereby addressing long-standing energy deficits. This paradigm shift has the potential to mitigate the risks associated with reliance on traditional fossil fuels and imports, thereby contributing to a more sustainable and resilient energy system.

“The presence of established fossil fuel and chemical industries in countries such as Nigeria, Angola and South Africa provides a solid foundation for hydrogen production and export. These industries possess existing substantial infrastructure and investment incentives that can be repurposed and upgraded to support hydrogen production. Furthermore, existing oil terminal infrastructures could be repurposed for liquid organic hydrogen carriers. This strategy is predicated on the maximization of existing assets and the reduction of the initial investment required to develop a hydrogen economy. Nevertheless, in order to circumvent the risk of technological lock-in and to facilitate a seamless transition to green hydrogen, the implementation of comprehensive decarbonization policies is imperative. These policies should aim to gradually phase out reliance on fossil fuels while promoting the adoption of clean, renewable energy sources.”[11]

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5. Appendix

5.1 Regional fact sheets

The presented factsheets summarize the different map layers that provide easily accessible information about the countries of the focus regions. Those various layers cover the aspects that are relevant for green hydrogen production like socio-economic indicators, land eligibility, renewable energy sources, groundwater sustainable yield, and hydrogen potentials.

5.1.1 Socio-political context assessment

The Energy framework and sustainability policies (EFP) is classified from a low score of 0 to a maximum of 1 for green hydrogen project implementation feasibility regarding current energy and power sector performances and future energy policies. Regarding current performance, it is measured by energy security and intensity, dependency on traditional biomass, investment and the use of renewable energy sources. The energy policies cover the published policies, the promotion of renewable energy, and the universal access to clean fuel and electricity targets feasibility.

The Hydrogen export feasibility (HFE) is classified from a low score of 0 to a maximum of 1 regarding export feasibility based on export, transport and electricity infrastructure performances. It includes the cost and ease of export based on Doing Business methodology and existing export infrastructure.

The Political and Regulatory Framework Indicator (RPF) is classified from a low score of 0 to a maximum of 1 regarding security and feasibility of green hydrogen project investment. This includes two composites' indexes assessing investment and governance scores based on Doing Business methodology and World Governance Index normalized to the region.

Table 10 The Energy Sector Framework and Policies feasibility (ESP), export and Transport Infrastructure feasibility (HEF), and the Political and Regulatory Framework feasibility (RPF) for West and South-eastern African countries.[9]

Country		EFP	HFE	RPF
Mauritius	MUS	0.60	0.50	0.95
Botswana	BWA	0.49	0.68	0.80
South Africa	ZAF	0.65	0.64	0.68
Namibia	NAM	0.69	0.53	0.70
Cabo Verde	CPV	0.47	0.61	0.84
Ghana	GHA	0.66	0.60	0.66
Kenya	KEN	0.71	0.53	0.48
Rwanda	RWA	0.38	0.62	0.72
Seychelles	SYC	0.40	0.56	0.74
Zambia	ZMB	0.66	0.44	0.58
Uganda	UGA	0.51	0.47	0.51
Lesotho	LSO	0.45	0.46	0.54
Senegal	SEN	0.47	0.41	0.58
Côte d'Ivoire	CIV	0.45	0.51	0.48
Mauritania	MRT	0.56	0.41	0.45
Malawi	MWI	0.52	0.33	0.53
Eswatini	SWZ	0.45	0.40	0.47
Burkina Faso	BFA	0.37	0.45	0.50
Angola	AGO	0.57	0.34	0.34
Mozambique	MOZ	0.48	0.31	0.47
Nigeria	NGA	0.50	0.43	0.32
Zimbabwe	ZWE	0.39	0.51	0.28
Benin	BEN	0.35	0.31	0.53
Gambia	GMB	0.29	0.36	0.49
Mali	MLI	0.40	0.35	0.39
Comoros	COM	0.31	0.42	0.37
Togo	TGO	0.36	0.31	0.43
Guinea	GIN	0.35	0.33	0.38
Sierra Leone	SLE	0.33	0.25	0.47
Niger	NER	0.33	0.28	0.43
Tanzania	TZA	0.36	0.09	0.50
Liberia	LBR	0.33	0.20	0.36
Guinea-Bissau	GNB	0.19	0.27	0.33
Congo DR	COD	0.41	0.05	0.20

5.1.2 Groundwater Assessment for West and South-eastern African

The national-level summary of groundwater sustainable yield estimates is provided for the years 2020 (2015–2035), 2030 (2015–2045), and 2050 (2036–2065) under the RCP2.6 and RCP8.5 climate scenarios for conservative (Table 11), medium (Table 12), and extreme (Table 13) environmental scenarios. In planning for water supply, three environmental scenarios are considered based on the percentage of annual recharge reserved for environmental flow (preserving nature itself). The extreme scenario allocates 30% of the recharge to environmental flow, leaving 70% for supplementary uses like green hydrogen production. The medium scenario sets aside 60% for environmental flow, resulting in 40% for other uses. The conservative scenario dedicates 90% to environmental flow, leaving just 10% for supplementary uses. These scenarios are considered for better comparison and to promote sustainability. Note that Table 11, Table 12 and Table 13 are available in the Supplementary from Winkler et al. [1]

Table 11 . The conservative groundwater sustainable yield estimation for 2020 (2015 – 2035), 2030 (2015 – 2045), and 2050 (2036 – 2065) for West and South-eastern African countries under RCP2.6 and RCP8.5 climate scenarios. [1]

Country	Groundwater sustainable yield (conservative scenario) [mm yr-1]					
	2020		2030		2050	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
Angola	29.8	28.7	29.6	28.6	27.3	26.4
Botswana	13.0	11.3	13.0	11.2	11.3	10.7
Democratic Republic of the Congo	28.7	27.4	27.7	27.0	25.2	24.9
Comoros	91.6	79.4	86.4	80.1	85.4	83.8
Lesotho	52.1	51.3	51.7	50.0	48.0	49.1
Madagascar	30.2	31.7	28.5	31.0	27.2	28.3
Mozambique	11.3	9.9	10.2	9.8	9.0	8.8
Mauritius	0.0	0.0	0.0	0.0	0.0	0.0
Malawi	7.2	5.7	5.5	4.9	3.5	3.1
Namibia	8.1	7.8	8.3	7.6	7.5	7.2
Swaziland	22.5	23.8	22.4	22.3	19.6	19.7
Seychelles	-	-	-	-	-	-
Tanzania	8.6	8.7	8.1	8.4	7.5	7.3
South Africa	15.7	14.8	15.7	14.5	13.9	13.9
Zambia	14.5	13.3	13.2	13.0	11.7	11.1
Zimbabwe	6.8	6.0	6.1	5.8	5.3	5.2
Kenya	3.9	3.7	3.3	3.3	2.4	3.1
Rwanda	9.3	7.5	6.8	6.0	3.5	3.5
Uganda	5.0	4.5	4.1	3.7	2.6	2.5
Benin	5.2	5.0	4.1	4.2	2.2	2.0
Burkina Faso	3.1	3.7	2.7	3.0	1.6	1.3
CÃ´te d'Ivoire	11.6	10.3	10.6	10.1	8.9	8.6
Cape Verde	-	-	-	-	-	-
Ghana	11.8	10.6	10.5	9.8	8.2	6.6
Guinea	29.5	27.3	28.5	26.5	25.3	24.4
Gambia	2.5	1.3	1.4	0.9	0.3	0.3
Guinea-Bissau	13.1	11.2	12.4	10.0	9.8	7.6
Liberia	56.8	50.8	55.8	51.5	51.4	50.0
Mali	2.5	2.4	2.3	2.3	1.9	1.7
Niger	4.0	4.1	3.8	3.8	3.2	2.8
Nigeria	10.9	10.3	9.2	8.7	6.1	5.2
Senegal	2.6	2.0	1.9	1.6	1.1	1.0
Sierra Leone	69.8	63.5	69.9	63.6	65.2	62.4
Togo	7.4	7.1	6.2	6.4	4.3	3.9
Mauritania	1.3	1.1	1.2	1.1	1.2	0.9

"-" indicates a lack of reliable input data in the simulations, not an absence of potential groundwater sustainable yield.

Table 12 The medium groundwater sustainable yield estimation for 2020 (2015 – 2035), 2030 (2015 – 2045), and 2050 (2036 – 2065) for West and South-eastern African countries under RCP2.6 and RCP8.5 climate scenarios. [1]

Country	Groundwater sustainable yield (medium scenario) [mm yr^{-1}]					
	2020		2030		2050	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
Angola	120.8	116.2	120.4	116.5	112.6	108.7
Botswana	52.4	45.4	52.1	45.2	45.6	43.1
Democratic Republic of the Congo	116.2	111.2	113.1	110.3	105.4	104.3
Comoros	366.7	317.7	345.7	320.4	341.8	335.4
Lesotho	216.5	213.3	216.6	209.4	206.0	209.6
Madagascar	137.7	144.8	132.4	143.6	132.7	137.7
Mozambique	46.9	41.2	42.8	41.0	39.0	38.5
Mauritius	-	-	-	-	-	-
Malawi	41.9	34.6	35.6	32.9	26.6	24.4
Namibia	32.9	31.7	33.5	30.7	30.4	29.2
Swaziland	107.6	113.0	108.1	107.8	99.7	99.4
Seychelles	-	-	-	-	-	-
Tanzania	38.7	38.9	37.4	38.6	37.3	36.7
South Africa	70.4	66.7	70.4	65.7	63.4	63.4
Zambia	62.0	57.2	57.0	56.5	52.1	49.7
Zimbabwe	31.9	28.3	29.1	28.1	26.3	25.8
Kenya	21.2	20.1	19.0	19.1	16.0	19.4
Rwanda	59.7	53.2	52.7	50.1	40.5	41.2
Uganda	27.4	25.5	24.7	22.6	18.7	17.9
Benin	28.3	27.5	25.7	26.0	20.8	18.8
Burkina Faso	17.8	20.6	16.8	18.6	13.7	12.1
CÃ´te d'Ivoire	53.2	48.0	50.5	48.4	46.5	45.0
Cape Verde	0.0	0.0	0.0	0.0	0.0	0.0
Ghana	56.9	52.0	53.0	49.9	46.3	38.9
Guinea	129.5	120.6	127.0	118.7	118.1	114.3
Gambia	18.7	12.6	14.5	11.3	6.9	7.8
Guinea-Bissau	61.2	53.6	59.6	49.9	53.8	44.4
Liberia	232.0	208.1	229.8	212.6	219.4	214.5
Mali	11.1	11.0	10.6	10.6	9.5	8.4
Niger	17.2	17.5	16.5	16.7	14.9	13.0
Nigeria	63.0	60.6	58.0	55.9	47.0	41.8
Senegal	13.3	10.7	11.0	9.3	7.9	7.5
Sierra Leone	300.3	274.8	302.6	277.3	290.9	280.4
Togo	43.4	41.8	39.6	40.2	33.2	30.2
Mauritania	5.2	4.5	4.9	4.4	4.8	3.9

"-" indicates a lack of reliable input data in the simulations, not an absence of potential groundwater sustainable yield.

Table 13 The extreme groundwater sustainable yield estimation for 2020 (2015 – 2035), 2030 (2015 – 2045), and 2050 (2036 – 2065) for West and South-eastern African countries under RCP2.6 and RCP8.5 climate scenarios. [1]

Country	Groundwater sustainable yield (extreme scenario) [mm yr^{-1}]					
	2020		2030		2050	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5	RCP2.6	RCP8.5
Angola	211.9	203.8	211.3	204.4	198.0	191.2
Botswana	91.7	79.5	91.3	79.2	79.8	75.5
Democratic Republic of the Congo	203.8	195.0	198.6	193.7	185.8	183.9
Comoros	641.7	556.0	605.0	560.8	598.1	587.1
Lesotho	381.1	375.6	381.7	369.0	364.2	370.3
Madagascar	248.2	260.9	239.4	259.3	241.6	250.6
Mozambique	82.7	72.6	75.6	72.4	69.2	68.4
Mauritius	-	-	-	-	-	-
Malawi	78.5	65.6	68.6	64.0	55.5	51.5
Namibia	57.6	55.5	58.7	53.9	53.4	51.3
Swaziland	193.2	202.6	194.5	194.0	181.1	180.6
Seychelles	-	-	-	-	-	-
Tanzania	69.2	69.5	67.1	69.2	68.1	67.0
South Africa	126.1	119.6	126.1	117.9	114.1	114.1
Zambia	110.0	101.5	101.2	100.2	92.9	88.7
Zimbabwe	57.4	51.1	52.5	50.8	47.8	46.9
Kenya	39.6	37.7	36.1	36.3	31.7	37.7
Rwanda	113.3	102.3	103.9	99.8	90.8	92.5
Uganda	50.7	47.5	46.9	43.4	38.7	37.2
Benin	52.1	50.5	48.1	48.8	41.9	38.2
Burkina Faso	33.0	37.9	31.7	35.1	27.9	25.2
CÃ´te d'Ivoire	95.2	85.9	90.8	87.1	85.1	82.5
Cape Verde	0.0	0.0	0.0	0.0	0.0	0.0
Ghana	103.1	94.4	96.9	91.6	87.1	73.8
Guinea	230.3	214.9	226.2	211.7	211.7	205.1
Gambia	35.5	24.8	28.9	23.1	16.9	18.7
Guinea-Bissau	109.6	96.3	107.2	90.2	98.2	81.6
Liberia	407.1	365.4	403.8	373.8	387.6	379.1
Mali	19.9	19.7	19.0	19.1	17.3	15.4
Niger	30.4	31.1	29.4	29.7	26.8	23.7
Nigeria	117.5	113.3	110.3	106.8	94.4	84.9
Senegal	24.6	19.8	20.8	17.6	15.7	15.0
Sierra Leone	531.1	486.5	535.5	491.3	516.8	498.9
Togo	80.5	77.6	74.6	75.6	65.1	59.8
Mauritania	9.1	8.0	8.7	7.7	8.4	6.9

"-" indicates a lack of reliable input data in the simulations, not an absence of potential groundwater sustainable yield.

5.1.3 Land eligibility for renewable energy technologies

Tables S1 and S2 are available in the Supplementary from Winkler et al.[1]

5.1.4 Renewable potentials

Table 14 Technical renewable electricity capacity potentials by country and technology. [1]

Country	Technical capacity potential [GW] by technology			
	Open-field PV	Onshore wind	Hydropower in 2030	Hydropower in 2050
Angola	21169	1328	8	8
Benin	39	7.5	0.32	0.58
Burkina Faso	3489	249	0.06	0.11
Botswana	3677	2071	-	-
Côte d'Ivoire	126	3.3	1.6	2.4
Democratic Republic of the Congo	24430	911	22	22
Comoros	2.7	0.04	-	-
Cape Verde	43	11	-	-
Ghana	774	117	1.9	2.3
Guinea	15	2.3	2.3	4.2
Gambia	114	8.7	-	-
Guinea-Bissau	224	2.1	0.02	0.02
Kenya	7581	895	1.6	1.6
Liberia	104	0.09	0.4	0.77
Lesotho	120	15	0.27	0.27
Madagascar	2706	953	0.45	0.45
Mali	30480	4950	0.44	1.2
Mozambique	13992	1153	6.1	6.1
Mauritania	29274	4058	-	-
Mauritius	6	0.13	-	-
Malawi	850	0.38	1.3	1.3
Namibia	3748	2760	0.65	0.65
Niger	29504	4618	0.35	0.35
Nigeria	10112	957	5.9	10
Rwanda	76	38	0.33	0.33
Senegal	2139	339	-	0.13
Sierra Leone	292	6.4	0.47	0.94
Swaziland	117	4.4	0.19	0.19
Seychelles	0.03	-	-	-
Togo	955	22	0.18	0.19
Tanzania	8135	190	4.6	5.3
Uganda	1957	115	3.3	3.9

South Africa	21298	3059	0.74	0.74
Zambia	9227	454	6.4	6.4
Zimbabwe	4520	684	3.5	3.5

Notes: values are rounded up to the nearest decimal. Zero values represent values under 0.05; "-" denotes countries for which the use of current input data did not result in any potential. For hydropower it denotes no hydropower plants with the status 'Existing', 'Committed', 'Candidate', 'Planned' with a capacity larger than 10MW were found for the corresponding year according to Sterl et al. [38]. There is no capacity potential change between 2030 and 2050 for onshore wind and open-field PV because the local preferences in the land eligibility analysis that determine the installable capacity remain fixed across the evaluated years. Consequently, the same amount of land, installable capacity, and ultimately electricity generation also remains the same. Onshore wind potentials lean more towards a 2050 scenario since a synthetic turbine with improved efficiency was used.

Table 15 Technical annual renewable electricity generation potentials by country and technology. [1]

Country	Technical annual generation potential [TWh/a] by technology			
	Open-field PV	Onshore wind	Hydropower in 2030 [38]	Hydropower in 2050 [38]
Angola	45869	1562	27	27
Benin	80	10	0.94	2
Burkina Faso	7346	454	0.11	0.22
Botswana	8891	3726	-	-
Côte d'Ivoire	239	3	6.5	10
Democratic Republic of the Congo	48209	716	152	152
Comoros	5.1	0.04	-	-
Cape Verde	97	30	-	-
Ghana	1493	119	6.3	7.4
Guinea	31	2.3	9	15
Gambia	242	15	-	-
Guinea-Bissau	466	2.8	0.05	0.05
Kenya	14517	2277	5.5	5.5
Liberia	187	0.09	1.3	2.4
Lesotho	290	34	1.2	1.2
Madagascar	5688	1841	2.3	2.3
Mali	67306	13117	1.8	4.3
Mozambique	28606	1655	20	20
Mauritania	66552	15394	-	-
Mauritius	11	0.34	-	-
Malawi	1800	0.48	5.1	5.1
Namibia	9520	5050	2.6	2.6
Niger	69641	12714	1.1	1.1
Nigeria	20564	1595	20	34
Rwanda	140	25	1.3	1.3
Senegal	4562	688	-	0.53
Sierra Leone	551	6	1.9	3.6
Swaziland	234	7.8	0.61	0.61
Seychelles	0.05	-	-	-

Togo	1827	24	0.43	0.48
Tanzania	16442	304	23	25
Uganda	3840	140	20	22
South Africa	52100	6357	0.81	0.81
Zambia	20529	640	16	16
Zimbabwe	10210	1004	13	13

Notes: values are rounded up to the nearest decimal. Zero values represent values under 0.05; "-" denotes countries for which the use of current input data did not result in any potential. For hydropower it denotes no hydropower plants with the status 'Existing', 'Committed', 'Candidate', 'Planned' with a capacity larger than 10MW were found for the corresponding year according to Sterl et al. [38]. There is no electricity generation potential change between 2030 and 2050 for onshore wind and open-field PV because the local preferences in the land eligibility analysis that determine the installable capacity remain fixed across the evaluated years. Consequently, the same amount of land, installable capacity, and ultimately electricity generation also remains the same. Onshore wind potentials lean more towards a 2050 scenario since a synthetic turbine with improved efficiency was used.

5.1.5 Green hydrogen potential

Table 16 National hydrogen potentials and energy demands. [1]

Country	**Potential**	**Energy demand**		
Full name	H_2 potential [TWh/a]	Electricity demand 2050 (H2 equivalent) [TWh/a]	H_2 demand 2050 [TWh/a]	Total demand/potential share [%]
Republic of Angola	32892	59.0	6.7	0.2%
Republic of Benin	61	19.1	1.8	34.3%
People's Republic of Burkina Faso	5302	19.7	1.9	0.4%
Republic of Botswana	8980	8.5	1.0	0.1%
Republic of Côte d'Ivoire	168	64.1	6.2	41.8%
Democratic Republic of the Congo	34058	46.5	4.5	0.2%
Union of the Comoros	4	1.8	0.1	48.4%
Republic of Cabo Verde	92	1.1	0.1	1.3%
Republic of Ghana	1113	42.3	4.1	4.2%
Republic of Guinea	25	33.0	3.2	144.5%
Republic of the Gambia	180	3.8	0.4	2.3%
Republic of Guinea-Bissau	324	1.8	0.2	0.6%
Republic of Kenya	12611	138.1	8.7	1.2%
Republic of Liberia	128	3.5	0.3	3.0%
Kingdom of Lesotho	233	4.1	0.5	2.0%
Republic of Madagascar	5330	49.1	3.1	1.0%
Republic of Mali	55099	11.0	1.1	0.02%
Republic of Mozambique	21318	33.2	3.8	0.2%
Islamic Republic of Mauritania	57272	8.2	0.8	0.02%
Republic of Mauritius	8	5.7	0.4	76.3%
Republic of Malawi	1266	27.8	3.2	2.4%
Republic of Namibia	10135	10.9	1.2	0.1%
Republic of the Niger	56220	7.8	0.8	0.02%
Federal Republic of Nigeria	15417	548.8	52.7	3.9%
Rwandese Republic	112	39.4	2.5	37.4%

Republic of Senegal	3683	31.1	3.0	1.0%
Republic of Sierra Leone	385	4.4	0.4	1.3%
Kingdom of Eswatini	170	3.3	0.4	2.2%
Republic of Seychelles	0.036	0.6	0.03	1632.7%
Togolese Republic	1273	5.0	0.5	0.4%
United Republic of Tanzania	11265	104.9	12.0	1.0%
Republic of Uganda	2742	110.4	7.0	4.3%
Republic of South Africa	41273	397.3	76.0	1.2%
Republic of Zambia	14599	63.8	7.3	0.5%
Republic of Zimbabwe	7855	14.6	1.7	0.2%
Total	401593	1923.5	216.95	0.05%

Table 17 Potential-weighted region-average LCOH per country for different expansion steps and years. [1]

Country	Levelized cost of hydrogen (LCOH) (region averages)			
Full name	1% expansion (2030)	25% expansion (2030)	1% expansion (2050)	25% expansion (2050)
Republic of Angola	2.7 €	2.8 €	2.0 €	2.0 €
Republic of Benin	2.9 €	2.9 €	2.0 €	2.1 €
People's Republic of Burkina Faso	2.8 €	2.8 €	2.0 €	2.0 €
Republic of Botswana	2.6 €	2.7 €	1.8 €	1.9 €
Republic of Côte d'Ivoire	3.0 €	3.0 €	2.1 €	2.1 €
Democratic Republic of the Congo	2.9 €	3.0 €	2.1 €	2.1 €
Union of the Comoros	2.9 €	2.9 €	2.0 €	2.1 €
Republic of Cabo Verde	2.4 €	2.6 €	1.9 €	1.9 €
Republic of Ghana	2.8 €	3.0 €	2.0 €	2.1 €
Republic of Guinea	2.6 €	2.6 €	1.9 €	1.9 €
Republic of the Gambia	2.8 €	2.8 €	2.0 €	2.0 €
Republic of Guinea-Bissau	2.9 €	2.9 €	2.1 €	2.0 €
Republic of Kenya	2.8 €	2.9 €	2.1 €	2.1 €
Republic of Liberia	3.2 €	3.2 €	2.2 €	2.3 €
Kingdom of Lesotho	2.6 €	2.6 €	1.8 €	1.9 €
Republic of Madagascar	2.6 €	2.7 €	1.9 €	2.0 €
Republic of Mali	2.7 €	2.7 €	1.9 €	1.9 €
Republic of Mozambique	2.8 €	2.9 €	2.0 €	2.0 €
Islamic Republic of Mauritania	2.2 €	2.4 €	1.7 €	1.8 €
Republic of Mauritius	2.9 €	3.0 €	2.1 €	2.1 €
Republic of Malawi	2.8 €	2.9 €	2.0 €	2.0 €
Republic of Namibia	2.6 €	2.7 €	1.8 €	2.0 €
Republic of the Niger	2.6 €	2.6 €	1.8 €	1.9 €
Federal Republic of Nigeria	2.8 €	2.9 €	2.0 €	2.0 €
Rwandese Republic	3.0 €	3.1 €	2.1 €	2.2 €
Republic of Senegal	2.8 €	2.8 €	2.0 €	2.0 €
Republic of Sierra Leone	2.7 €	3.1 €	2.1 €	2.2 €
Kingdom of Eswatini	3.0 €	3.1 €	2.1 €	2.2 €

Republic of Seychelles	3.2 €	3.2 €	2.2 €	2.3 €
Togolese Republic	3.0 €	3.0 €	2.1 €	2.1 €
United Republic of Tanzania	2.9 €	2.9 €	2.1 €	2.1 €
Republic of Uganda	2.9 €	3.0 €	2.1 €	2.1 €
Republic of South Africa	2.6 €	2.6 €	1.8 €	1.8 €
Republic of Zambia	2.7 €	2.8 €	2.0 €	2.0 €
Republic of Zimbabwe	2.8 €	2.8 €	2.0 €	2.0 €
Total	2.63 €	2.70 €	1.90 €	1.94 €

5.2 Events

5.2.1 Stakeholders' mobilization workshop in Accra

11th -12th November 2019

A two-day Brainstorming Workshop on Green Hydrogen was held at the headquarter of the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), Accra, Ghana on 11th and 12th of November, 2019. 23 participants were drawn from an array of stakeholders from 10 West African countries and Germany to discuss the topic of green hydrogen and a regional potential map for this key technology in the energy transition as depicted in Figure 52.

The experts constituted a West African multidisciplinary technical committee chaired by the former executive director of WASCAL, Dr. Moumini Savadogo, to represent the interest of the region in the project. Together with a project team at Forschungszentrum Jülich, WASCAL has committed to work on an interactive potential map to target promising locations in Sub-Saharan Africa for the establishment of a green hydrogen production and transport infrastructure. It is aimed to lay the foundations for pioneering demonstration projects with relevant partners from industry and scientific institutions in the future.

Figure 52: Technical committee and representatives from Jülich in Accra, Ghana

5.2.2. Formal inception of the H2Atlas project

10th June 2020

The project was formally commissioned by the former parliamentary state secretary of BMFTR, Mr. Thomas Rachel which is illustrated in Figure 53. This event was an important milestone as it marked the beginning of new partnership between Africa and Germany in exploring the mutual benefits of a green hydrogen economy for both parties.

The project is being implemented by a team of interdisciplinary experts in Forschungszentrum Jülich in partnership with the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) and the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL).

Figure 53: Formal inception of the H2Atlas project at Forschungszentrum Jülich, Germany

5.2.3 West African project data validation workshop

07th – 27th August 2020

A virtual data validation workshops held across all the countries from 7 to 27 August 2020 has been organized by WASCAL. Collected local data were reviewed and validated by the 15 member countries of ECOWAS. The national teams of each country presented the data collected to the members of the regional technical committee. Upon review and careful examinations, suggestions were made for improvement while also requesting that missing data needed to be collected as the validity and reliability of the atlas depends on the validity and reliability of the input data collected by the national teams.

5.2.4 Inception workshop of H2Atlas-Africa for the region in Southern Africa

18th August 2020

SASSCAL successfully hosted its virtual inception meeting on August 18, marking the kick-off of the H2Alas-Africa project in Southern Africa. Forschungszentrum Jülich worked hand in hand with SASSCAL and SACREE. Representatives from all Southern African Development Community (SADC) member countries participated. The meeting was also attended by the SASSCAL Governing Board chair, Mrs Jane Chinkusu as well as the Vice Board Chair Prof Gabriel Luis Miguel. In his speech, Prof Miguel advocated for joint partnerships and solidarity in research to find solutions for sustainable development and regional integration and cooperation.

5.2.5 Virtual training workshop on green hydrogen technology for West African regional committee and national team leaders

19th August 2020

Forschungszentrum Jülich successfully hosted a one-day online workshop on the basics of green hydrogen technology on 19th of August 2020. The interactive workshop was aimed at providing a basic introductory technical information on the subject of green hydrogen for the members of the regional technical committee and country team leaders for West Africa.

The lecture was given by Prof. Dr. Detlef Stolten, the director of the Institute of Energy and Climate Research – Techno-economic System Analysis, Forschungszentrum Jülich.

5.2.6 National teams engagement meeting between Southern Africa and Forschungszentrum Jülich

16th September 2020

The Southern African Science Centre for Climate Change and Adaptive Land Management (SASSACL) held its National Teams Engagement meeting on the 16th of September 2020. The Southern Africa Development Community (SADC) Centre for Renewable Energy and Energy Efficiency (SACREEE) and representatives from 12 Southern African countries participated in this virtual meeting. The purpose of this meeting was to further present the project to all leaders of the national teams. The project work packages including the collection of local data required for the atlas were discussed.

5.2.7 First joint meeting between West African Technical Committee and Forschungszentrum Jülich

21st September 2020

The West African Technical Committee and the Forschungszentrum Jülich project teams had a joint virtual meeting to discuss work progress. Mrs. Kerstin Annassi (Head of Basic Research Energy Systems of Projektträger Jülich) welcomed the participants on behalf of the Federal Ministry of Research, Technology and Space (BMFTR). She emphasized the importance of exchange of information and coordination of the different tasks being undertaken by both teams. She assured the project teams of the continual support of BMFTR.

During the meeting, project coordinator, Dr. Solomon Agbo, gave a status overview of the project activities. He highlighted the increasing interest of several stakeholders from industry, academia, government agencies, media, and private sector on the project and the project results.

The executive director of WASCAL, Dr. Savadogo, made a detailed presentation of the collected data from across West Africa. These data are climate, energy and socio-economic data required as input for determining the green hydrogen potential. He explained that the collected data had been verified and validated by the regional technical committee. He expressed his gratitude to both the national and regional teams for this.

Further presentations were given by the members of the Jülich project team. Each working group presented a status update of its work.

5.2.8 Virtual green hydrogen regional validation workshop for Southern Africa

02nd August 2021

SASSCAL as the coordinating partner in Southern Africa successfully hosted a four-day virtual Green Hydrogen Regional Data Validation Workshop from the 2nd to the 5th of August 2021. The high-level opening ceremony, held on Monday 2nd of August 2021, attracted various high-level personalities from members of SASSCAL Council of Ministers, Minister representatives from SADC, Ambassadors, High commissioners, SASSCAL Board Members, Heads of Developmental Agencies, Businesses, and other relevant stakeholders in SADC. The German partners have been represented by Mrs. Kerstin Annassi, the Head of Basic Research Energy Systems of Projektträger Jülich, and Dr. Solomon Agbo, the H2Atlas project coordinator of Forschungszentrum Jülich. The opening ceremony was presided by Dr. Jane Olwoch, Executive Director of SASSCAL.

The aim of this workshop was to provide an opportunity for the Southern Africa Regional Technical Committee (SARTC), comprising group of experts to assess, review and validate the bulk of the data collected at national level. Sixty scientists and engineers from Southern Africa have been collecting input data required to develop the H2Atlas since the launch of the project on 18th of August 2020.

5.2.9 Preparatory workshop on the potential of green hydrogen production in East Africa and Mauretania

14th – 17th March 2022

The project H2Atlas-Africa was extended to Kenya, Rwanda, Uganda, and Mauretania. The preparatory workshop was hosted by the Konrad-Adenauer Stiftung (KAS) and took place at Strathmore Business School in Nairobi, Kenya at the Strathmore University.

Figure 54: Participants of the stakeholders' mobilization workshop in Nairobi, Kenya

Various relevant stakeholders, including representatives of the Ministry of Energy and Petroleum Kenya, and representatives of the Policy Advisor for Development Cooperation of the German Embassy in Nairobi, the regional technical committee for the planned project, the four national teams, representatives of the East African Center of Excellence for Renewable Energy and Efficiency, Members of the Konrad-Adenauer-Stiftung in Kenya, and Forschungszentrum Jülich team attended this event as illustrated in Figure 54. The project methodology as well as the required local data sets were outlined by the Jülich team members based on the first results for the focus region West Africa during this workshop (Figure 55).

Figure 55: Presentation of the first H2Atlas results and technical discussion at Strathmore Business School in Nairobi, Kenya

5.2.10 Technical workshop in Windhoek

23rd -25th August 2022

During a 3-day workshop experts from Forschungszentrum Jülich and Southern Africa reviewed the H2Atlas-Africa results for the region. Participants were experts from the 12 SADC country teams (Angola, Botswana, Eswatini, Democratic Republic of Congo, Malawi, Mauritius, Mozambique, Namibia, South Africa, Tanzania, Zambia, and Zimbabwe) shown in Figure 56. In the workshop the submitted data have been validated and gaps identified. A comprehensive explanation of the simulations used have been provided by the Julich team which allowed feedback from local experts to tailor the results to local preferences. This technical workshop enabled a close and intense exchange and cooperation.

Figure 56: Technical committee of Southern Africa, National team members, and FZJ scientists in Windhoek, Namibia

5.2.11 Exchange workshop in Accra

29th -31st August 2022

Forschungszentrum Jülich project team participated in an exchange workshop that was hosted by the project partner, West African Science Service Centre for Climate Change and Adapted Land Use (WASCAL) in Accra from 29th -31st of August 2022. The team from Forschungszentrum Jülich, together with the West African regional technical committee of the project, the national team leaders of all 15 ECOWAS countries and their team members presented in Figure 57 have reviewed in detail the current version of the green hydrogen production atlas for the region. Data gaps have been identified and local preferences as well as feedback have been collected. These were implemented in the final version of the atlas.

Figure 57: Visit to WASCAL headquarter in Accra, Ghana

5.2.12 Stakeholder Mobilization Workshop on the Atlas of Green Hydrogen Generation Potentials in Africa

14th -15th December 2023 in Musanze, Rwanda

The Stakeholder Mobilization Workshop was, held in Musanze, Rwanda on December 14-15, 2023, and was organized by the University of Rwanda. A dynamic platform for dialogue on the nation's green hydrogen generation potential has been created among a wide range of stakeholders. It enhanced the stakeholders' understanding and perspectives. The commitment to data sharing, beyond just being a procedural agreement, reflects a deeper sense of collaboration and mutual trust among the stakeholders. This collective dedication is a foundational pillar for the effective implementation of the H2Atlas-Africa project, signifying a major stride in Rwanda's sustainable energy initiatives.

The event achieved its primary goals, notably establishing a common understanding among participants about the project's direction and the critical role of data sharing. This agreement underscores a strong collective resolve towards transparency and cooperation, which are crucial elements for the successful realization of the H2Atlas-Africa project.

5.2.13 H2Atlas National Mobilization Workshop

06th December 2023 at Uganda Industrial Research Institute, Uganda

A national mobilization workshop was organised by Uganda Cleaner Production Centre (UCPC) on 06th December 2023 to sensitize the local communities and all relevant stakeholders regarding the subject of green hydrogen and its role in transition to green economy. It attracted a total of 52 key stakeholders from regulatory institutions, academia, government ministries, and NGOs (see Figure 58). In the new Energy Policy 2023, Uganda is looking to diversify its renewable energy sources and other new technologies. The Atlas on Green Hydrogen Generation potentials project is a link between economic development while tackling the challenge of climate change as energy from green hydrogen is clean and sustainable. Additionally, it provides an opportunity to improve energy mix and security.

Figure 58: National mobilization workshop at Uganda Industrial Research Institute in Kampala, Uganda

The underlying principle and common understanding are that climate change and the need for sustainable development are global challenges that must be addressed relying on cross-border partnerships based on trust, understanding and fairness.

5.2.14 Stakeholders`Workshop on the Atlas of Green Hydrogen Generation Potentials

25th – 26th January 2024 Nairobi, Kenya

Machakos University has organized a two-day stakeholders` workshop in Nairobi, Kenya. The workshop aimed to address a wide range of objectives set by the national technical team and stakeholders (shown in Figure 59) including the understanding of Green Hydrogen production potentials and its viability as an alternative renewable energy source, and pinpointing areas for research involvement to make production and commercialization of Green Hydrogen a reality in Kenya.
Furthermore, the need for training, capacity building and strengthening the local economy was discussed.

Figure 59: Stakeholders`workshop in Nairobi, Kenya

The participants agreed on the following recommendations*:*

i) Designing policy provisions that will take into account land access, use, planning and zoning for Green Hydrogen project;
ii) Energy bodies and institutions (especially Energy and Petroleum Regulatory Authority [EPRA]) should collaborate with other research institutions in the development of relevant policies for Green Hydrogen production, infrastructure development and usage;
iii) Carrying out a comprehensive review of the policy, legal and regulatory framework on issues pertaining to the whole energy sector to accommodate new renewable energy initiatives including Green Hydrogen.

5.2.15 Technical workshop in Kampala, Uganda

18th -20th June 2024

In the three day exchange workshop, experts from Forschungszentrum Jülich have presented results for the four focus countries: Kenya, Rwanda, Uganda, and Mauritania (see Figure 60). This technical workshop was organised by Uganda Cleaner Production Centre (UCPC).

Figure 60: Technical exchange workshop in Kampala, Uganda

During the first phase of the project, the partners collected national data which have been provided to the team at Forschungszentrum Jülich. These datasets were processed and used for simulations. Together with the local partners the datasets have been reviewed and the interactive map has been presented in detail. Minor data gaps have been identified and local preferences have been collected. The final version of the H_2Atlas is hoped to be published soon.

The need for training, capacity building, and strengthening the collaboration among the countries as well as demonstration projects on green hydrogen production have been emphasised.

5.3 Follow-up projects

The H2Atlas-Africa project has inspired scientists and the divers stakeholders. Its unique results have paved the way for a number of follow-up projects and programs thanks to funding from BMFTR. Four of such projects are described below.

5.3.1 IMP-EGH

International Masters Program in Energy and Green Hydrogen" (IMP-EGH) is a joint program between the Forschungszentrum Jülich, RWTH Aachen, and University of Rostock along with four West African universities and, the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL). The German Federal Ministry of Research, Technology and Space (BMFTR) is funding the two-year course as part of its capacity building activities in Africa with eight million euros initially until December 2025. Students from all 15 West African countries benefit from the program. The students are taught by lecturers from the partner African and German universities and institutions.

The Master's program consists of six different specialization tracks from which the students can choose:

- Track 1: Hydrogen production and technology
- Track 2: Photovoltaics
- Track 3: Economics, Policies and Infrastructure
- Track 4: Bioenergy and Biofuels
- Track 5: Georesources
- Track 6: Energy systems analysis

In the first and second semesters, the students are taught the fundamentals of energy studies. During the third semester the students take specialized courses in one of the partner universities depending on the chosen track at the Université Felix Houphouet Boigny (Côte d'Ivoire), the Université de Lomé (Togo), Université Cheikh Anta Diop de Dakar (Senegal) and the Université Abdou Moumouni de Niamey (Niger). In addition, the students spend the fourth semester in Germany to gain practical experience and conduct their theses. These new specialists for renewable energy and green hydrogen graduate from their host university in West Africa

5.3.2 DryHy

The goal of the project is a water-conscious production of green hydrogen and e-fuels in dry regions by using direct air capture. Herby water and CO2 which are required for electrolysis are extracted from the ambient air to generate methanol or its derivates. This means that electrolysis can be operated in arid regions, which conserves drinking water resources for human usage as well as the flora and fauna. The generated products are suitable for transportation over long distances and possess the potential for direct utilization.

This project has been commissioned in April 2023 and is divided into two parts until completion in March 2029. During the first phase, relevant technologies are mainly explored. Economic analyses are carried out and partnerships are established. This phase is planned to be completed in March 2026 and will be followed by pilot implementation in the research environment under real conditions in an arid region of West Africa. Capacity building is incorporated through the involvement of master's students and doctoral researchers from Africa, organized workshops, and engagement with stakeholders from politics, business, science and society. This approach enables the acceptance of this technology and ensures support for the successful implementation by the locals. Partnering in this project are Forschungszentrum Jülich, RWTH Aachen University, Volkswagen Group and FEV.

5.3.3 PV2HBurkina

The project aims to provide a concrete technical response to the negative impact of dust on solar PV power plants and to propose ways to optimize the production of green hydrogen from solar PV systems under the specific climatic conditions of the Sahelian region in West Africa. The project site is the 33 MW Zagtouli photovoltaic solar power plant, located on the western outskirts of the city of Ouagadougou in Burkina Faso. The project will analyze the effects of dust on the performance of the plant and assess the effectiveness of the techniques used for cleaning PV modules. It will conduct a global benchmark of solar module cleaning technologies to identify the relevant technical solution in the case of the Zagtouli solar power plant.
The 2 year project started in January 2023 and is implemented by the consortium comprising University Joseph KI-ZERBO, University Abdou Moumouni, the Ministry of Energy (Burkina Faso), the Ministry of Higher Education and Research (Burkina Faso), SONABEL, and Forschungszentrum Jülich.

5.3.4 Joint Communique of Intent (JCoI), Namibia

On 25th of August 2021, the Namibian Government and the German Federal Ministry of Research, Technology and Space Germany (BMFTR) signed a Joint Communique of Intent (JCoI) to accelerate green hydrogen development in Southern Africa. This cooperation fosters joint efforts in the fields of green hydrogen and its associated derivatives, renewable electricity and associated infrastructure development. The JCoI is funded with €40 million euros for a period of five years from January 2022. It is based on three pillars namely development of a National Green Hydrogen Strategy, pilot projects implementation and capacity building through scholarships for the training and further education of local specialists in Namibia. The scholarship started 2022 and is funded by €5 million euros until 2025.

In the framework of JCoI, pilot projects have been chosen and are funded by BMFTR. The implementation of the project is coordinated by Southern African Science Service Centre for Climate Chang and Adaptive Land Management (SASSCAL).

Pilot project 1: Daures Green Hydrogen Village

The production and utilisation of green hydrogen is being investigated in a dedicated R&D environment in a newly founded village in the municipality of Daures. The aim of Africa`s first Net-zero village is to explore pathways to carbon neutrality in Namibia with hydrogen as the key source. This 18-months project was launched December 2022 and has a total funding amount of €12.3 million euros.

Focus of this pilot project is the sustainable production of green hydrogen and ammonia from renewable sources; sustainable "green" agricultural products from greenhouses; development of green schemes that create local employment and demonstration of green hydrogen applications.

Pilot project 2: Cleanergy refuelling station

In the vicinity of port Walvis Bay hydrogen production from solar power, its storage possibility, transport, and distribution are being investigated to accelerate the defossilation of the port. Trailer refuelling systems are being installed to facilitate the refuelling of land- or sea-based applications. This €13.3 million euro project was commissioned in November 2023 and will be completed in October 2025.

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