Int. J. Renew. Energy Dev. 2025, 14 (4), 751-766

Contents list available at CBIORE journal website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.cbiore.id

Research Article

Energy resource development in the DRC: A scenario planning for hydroelectric potential development by 2050 based on OSeMOSYS

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Abstract. Energy planning is a privileged scientific tool, enabling quantified analyses of the energy future of countries or regions of the world. These analyses provide a scientific basis for energy policies and implementation strategies. The Democratic Republic of Congo (DRC), despite its considerable hydroelectric potential, makes little use of its resources due to various challenges, leaving a large part of the population without access to electricity, which hampers community and economic development. This article analyzes the opportunities for developing the hydroelectric potential of the DRC up to 2050. Using OSeMOSYS (Open-Source Energy Modelling System), prospective modelling was carried out to assess the technical, economic and environmental impacts of an ambitious energy scenario centered on hydropower (Scenario HYDRO). The study develops an energy modelling approach for the DRC, considering demand, supply and energy policies, based on reliable data and aimed at optimizing the use of resources, in particular hydroelectric potential. The results indicate a potential installed capacity of 23 GW by 2050, dominated by hydropower (83%). This scenario meets the growing needs of national electrification, with 70% of the energy designated for the residential sector. The study highlights a significant reduction in CO_2 emissions, estimated at 1,229 Mt cumulative by 2050. However, achieving these targets will require around USD 100 billion in investment. The results provide a sound basis for the development of energy policies in the DRC that will promote universal access to sustainable energy, reduce carbon emissions, reduce pressure on forests and ensure energy security. The results of this study recommend massive investment in hydropower, standardization of the electricity sector and improved data collection to achieve universal electrification and significantly reduce CO_2 emissions in the DRC by 2050.

Keywords: Energy modelling, OSeMOSYS, hydropower, Democratic Republic of Congo, energy transition, CO_2 emissions reduction.

Received: 11th Feb 2025; Revised: 17th April 2025; Accepted: 8th May 2025; Available online: 30th May 2025

1. Introduction

Since 1997, world leaders are committed to achieving the United Nations' Millenium Development Goals (MDGs), which have been converted into the Sustainable Development Goal 7 (SDG) in 2012. Goal 7 of the SDGs focuses on ensuring access for all to reliable, sustainable and modern energy services at an affordable cost) to address some specific and urgent challenges facing the global energy system. These include the predominant usage of fossil fuels, which contrasts with the fight against climate change and the high variability of prices in the energy market (Nhamo, Nhemachena, Nhamo, & Vuyo Mjimba, 2020).

The principle of large-scale safe energy supply, capable of supplementing the planned efforts for Greenhouse gas (GHG) emissions' reduction, may be acceptable as a " plan A" but it shall be scaled up within the limits the country economic growth, financial affordability, technological change impact and social adaptation. As stated by Mike Childs, Head of science, policy and research at Friends of the Earth (UK) "… we don't need to invest in harebrained schemes […] when we have no idea at all what impact this may have […]" (Luwesi , 2022).

The global context of energy transition is part of a growing climate emergency, marked by extreme events and pressure on natural resources. According to Progiou *et al.* (2022), the COVID-19 pandemic has highlighted the impact of human activities on air pollution, illustrating the possibility of rapid changes in emissions. On the other hand, Martín-Ortega et al. (2024) insist on the transparency and integration of mitigation efforts through approaches such as the MITICA (Mitigation-Inventory Tool for Integrated Climate Action) program. These dynamics call for robust energy planning models, integrating both mitigation and adaptation imperatives.

As such, this study is part of a broader reflection on the sustainable management of energy resources in an uncertain climate context, where forward planning becomes a strategic tool for adaptation. The case of the DRC, with its socio-economic vulnerabilities and exceptional hydroelectric potential, represents a relevant field of analysis for thinking

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https://doi.org/10.61435/ijred.2025.61121
ISSN: 2252-4940/© 2025.The Author(s). Published by CBIORE

about low-carbon energy trajectories (Nydrioti, Sebos, Kitsara, Assimacopoulos, & Dionysios, 2024).

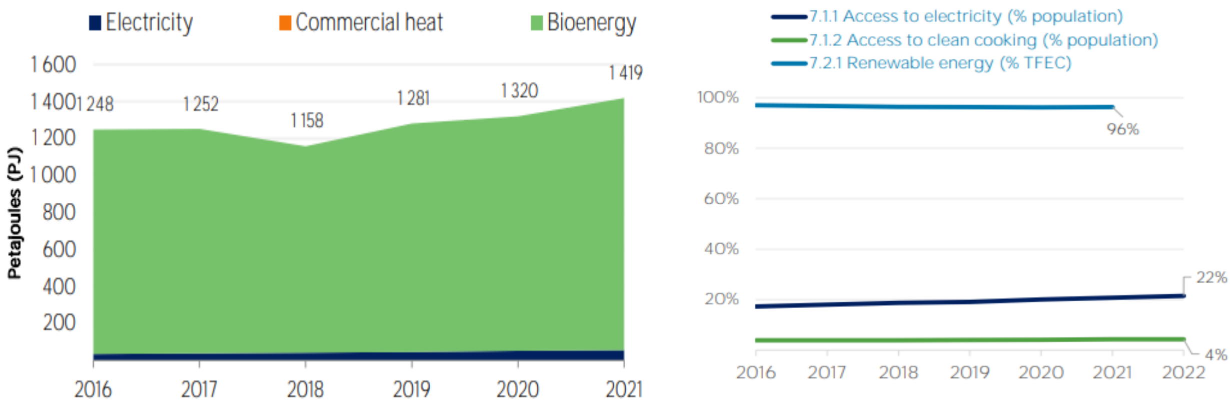
Scenario planning is a tool that provides foresight and can be used to evaluate the country's future energy demands and provide a scientific basis for policy-making and energy supply in the long run (Schumacher, 1985). It enables establishing a balance between the country's future energy needs and supply levels, to cover all its areas and all its uses (Hlopov, 2019). Hence, energy planning shall first analyze the constraints to its supply prior to suggesting the best options for decision-making.

A number of academic organizations and research institutions have considered various possible energy-climate trajectories to limit the rise of fossil energy supply and its corollaries on the average temperatures to below 2°C, given the uncertainty and scale of the changes linked to climate issues and energy technology, as well as their socio-economic and environmental effects (Lehtilä & Koljonen, 2018). Other institutes, intergovernmental organizations and companies have carried out numerous studies on complex trajectories related to energy production, having in mind that this sector requires solid long-term infrastructure development to be able to cater for all its uses and all the areas of the economy, notwithstanding both local and global environmental uncertainties (Hafemeister, Kammen, Levi, & Schwartz, 2011) (Council, 2010). Prediction models are therefore essential in most energy-climate scenarios to assess the impact of energy options and assist political and economic decision-makers, to enable energy system optimization within the framework of a long-term strategy (Eikeland & Skjærseth, 2016). Such energy optimization models are effective support tools for designing energy policies for governments and other decision-makers (Morriet, Wurtz, & Debizet, 2022).

This study aims at developing a model for planning DRC's electrification to (i) reduce dependence on wood energy and facilitate access to electricity (MEDD, 2021) ; (ii) develop renewable energy sources and optimize the energy mix (MRHE, 2022) ; (iii) enhance access to electricity in an equitable and sustainable way (MRHE, 2022). The study is based on a key assumption stating that strategic energy planning for hydroelectric potential plays a significant role in providing accurate data to guide policy, decision and investment making in the energy and water sector.

Unlike many studies focused on very large-scale hydroelectric infrastructures such as Grand Inga, our approach favors realistic, decentralized scenario planning, based on OSeMOSYS, to optimize national electrification by 2050. The originality of this study lies in its unique combination of prospective modelling and the precise evaluation of avoided emissions. This is the first application of this approach to the DRC at this temporal and spatial scale, providing operational data for the formulation of energy policies consistent with climate objectives.

The Democratic Republic of Congo (DRC) is one of the richest African countries but at the same time, globally poorest in terms of GDP per capita, which is estimated slightly below USD 2 per day. The country's GDP is expected to reach USD 69.5 billion by the end of 2024, with an annual growth rate of 5.7%, a gross investment rate of 20,4% and final consumption rate of 38,3% from 2002 to 2021. The country's economy weakness is mainly tied to its extremely low energy consumption levels, compared with its production potential, Also, the country has one of the lowest rates of Human Development Index (HDI), due notably to very low electricity access rate (Luwesi, 2024).



Total energy supply by sources

Total energy access by sources

Fig. 1 Total energy supply and access by sources in the DRC (IRENA, 2024)

Table 1
Electricity power generation in the DRC (in GWh)

Source	2014	2015	2016	2017	2018	2019	2020	2021
Hydro	8820	8916	9099	9324	10657	11621	12306	12976
Thermal power plant (Diesel)	9	4	12	12	6	5	5	5
Thermal distribution grid	11	11	10	6	7	8	7	3
Solar power plant	1	1	1	5	7	28	28	30
Biomass	19	21	22	20	27	27	27	27
Total	8860	8953	9144	9367	10704	11689	12373	13041

Source: *(IEA, 2019) (BCC, 2023)*

The DRC's hydroelectricity access rate is one of the least access rates in the world, ranging between 19 and 22%, with an estimated per-urban and rural rate of about 9% (Fig.1) (SE4ALL-RDC, 2019). Also, that electricity access rate is still lower compared to the African continent average of 31%, on one end. On the other end, energy security and climate-resilient development in the DRC are dormant due to the lack of a country visionary leadership and rigorous planning to increase significantly energy installations and electricity security for all (SARW, 2024).

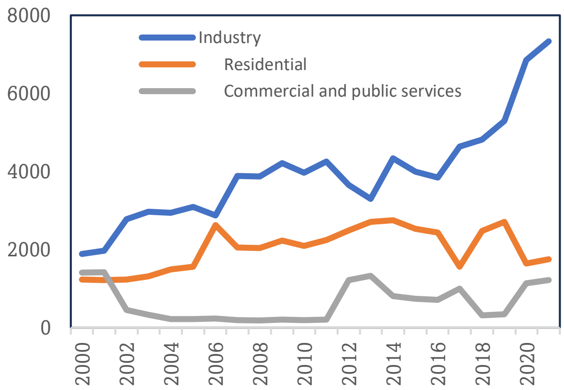
Hydroelectric power stations only contribute 2.1% of the country's energy output, with only 2.95 GW of installed capacity, the main energy source being drawn from the existing wood and biomass energy (96.1%). solar energy plants (0.1%) and imported and domestic oil installations (1.7%), including thermal plants (diesel-powered generators) are insignificant to halve the actual energy needs of the DRC (Table 1) (ARE, 2023). Table 1 confirms the fact that electricity generation in the DRC energy mix is dominated by hydroelectricity, followed by diesel-fired power plants; Solar energy became prominent starting from 2017. Hence, most people, especially in rural areas, are highly dependent on bioenergy resources, which contribute to 96% of the DRC's Greenhouse gas emissions.

The installed hydroelectric capacity of the DRC remains insufficient to meet the country's energy needs with increasing populations' growth and industrialization (Fig. 2).These limitations hamper community development, education and economic growth (IRENA, 2024) (WBG, 2023) (PDGIE, 2018). Yet, the DRC has considerable hydroelectric potential estimated to 113 GW, thanks to the mighty Congo river, and the Grand Inga projects alone (SARW, 2024). However, much of this potential remains untapped due to technical, financial and environmental challenges. (Resource Matters, 2020). The major challenge lies in implementing energy development models that maximize the use of these resources to meet the country's growing electricity needs. These challenges have prompted a reflection for reinventing the future of the DRC's energy sector. the country is reimagining huge projects like the Grand Inga project, by developing off-grid and micro-grid systems to make a transition towards clean, safe and ecological energy systems to achieve the nexus between energy, economy and environment (3Es) and reduce inequalities (FMI, 2022).

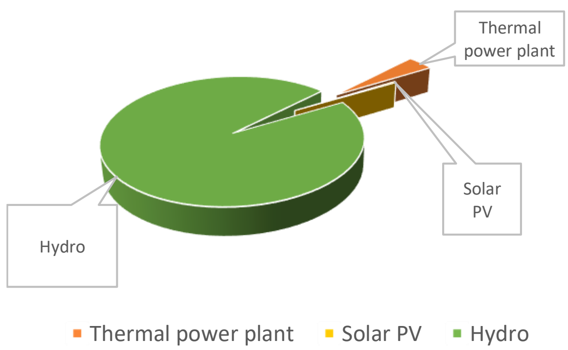
In its National Energy Policy (PNE), the DRC is committed to reducing the share of wood-energy consumption by half its energy mix by the year 2035 (MRHE, 2022). However, the proposed actions for strengthening energy supply in the country lack a long-term vision and do not result in a sound energy planning to attract adequate funding from development banks and other financial institutions. In addition, the Ministry of the Environment and Sustainable Development (MEDD) has initiated a national climate change adaptation plan (PNA), which foresees a potential reduction of 120.34 Mt CO2e by 2030 in the energy sector. Yet, The DRC's annual GHG emissions are currently estimated to 677 $MtCo_2e$, representing 0.49% of the global world emissions (MEDD, 2022) (Ritchie & Roser, 2024). Hence the need for scenario planning to set the pace for the transformation of the energy sector and provide an appraisal of a long-term energy planning strategy from a government perspective.

Financial institutions are nowadays frustrated for the lack of demand of funds for investments and the poor quality of projects. To overcome these obstacles, the new trend is focusing on 'trust funds' to develop infrastructure for the energy and water sector, to help the poor who cannot afford to pay and those "unwilling to pay", without necessarily are subsidizing the service. Examples of such trust funds for infrastructure include the Africa infrastructure trust fund of the European Investment Bank, the NEPAD trust fund for infrastructure of the African Development Bank (AfDB), also have under used and project preparation facilities of UN agencies and other development banks. Prior to awarding such trust funds for infrastructure development in the energy and water sector, a scenario planning approach is used to project the future business environment, since off the shelf generic planning tools do not work for this sector.

Energy and water sector development requires both infrastructure and operating financial resources to make the services available to all, anywhere and at any time. Innovative instruments and a novel risk-thinking and taking approaches are required to strategically plan and attract investors. This is generally streamlined through a sound analysis of the TOWS (Threats and Opportunities, Weaknesses and Strengths) and of the DPSIR (Drivers, Pressures, States, Impact and Response). Both the TOWS and DPSIR environmental assessment frameworks use a scenario planning to provide an outlook of a planning strategy from a government perspective. This section showcases of the Strategic planning approach (SPA) for the water sector of the Lesotho Finance Ministry, and the applications of the Open-Source Spatial Electrification Tool (OnSSET) of the University of Cape Town in the DRC energy



a) Electricity consumption by sector (MWh-yr)



b) Electricity consumption by source in 2022

Fig. 2 Electricity consumption by sector (MWh-yr) and source in 2022 in the DRC (IEA, 2019) (ARE, 2023)

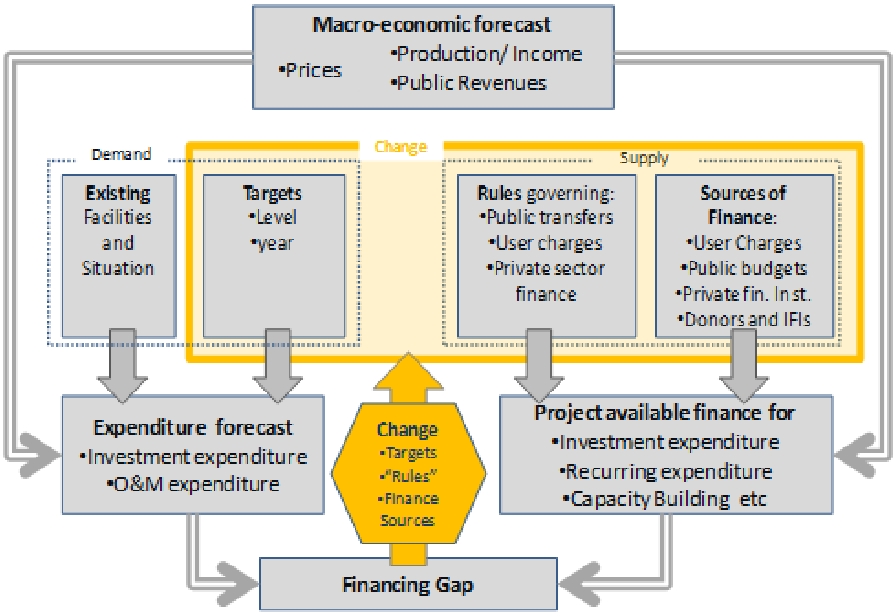


Fig. 3 Feasible Planning Methodology for the Lesotho Country SFP (Arntzen & Luwesi, 2018)

sector using TEMBA (The Energy Model Base for Africa) and OSeMOSYS.

A scenario planning approach used projections of both the needs and resources, to develop initial planning tools and capacity building, as well as the long-term development of the sector, to ensure its sustainability. This comprehensive approach is structured according to the sub-sector's sub-divisions and the components of planning, using "least" benefits and "most-damaging" cost models. The latter are based on key assumptions of each sub-sector development (Luwesi & Beyene, Innovative Water Finance in Africa – Economics and Principles of Financial Innovations for Water Managers, 2023) present a 'strategic planning approach (SPA)' for the water sector in Southern Africa based on the budgeting process of the Finance Ministry. A Strategic financial planning (SFP) tool was developed for Lesotho, using a scenario planning to analyze the needs, resources and gaps in financing, prior to accessing funds and to decision-making on the resources. A structured methodology for analysing information and data was retrieved from the OECD 'FEASIBLE' planning methodology (Fig. 3). The sequences of financing strategies in the Lesotho SFP were based on the described and quantified principles of the water policy using unit cost models. The funding needs were based on five key assumptions: Urban sanitation development (USan), Rural sanitation development (RSan), Sewerage development (Sew), Urban Water Services development (UWS), and Rural Water Services development (RWS). These assumptions were analyzed in accordance with the following four scenarios aiming at achieving a full cost recovery for urban water and sanitation (and sewerage) services (Fig. 4): Business As Usual (Scenario 1), High Growth with Rural Development Focus (Scenario 2), High Growth with Urban and Industrial Focus (Scenario 3), and Low Growth (Scenario 4) (Arntzen & Luwesi, 2018).

The models were developed by the EU Water Initiative – Finance Working Group (EUWI-FWG) to have a wider application in more than one country and help in developing local tools in Armenia, Georgia, Moldova, Kyrgyz Republic. The financing strategy had a large degree of 'user payment for services' and identifies the need for a 'social safety net' to ensure that services also reach the poorer parts of the population. Since there was no 'one size fits all' and that the models' content needed to be 'owned' by each country under study, the SFP tool had to be re-designed and updated prior and during the funding negotiations, to allow for transparency. This provided a key feedback and inputs for realistic figures, according to the developments experienced in the water sector of each country. It did also provide facts for a reality check that were essential for the Finance Ministry to convince the OECD and bilateral donors to support the country SFP in order to fill the gaps in financing (Arntzen & Luwesi, 2018).

Resource Matters in partnership with the Energy Systems Research Group at the University of Cape Town, conducted a study in 2019 on electrification planning of the DRC through a geospatial energy planning model known as OnSSET (Open-Source Spatial Electrification Tool) to provide different scenarios for optimizing infrastructure investments in large-scale supply solutions from the central grid. The proposed scenario planning was based on a robust and realistic scenario of electrification with mini grids having an installed capacity of less than 2 MW. The other scenario considers most existing inadequate or costly plans, those favoring large, centralized

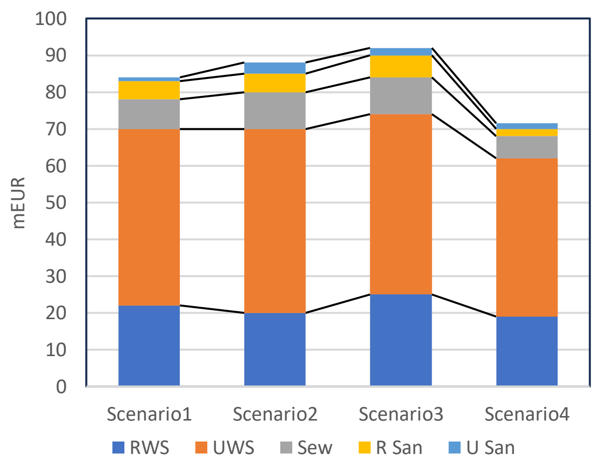


Fig. 4 Four funding needs' scenarios for Lesotho SFP (Arntzen & Luwesi, 2018)

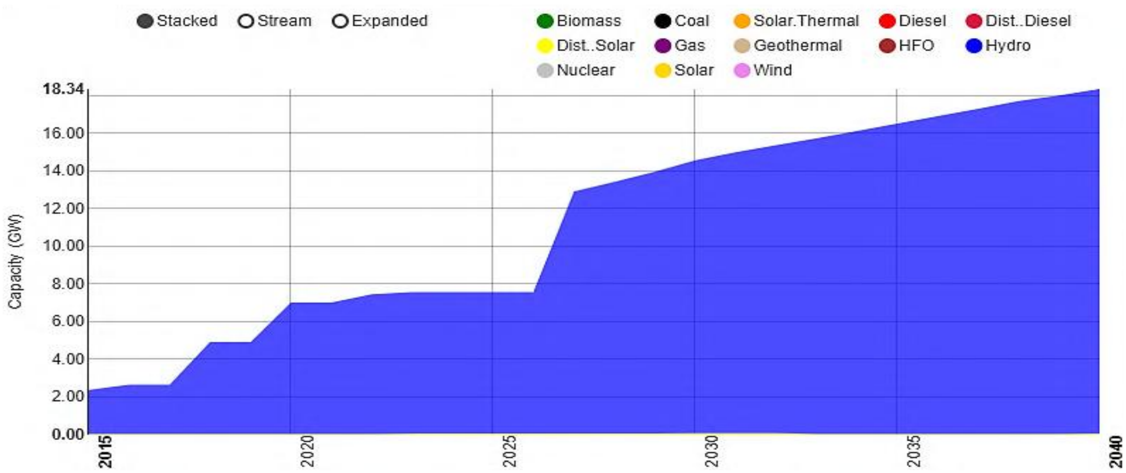


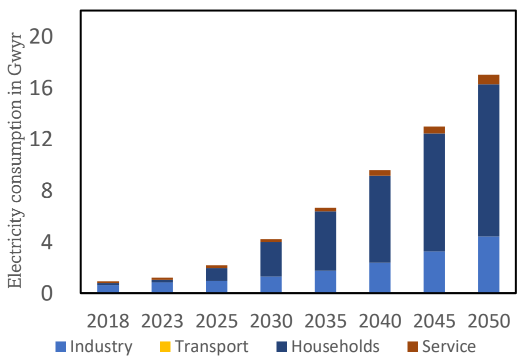
Fig. 5 TEMBA model results (Resource Matters, 2020)

hydroelectric investments that require a vast extension of the transmission grid, while rural areas and demand centers are far from the grid. Data from TEMBA (The Energy Model Base for Africa), the MAED (Modelling Analysis for Energy Demand) and OSeMOSYS (Open-Source Energy Modelling System) applications were utilized to develop the OnSSET for the DRC (Resource Matters, 2020).

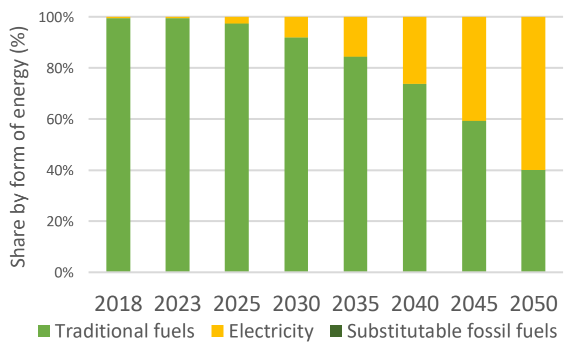
These research findings show that hydropower is the most efficient resource for supplying power in the DRC (Fig. 5). Installed hydro capacity is projected at 7GW in 2025, 14GW in 2030 and 18GW in 2040, mainly made up of mini-hydro plants and mini-grids (<10MW) (Resource Matters, 2020). However, this model has some many limitations. One of these limitations include the investment cost, which is associated with the acquisition of electrification technologies. The installation cost of energy infrastructure largely depends on the conditions of access to the site of installation. Another limitation of this model is its inability to estimate the cost of accessing and transporting materials to a given site, which means that it cannot reflect the variation in costs of installing the same technology in different locations. There is also a maximum hydroelectric potential by site of 10 MW. This limits the DRC energy potential to 1,366 MW, i.e. 2% of the country's total potential (ARTELIA, SA, & SHER, 2021).

In addition, Kibungu (2024) carried out a study on the development of an electrification scenario for the DRC from 2018 to 2050, with a view to decarbonizing its energy balance, using the Modelling Analysis for Energy Demand (MAED) tool (Kibungu, 2024). This electrification scenario was based on two major key assumptions. First, the ambitious electrification action plan targets 100% electrification in urban areas and 40% in rural areas. This assumption is justified by the government's determination to restructure its electrification policy for the country. Second, there is an increased priority given to renewable energy sources, specifically hydropower, and other clean electrification sources, with massive deployment of existing and innovative technologies that cater for GHG emissions' reduction. This scenario planning indicated a modelling approach that meets the challenges of electrification and energy transition, focusing on technical, economic and social aspects of implementing the objective of reducing wood energy in the country's energy balance. The final electricity demand trends by sector of activity and residential areas' energy type are shown in Fig. 6.

Fig. 7 shows on one side possible changes in the consumption patterns of key economic sectors, notably industry, services and residential in the DRC. On the other side, the main energy source for households in the reference year 2018 is biomass, with 94% of basic energy consumption based on biomass (charcoal and firewood). However, in this scenario plan of electricity consumption in residential areas, household electrification will increase around 12 GW by the year 2050, with a total energy use share of 60%. Specific dynamic factors influencing electricity final demand and the impact of household energy efficiency in the electrification scenario may explain such consumption. This detailed approach provides crucial information for energy policies targeting household



a) Trend in final electricity demand by sector



b) Trend in final electricity demand by energy type for households

Fig. 6 Trend in final electricity demand by sector and energy type for households (Kibungu, 2024)

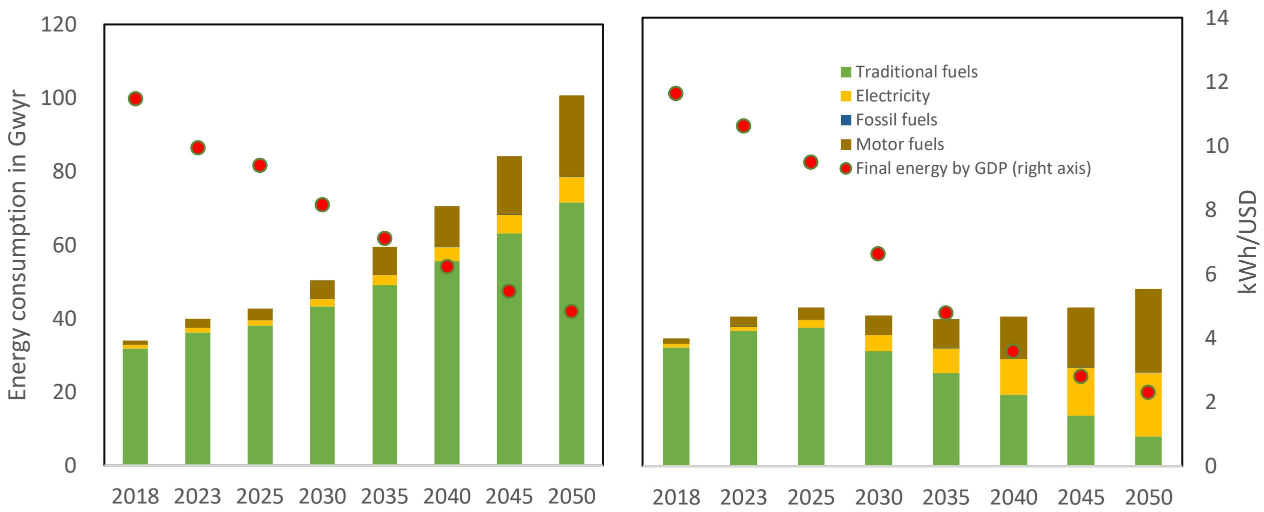


Fig. 7 Projected energy demand for the BAU and HYDRO energy scenario

electrification to promote more sustainable and efficient consumption practices (Namazkhan, 2022).

This electrification scenario highlights its major environmental implications. The total cumulative avoided carbon emissions after the implementation of electrification in residential areas are estimated to 1,640 Mt CO2 by the year 2050, with an annual emissions avoidance of 129.48 Mt CO2 in 2050 (Fig. 8). Compared with oil production (in Tons), the Grand Inga dams have the potential of generating energy that equates to 30 million Tons of oil per annum, thus avoiding an estimated amount of 11.5 $MtCo_2e$ annually (SARW, 2024). This implies that electricity is a more environmentally friendly solution for climate mitigation and sustainable industrialization and economic growth in the African continent. As outlined in Agenda 2063, energy development shall be aligned with the objective of achieving faster economic growth while fully realizing the key sustainable development goals by 2030. These include ensuring universal access to electricity and clean cooking facilities, as well as significantly reducing premature deaths linked to pollution (IEA, 2019)

Consequently, the scenario planning for the DRC by the International Energy Agency (IEA) comprises two scenarios developed for the period starting from 2019 to 2040, the DRC "Stated policies" and "Africa Case". The Agenda 2063 roadmap is used as “Africa case” scenario to emphasize the importance of tackling energy infrastructure deficits, which are seen as a major obstacle to economic growth in the continent. The DRC "Stated policies" scenario presents the DRC's energy development trends based on the National Energy Policy (PNE) and previous stated policies for clean and less costly energy solutions that improve access to electricity. Fig. 9 shows the cumulative investment needed for achieving sustainable electrification and reducing primary energy consumption in the DRC and Africa at large. The "Stated Policies" scenario shows that there is need of a cumulative investment flows of about $80 billion over the period 2018 to 2040 to enhance access to “electricity to all” in the DRC. The “Africa case” scenario shows how hydropower and solar power can improve such accessibility to electricity in the DRC with a projected installed hydroelectric capacity of about 10 Mtoe, or 13.3 GW by 2040 (IEA, 2019).

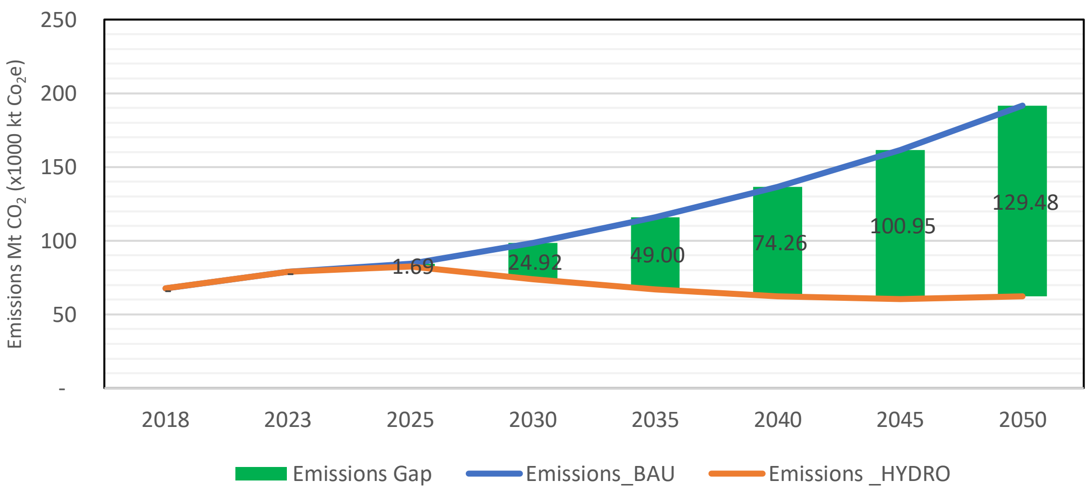
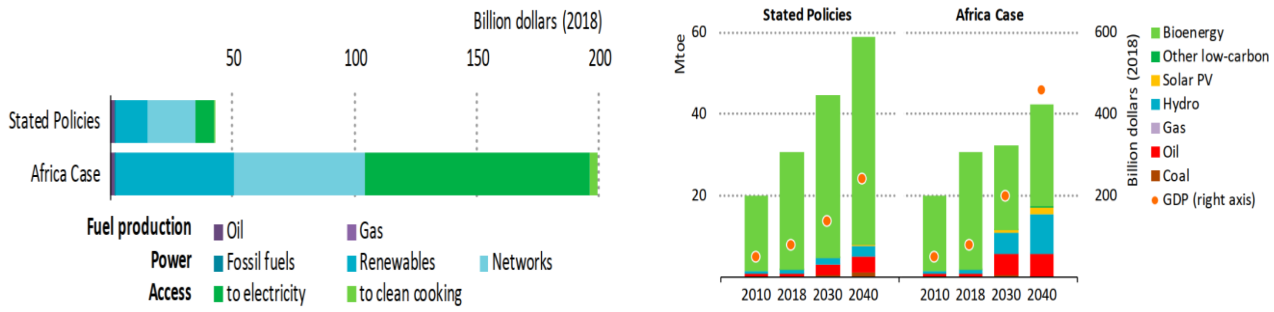


Fig. 8 CO_2 emissions gap in the residential sector (Kibungu, 2024)



a) Cumulative investment needs (2018-2040)

b) Primary energy consumption per GDP (2010-2040)

Fig. 9 Levels of investment needs and primary energy consumption in the DRC and Africa (IEA, 2019)

2. Methods

2.1 OSeMOSYS model selection and usage

To ensure energy policy development, various organizations have resorted to different energy optimization models based on their ability to integrate decarbonization trajectories in planning. Such kinds of models include the Open-Source Energy Modelling System (OSeMOSYS) (Barnes, Shivakumar, Brinkerink, & Niet, 2022). The tool is especially designed for energy systems in developing regions, particularly in Africa and South America, and has been the subject of several in-depth studies (Kumar, Maragatham, 2020). In South America, the OSeMOSYS SAMBA model has been designed to analyze the power systems of thirteen countries, focusing on the energy mix and opportunities for cross-border electricity exchanges (Moura, Legey, & Howells, 2018). This approach has enabled the assessment of potential synergies between the various national networks.

A study carried out by (Welsch *et al.,* 2012) assesses the OSeMOSYS codes' updating to enable modelling renewable electricity generation and assess the potential contribution of Smart Grid options that prioritize demand types, demand shifting and storage options. (Fattori, Anglani, & N., 2016) look at a local Multi-regional energy model (MELiSsa) for a specific area, the Lombardy region. The MELiSsa model is based on the basic logic structure of OSeMOSYS, developed to analyze the residential sector (space heating in single-family homes and apartment buildings). Some updates and additions to the OSeMOSYS codes concerning technological capacity and aggregate emission limits have been included to adapt its structure to this case study. (Fragnière, Kanala, Moresino, & Smeureanu, 2017) demonstrated the flexibility of OSeMOSYS codes including the ability to link OSeMOSYS directly to a top-down model (choice share model describing end-user energy consumption preferences) to provide consistency to technology distribution by integrating end-user energy behaviors. (Plazas-Niño, Ortiz-Pimiento, & Quirós-Tortós, 2023) used the OSeMOSYS model to model decarbonization trajectories and support energy planning in Colombia.

OSeMOSYS is designed to incorporate a wide range of present and future technologies, fuel types and end products to meet the requirements of various predefined energy services (SLIMANI, KADRANI, EL HARRAKI, & EZZAHID, 2024). During the optimization process supply must respect a production constraint, if a "least-cost solution" is to be obtained (Kumar, 2020). This production must be sufficient to satisfy both specific use and exogenous demand at a given time.

The relationships in OSeMOSYS are formulated with mathematical equations so that the model is solved by minimizing the total discounted costs of the energy system (Kumar, 2020).

Let FO, the objective function in OSeMOSYS for time period t, given by (Kumar, 2020) (Equation 1) below:

$$FO = min\,[\,\textstyle\sum_{T=1}^{N}(CI_{t,T} + FC_{t,T} + VC_{t,T}) + \sum_{T=1}^{N}(St)] \qquad (1)$$

Where: t is number of years, T = 1,…,N with N the type of technology, CI is the Capital Investment cost for time period t and technology N, FC is the Fixed operating Cost for time period t and technology N, VC is the variable operating cost and fuel cost for time period t and technology N, and St is the storage cost for N technology

The choice of OSeMOSYS in this study is justified by its two major advantages:

- Firstly, its optimization methodology based on linear programming: This approach makes it possible to minimize an objective function (FO) under various constraints, thus meeting the energy needs of a given geographical area; and
- Secondly, the open and transparent structure of the OSeMOSYS coding makes it easy to adapt and improve the planning outcome.

2.2 Data collection and content analysis

To develop an energy modelling approach tailored to the specific characteristics of the DRC, the study considering demand and supply, as well as national and international energy policies, this study used secondary data from reliable sources such the Ministry of Electricity and Hydraulic Resources, international organizations and other related entities. The analysis encompassed numerous mathematical optimization models for the country's energy resources, based on a deep understanding of the local context, to enhance the DRC's hydroelectric potential. To adequately understand the local context, the analysis involved a "thematic content analysis" featuring the specific characteristics of the DRC, including its large population, GDP as well as national and international energy policies.

The OSeMOSYS energy system optimization model involves an elaborate representation of the interdependence between the various energy carriers, conversion technologies, transmission and storage systems as described in the reference energy system (Fig. 10). This makes it possible to assess the different technological paths and how technologies can interact

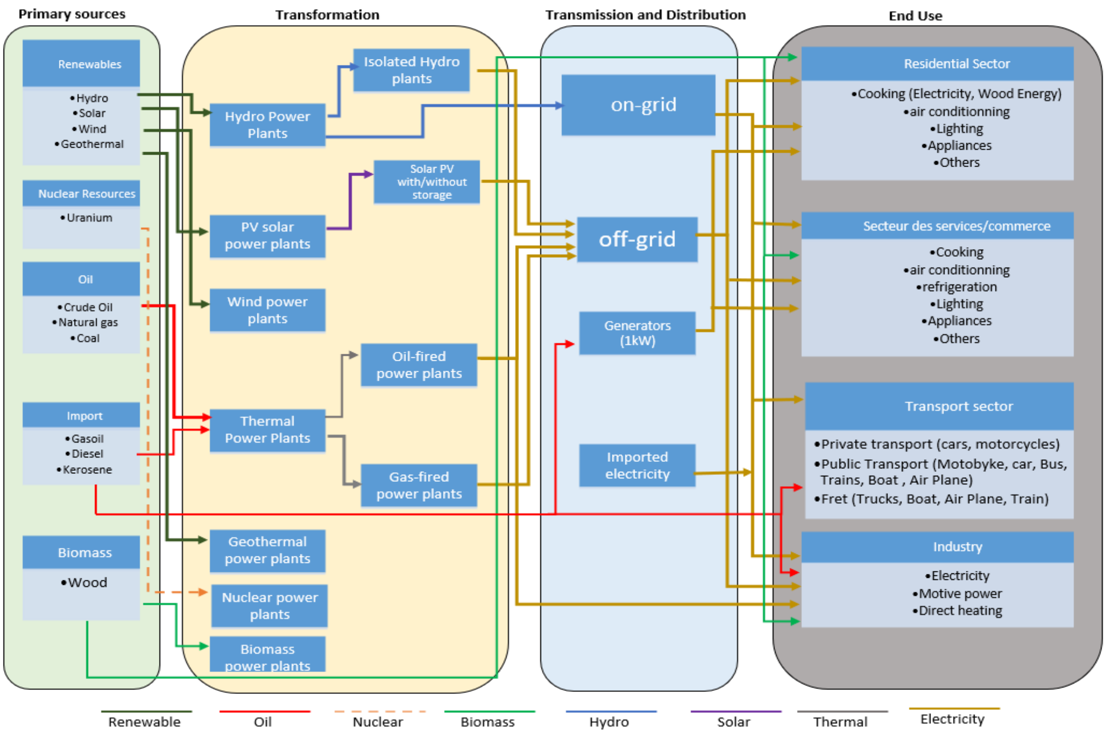


Fig. 10 Reference energy system scenario for the DRC (IEA, 2019) (IEA, 2023) (IEA, 2022) **(IRENA, 2021)**

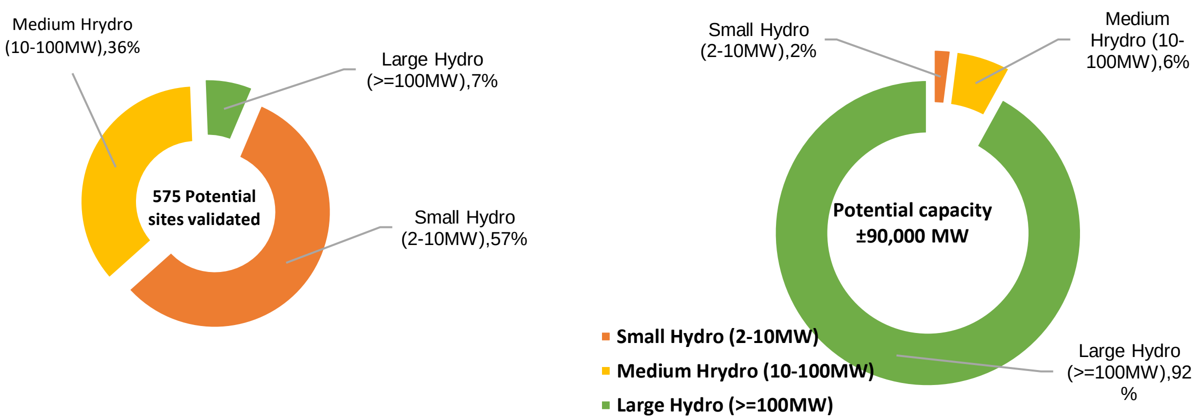


Fig. 11 Distribution of the DRC's hydroelectric potential (>2MW) (ARTELIA, SA, & SHER, 2021) (MRHE, 2016)

Table 2
DRC's energy potential

N°	Energy resource	Potential Energy
1	Hydro	More than 90,000 MW
2	Solar	Sunshine band between 3500 and 6750 Wh/m².
3	Wind	Limited potential
4	Geothermal	Potential not yet assessed
5	Biomass	High potential with 145,000,000 Ha of forest cover
6	Hydrocarbons	Marginal production of 25,000 BBL/D Global reserves estimated at 5,692 billion BBL
7	Gas (oil and methane)	10-20 billion Nm^3 / 278 billion Nm3
8	Biogas and biofuels	Huge potential in plant resources for their development

Source: (ARE, 2023)

to bring about systemic change over time. As shown in Table 2, the DRC has significant energy potential, particularly in terms of hydraulic, solar, wind, geothermal and other resources. The hydroelectric potential of the country is around 90,000 MW spread over 575 sites and represents around 13% of the world's potential (ARTELIA, SA, & SHER, 2021). The previously identified potential sites cover run-of-river and reservoir-type schemes (Fig. 11).

Table 3
Residual capacity data for existing technologies in the DRC

Sector/Unit	Technology	CODE	2018	2030	2040	2050
Installed capacity (GW-year)	Solar PV (without storage)	PWRSOL001	0	0.009	0.009	0.009
	Solar PV (with storage)	PWRSOL002	0.0006	0.0034	0.0034	0.0034
	Large Hydro (>100MW)	PWRHYD001	2.533	2.533	2.533	2.533
	Medium Hydro (10-100MW)	PWRHYD002	0.418	0.418	0.418	0.418
	Off-Grid Hydro	PWRHYD004	0.1109	0.1416	0.1416	0.1416
	Thermal power plant	PWROCH002	0.059	0.059	0.059	0.059
Industry Demand (PJ/year)	Biomass	DEMINDBIO	0.128	0.201	0.262	0.27
	Motor fuel	DEMINDELC	0.5543	1.09	1.91	3.33
	Electricity	DEMINDELC	19.45	40.66	75.15	138.89
Household demand (PJ/year)	Biomass	DEMRESKCNBIO	1,190.62	972.11	601.28	251.50
	Substitutable fossil fuels	DEMRESKCNOIL	0.080	0.1127	0.149	0.201
	Electricity	DEMRESCKELC	5.777	16.021	31.99	59.180
Services (PJ/an)	Electricity	DEMCOMELC	3.603	7.1975	12.801	22.787

Source: (Kibungu, 2024) (ARE, 2023) (Carla & Allington Lucy, 2021)

2.3. Model data input

2.3.1. Residual capacity

Residual capacity represents the installed capacity of a technology at a point of time (e.g. each year). Table 3 illustrates residual capacity data for selected technologies, including projected electricity generation data from 2018 to 2030, as detailed in the 2022 ARE report (ARE, 2023). Other installed capacities for conversion technologies are assumed to remain constant until 2050. On the demand side, installed capacity has decreased linearly with the operational lifespan of technology (Table 4).

For end-use technologies, an estimate of the residual capacity in 2021 was done, assuming that installed capacity was fully utilized to meet the demand. In addition, data on emission factors have been maintained by default from the template file provided by the starter data kit for the Democratic Republic of Congo (Carla & Allington Lucy, 2021).

2.3.2. Investment cost

Investment cost data were collected from the DRC template file provided by the starter data kit (Carla & Allington Lucy, 2021). Assumptions concerning costs, conversion efficiencies and lifetimes for the various power plants, storage technologies and electrolysis systems were based on a careful analysis of a wide range of recent studies (Carla & Allington Lucy, 2021), including specific data sources such as the International Energy Agency (IEA, 2022). Detailed technical and economic parameters associated with the various electricity generation and storage technologies considered in the model are presented in Table 5.

CO_2 equivalent emissions' calculations were carried out using the Global Warming Potential (GWP) values (GHGP, 2024). The corresponding annual electricity production was divided by the theoretical electricity production, if the installed capacity operates fulltime (100% of the time) (Carla & Allington Lucy, 2021).

Table 4
Operational lifespan of various energy technologies

Technology	Operational Lifespan
Biomass power plant	30
Geothermal power plant	25
Light oil-fired power plant	25
Oil-fired gas turbine (SCGT)	25
Gas-fired power plant (CCGT)	30
Gas-fired power plant (SCGT)	25
Solar PV (utility)	24
CSP without storage	30
CSP with storage	30
Large Hydro (dam) (>100MW)	50
Medium Hydro (10-100MW)	50
Small Hydro (<10MW)	50
Onshore wind	25
Nuclear power plant	50
PV system with storage	24
Onshore wind turbine with storage	25
Light oil-fired generator (1kW)	10
Solar PV (distributed with storage)	24

Source: (Carla & Allington Lucy, 2021)

Table 5
Cost of capital for key years in USD/MW

Code	Technology	2020	2030	2040	2050
PWRBIO001	Biomass power plant	2500	2500	2500	2500
PWRCOA001	Coal-fired power plant	2500	2500	2500	2500
PWRGEO	Geothermal power plant	4000	4000	4000	4000
PWROHC001	Light fuel oil power plant	1200	1200	1200	1200
PWROHC002	Thermal power plant (SCGT)	1450	1450	1450	1450
PWRNGS001	Gas-fired power plant (CCGT)	1200	1200	1200	1200
PWRNGS002	Gas-fired power plant (SCGT)	700	700	700	700
PWRSOL001	Solar PV (utility)	1378	886	723	723
PWRCSP001	CSP without storage	4058	2634	2562	2562
PWRCSP002	CSP with storage	5797	3763	3660	3660
PWRHYD001	Large Hydro (>100MW)	3000	3000	3000	3000
PWRHYD002	Medium Hydro (10-100MW)	2500	2500	2500	2500
PWRHYD003	Small Hydro (<10MW)	3000	3000	3000	3000
PWRWND001	Onshore wind	1489	1087	933	933
PWRNUC	Nuclear power plant	6137	6137	6137	6137
PWRSOL001S	Solar PV with 2h storage	2087	1220	992	927
PWRWND001S	Wind farm with storage	1735.2	1202.8	1026.6	1004.3
PWROHC003	Light oil-fired generator (1kW)	750	750	750	750
PWRSOL002	Solar PV with storage	4320	2700	2091	2091
PWRHYD004	Off-grid hydropower	3000	3000	3000	3000

Source: (Carla & Allington Lucy, 2021)

2.4. Hydroelectricity scenario analysis

The study used the HYDRO scenario to unveil the will of the Congolese Government for developing its hydroelectric potential through the construction of large power plants (>100 MW). The assessment is based on the projections of DRC energy demand and electrification scenario for 2050 (Kibungu, 2024).

The HYDRO scenario planning was based on three main assumptions related to the total demand share, the periodic construction of hydropower plants, and on-grid connection of isolated power plants. First, the maximum share of total demand that can be met by variable renewables was limited up to 15% for large-scale photovoltaics, onshore wind and large-scale photovoltaics with storage can each meet (of demand), and up to 5% for onshore wind with storage. The analysis did not intend to offer a detailed study on the system flexibility; however, these constraints were included in the modelling to ensure that the system is operational in the event of high renewable energy shares. Biomass was set to meet electricity demand up to 30%. Electricity imports and exports were modelled in a simplified way, with single imported and exported technologies constrained to import and export of electricity in accordance with energy balance data for the DRC (IEA, 2023). Besides, the model assumed the construction of 5 large-scale hydroelectric power plants and associated power lines every 5 years, i.e. an injection of an average of 500 MW On-Grid every 5 years. And the on-grid connection of isolated power plants was also assumed to be possible. It shall be noted that, the energy produced by the Grand Inga project was not considered in the model since it is of sub-regional interest and exported rather than used for domestic consumption. was, it Also, the Inga site was excluded from the scenario planning due its ambitious political expectations among the priority projects of the Southern African Development Community (SADC), the New Partnership for African Development (NEPAD) and the World Energy Council (WEC) (Jacquemot, 2021).

Finally, the results of this HYDRO scenario planning were compared with a reference BAU scenario (Business As Usual) to evaluate the gap in energy supply and its resulting impact in the economy, in the event that the government did commit itself to invest in the energy sector

3. Results and Discussions

The modelling results focus on the three technologies used in the DRC, namely hydroelectricity, solar power and thermal generators. They are presented in terms of installed capacity, energy generated yearly, the supply situation in relation to energy demand, energy consumption in the industrial, commercial and residential sectors, and the investment required to achieve the energy potential described by the best scenario.

3.1. Installed capacity

Fig. 12 shows an installed capacity of 23 GW by 2050 under the HYDRO scenario, hydroelectricity having a lion share of 18 GW. The reduction in the use of fossil fuels in the energy mix is remarkable, representing less than 1% by 2050. Yet, under the BAU scenario only 7.2 GW are generated by 2050, mainly by hydroelectricity and solar power within the targets of ARE (2022) annual report. Nonetheless, the persistence of the thermal generator in the energy mix remains unavoidable. Most solar power plant projects are coupled with diesel generators to overcome the problems of intermittent solar energy and provide a back-up solution in the event of a shortage or lack of electricity supply for various reasons. This growth trend of fossil fuel energy in this scenario is directly linked to the implementation of photovoltaic technology

Nowadays, there is a regain of interest in developing the DRC hydroelectric potential to power Africa through the Grand Inga dam. The DRC government has also gained an international prestige as a “country-solution”, when it comes to climate mitigation. The DRC has given away much of its mineral and forest resources to get the Grand Inga Dam be constructed by any means. However, the country focus on Grand Inga projects has long been a lost fight in addressing the DRC renewable energy conundrum due to its political, geostrategic, and financial challenges (Gnassou, 2019). This fantastic dam

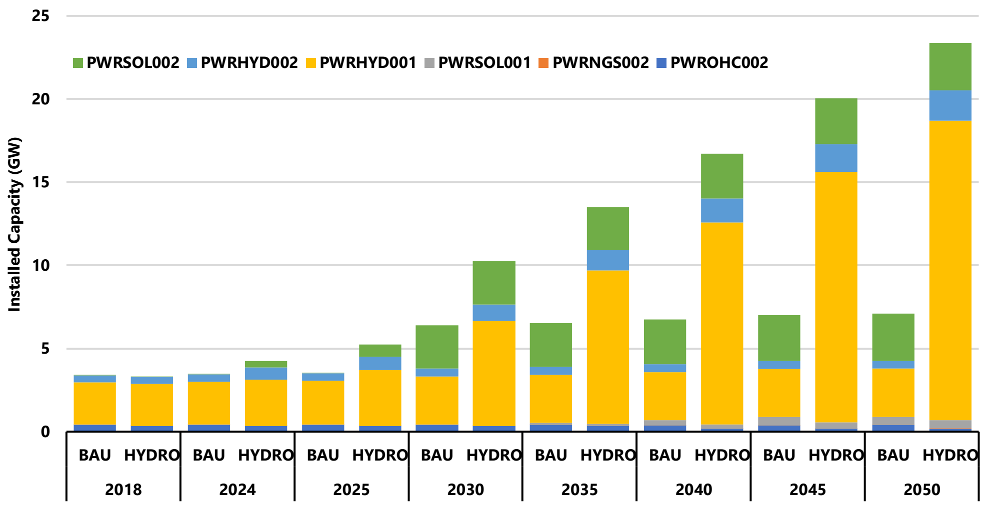


Fig. 12 Installed capacity of analyzed power plants by scenarios (Authors, 2025)

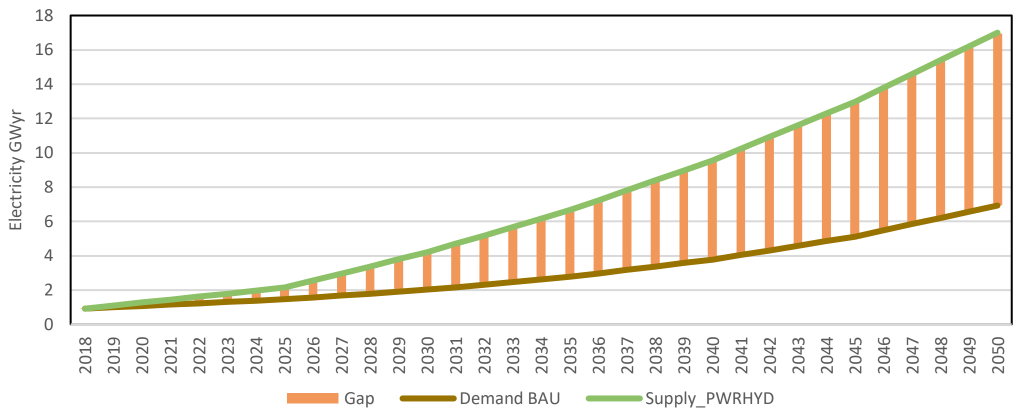


Fig. 13 Gap between electricity demand and supply (Authors, 2025)

project has been the most powerful scheme of our time that has threatened the electrification dreams of the Congolese people and has let down the African dream to remain unfulfilled. Consequently, Grand Inga hydropower project remains a potent fantasy rather than actuality itself (Warner, Jomantas, Jones, Ansari, & de Vries, 2019).

To overcome this Grand Inga dam conundrum, this study has shown how the DRC may develop its enormous hydroelectric potential beyond the Grand Inga projects to ensure the country's electrification. Hydroelectricity is actually the main source of renewable energy in the country, as revealed by the TEMBA model (Resource Matters, 2020). Other technologies, such as solar and wind power, should be promoted as a complement to the energy mix as part of an emergency initiative, pending the implementation of a nationwide interconnected grid supported by stable hydroelectric power (UN, 2019).

On the other hand, the use of fossil fuels to maintain solar energy solution remains a constraint, since thermal generators will be used to compensate for the intermittent nature of solar energy. yet, the BAU reference scenario does not in actuality emphasize on the net-zero emissions energy transition by 2050, maintaining dependence on fossil fuels for the availability of electricity.

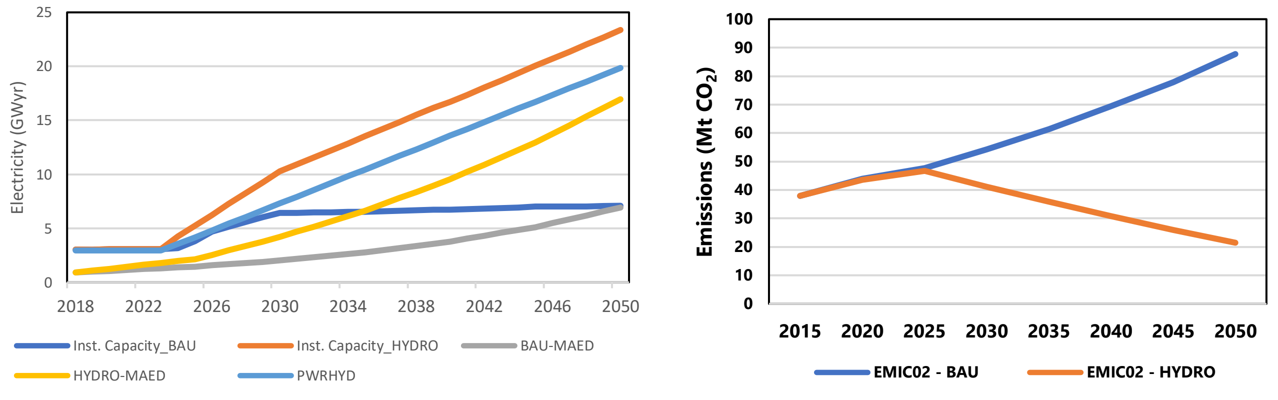
3.2. Supply versus demand

The energy gap between the BAU and HYDRO scenarios by 2050 is 10 GW, which can be bridged by achieving the electrification target of the country's households (Fig. 13). The HYDRO scenario generates a production surplus compared to the needs (demand), thus opening opportunities for the Central African sub-region's electricity export market. The electricity market in the DRC featured by a demand that extends beyond the national boundaries, with pressures from the ECCAS and SADC sub-regions, which constitute other markets with significant electricity needs (OECD, 2016).

When overlaying energy supply and demand curves, the HYDRO scenario shows that installed hydropower capacity (PWRHYD) alone can meet electricity demand (HYDRO-MAED) and guarantee by 100% households' electrification by the year 2050. Yet, energy generated under the BAU scenario is below the installed hydropower capacity but can meet its weak demand by 2050 (Fig. 14a.).

3.3. GHG emissions

Fig. 14b. shows a decreasing trend in CO_2 emissions under the HYDRO scenario, in contrast to the Reference Scenario (BAU), which keeps growing. The potential reduction of cumulative emissions by 2030 and 2050 under the HYDRO scenario is estimated to 484.1 and 1,229.15 Mt CO_2, respectively. It represents an effective decarbonization plan in line with the Paris climate agreements. Thence, the national electrification policy has a considerable impact on CO_2 emissions.



a. Overlaid energy supply and demand curves **b.** CO_2 emissions

Fig. 14 Overlaid energy supply and demand curves with CO_2 emissions under the HYDRO and BAU scenarios (Authors, 2025)

In terms of CO_2 emissions, the HYDRO scenario is much more ambitious, with a reduction potential of 484.1 Mt CO_2e in 2030, compared to 120.34 Mt CO_2e potential reduction forecasted by the National climate change adaptation plan (PANA) (MEDD, 2022). This CO_2e potential reduction in the energy sector is a key input to the DRC Nationally Determined Contributions (NDC), for it contributes significantly to the use of wood energy while promoting clean cooking and productive uses. It is also a key input to the economic growth, human development and social welfare through employment and job creation, foreign trade balance, improvement of life quality and poverty reduction (SARW, 2024).

3.4. Capital and investment cost

The costs of power generation, transmission and distribution to meet the ambitions described by each scenario are shown in Figs. 15 and 16. Annual investment cost for power generation, transmission and distribution under the HYDRO scenario are estimated to US$ 4 billion versus US$ 0.72 billion under the BAU scenario, thus making a cumulative investment of US$ 100 billion under the HYDRO scenario and US$ 18 billion under the BAU scenario, in 25 years (Fig. 15). In fact, under the HYDRO scenario, it requires about US$ 1.7 billion yearly for hydropower generation, and US$ 2.3 billion yearly for other power sources generation, transmission and distribution lines. Figure 16a. shows that investment in the BAU scenario is directed on a large scale towards solar power plants with storage (PWRSOL002) as described in the projection of the Electricity Regulatory Authority report (ARE,2021). However, in the HYDRO scenario, investments are made in the energy mix up to 2030, with a particular focus on hydroelectric power plants in the last 20 years of planning.

The annual investment costs for generation, transmission and distribution for the scenarios analyzed are shown on Fig. 16b. The projected electrification of households throughout the DRC requires as much investment in distribution, at 80% of the cost, as in generation. The investment cost involved in the country's electrification is too high. In fact, it requires about US$ 100 billion in 25 years under the HYDRO scenario, and US$ 18 billion under the BAU scenario. Hydropower generation alone requires US$ 1.7 billion yearly, thus making a cumulative investment of US$ 42.5 billion in 25 years, put aside transmission and distribution costs. The HYDRO scenario is in line with the Africa Case scenario produced by IEA. Investment costs for the projections made in the two scenarios are similar in magnitude (IEA, 2019).

The development of DRC's hydropower potential is a subject whose stakes include the sovereignty response to issues of armed conflict, political instability, rural exodus, disparity in development between mining areas and the rest of the country,

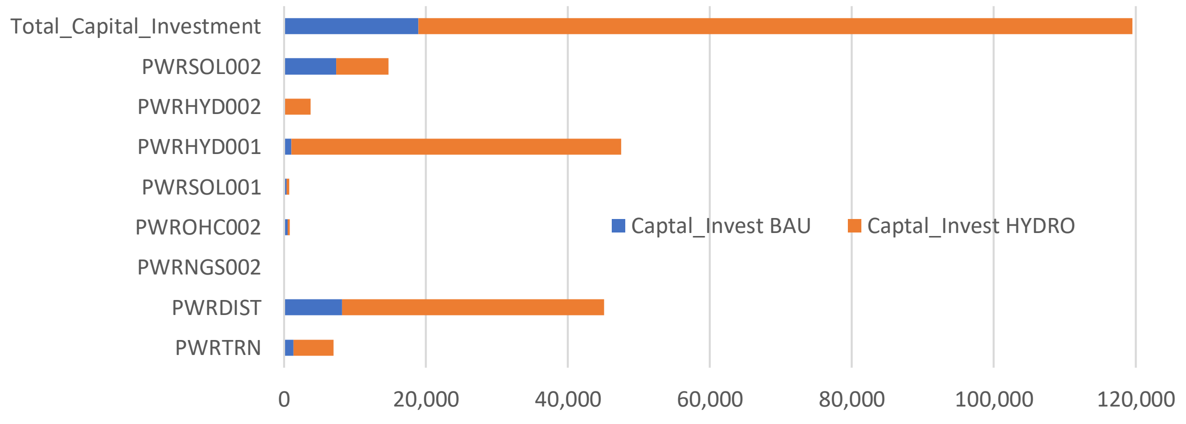
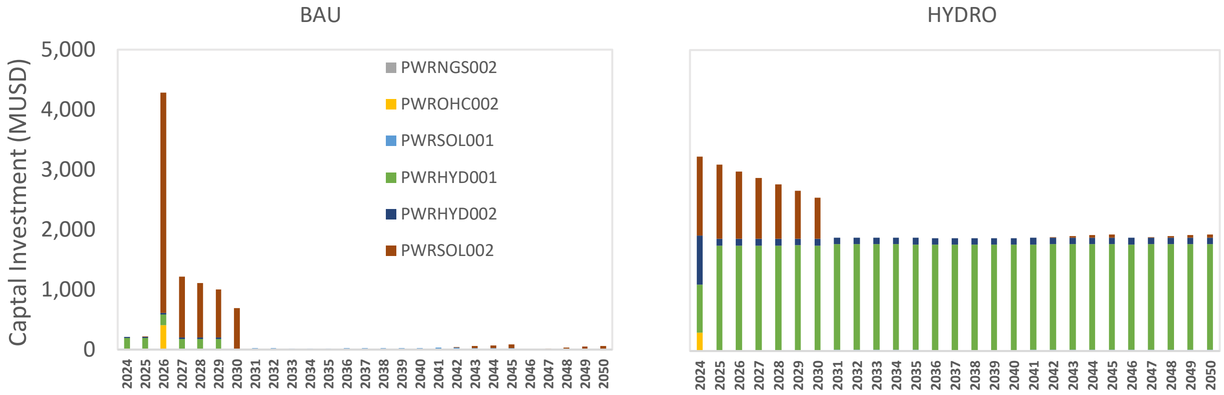
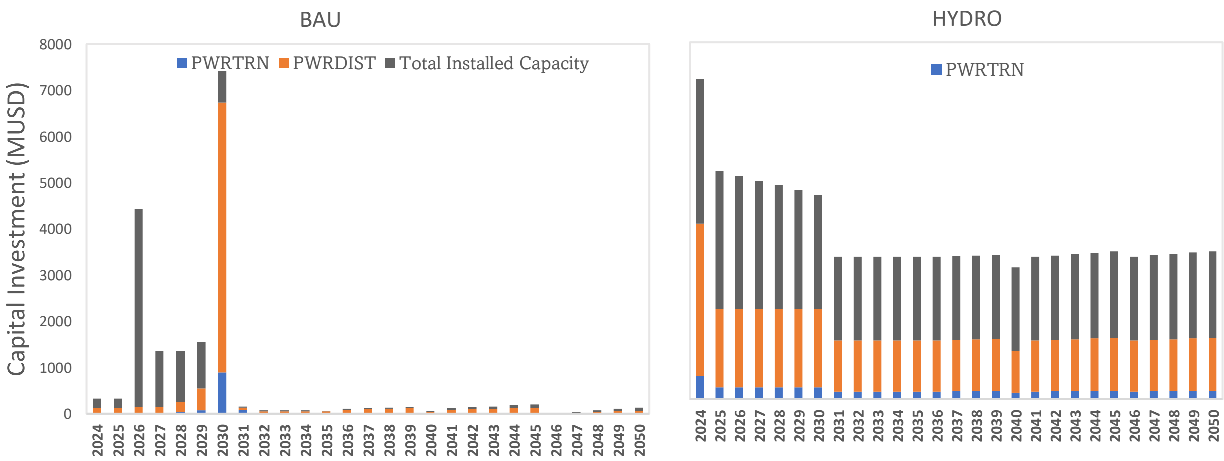


Fig. 15 Estimated total investment cost under different scenarios (Authors, 2025)



a. Estimated investment cost by type of technology



b. Estimated investment costs for generation, transmission and distribution

Fig. 16 Estimated investment costs (Authors, 2025)

and so on. It therefore requires strong political support and a significant commitment if it is to be realistically achievable (OCDE, 2011).

4. Study limitations and opportunities of further research

Despite the richness of the results presented, there are a few limitations to this study that need to be recognized in order to guide future work. Firstly, the HYDRO scenario is based on assumptions of large-scale hydroelectric infrastructure development, which although plausible, are highly dependent on uncertain political and financial factors. Secondly, OSeMOSYS used in this study, while appropriate for long-term energy planning, does not fully incorporate the dynamics of local infrastructure costs, nor the social issues involved in project acceptability.

In addition, certain promising energy vectors, such as green hydrogen, energy storage, and waste-to-energy conversion, have not been fully explored due to a lack of reliable data. Similarly, the effects of climate change on the availability of water resources and the variability of hydroelectric production have not been modelled in detail. Therefore, for further research, it is advisable to integrate within OSeMOSYS emerging sources of energy to combat climate change. Future research shall focus on new and renewable energy sources such as green hydrogen, energy storage, and waste-to-energy conversion, etc. Besides, there is a need for further engineering and economic research for the development of a hybrid model that combines technical-economic parameters with climate scenarios. Finally, due to the decried impact of large-scale dams on riverine communities, it is commendable to assess social and economic impacts of large-scale electrification, especially in rural areas.

5. Conclusion and Recommendations

The aim of our research was to carry out a quantified analysis of the DRC's energy future, starting from the current supply (2018) to identify the future supply (2050), future impacts and redefine new options for energy development in line with socio-economic development objectives that respect the environment for the benefit of future generations. By integrating the global climate dimension, this study contributes to the literature on mitigation strategies in southern countries, with an operational perspective on prospective modelling tools. It thus enriches the work on energy governance in sub-Saharan Africa, by proposing a realistic roadmap for energy transition.

This study proposes an innovative approach to energy planning based on OSeMOSYS applied to the DRC, highlighting the HYDRO scenario as a vector for structural transformation of the energy sector. By demonstrating the feasibility of an energy mix concentrated on hydropower and quantifying the environmental benefits, this research provides a strategic reference for political decision-makers, donors and development players. Unlike many studies that concentrate on very large-scale hydroelectric projects such as Grand Inga, our methodology emphasizes practical, decentralized scenario planning using OSeMOSYS to optimize national electrification by 2050. The novelty of this research lies in its distinctive integration of forward-looking modelling with a detailed assessment of emissions avoided. This represents the first application of such an approach to the Democratic Republic of Congo at this particular temporal and spatial scale, offering actionable data to guide energy policy development aligned with climate goals.

The results of this scenario planning exercise are as follows:

- Total final demand for electrical energy in the DRC by 2050 will be around 17 GW-years, of which 11.9 GW-years (70%) will be for the residential sector, 4.4 GW-years (26%) for the industrial sector, and 0.7 GW-years (4%) for services.
- The HYDRO scenario for developing the country's hydroelectric potential, based on OSeMOSYS, has improved the energy supply of electricity by increasing installed capacity to 23 GW by 2050, with 83% of capacity based on hydroelectricity and 7% on solar photovoltaics. Once available, this capacity would be able to satisfy energy demand for the industrial, residential and service sectors.
- The total investment needed by 2050 to develop these capacities in the HYDRO scenario is around 100.0 billion dollars, including around 40 billion dollars for the development of hydroelectric power plants at a rate of 1.7 billion dollars per year from 2024.
- The cumulative carbon emissions that will be avoided by implementing the electrification scenario are estimated at 1,229.15 Mt CO_2 by 2050, the year in which emissions will be reduced to 21.5 Mt CO_2.
- DRC's energy potential offers several exploitable alternatives for the electrification of the country, which have not been considered in the HYDRO scenario, which is the subject of our study. Some technologies are still less developed due to a lack of clear regulations and an ambitious, integrated energy policy, notably in the development of technologies for converting biomass into electricity (biomass combustion plants, gasification systems, etc.), biogas, green hydrogen, geothermal energy and uranium.
- The integration of these technologies into energy scenarios for the electrification of the DRC, with a view to their use in the energy mix, could be the subject of future research.

These results have direct operational implications for the development of energy policies in the DRC. The HYDRO scenario demonstrates not only the technical feasibility of large-scale electrification based on hydropower, but also its significant impact on reducing greenhouse gas emissions. This planning provides decision-makers with a clear investment framework (around 100 billion USD) to achieve the goal of universal access to electricity that can help strengthen the investment cases to be submitted to international financial institutions and green climate funds. Also, it provides a scientific basis to guide national climate policies, notably in updating Nationally Determined Contributions (NDCs), a diplomatic lever for international climate negotiations and financing the energy transition, and an argument in favour of revising strategic priorities, particularly about the Grand Inga project, to promote decentralized, progressive and inclusive solutions.

Based on the study results, below are some guidelines for the orientation of national energy policies:

- Invest massively in the construction and interconnection of large-scale hydroelectric plants and associated lines to form the national electrification corridor.
- Invest in the construction of small and medium-sized hydroelectric power plants, as well as solar power plants with the possibility of interconnection to the national corridor, to electrify rural areas far from major urban centers and gradually replace diesel-fired thermal power plants.
- Standardize the electricity sector by defining standards to facilitate implementation of the power plant interconnection strategy.

By following these guidelines, the DRC could achieve its ambitious goals of electrification and universal access to electricity services, reducing pressure on the forest and cutting CO_2 emissions by 2050, while ensuring the country's energy security and economic development, as well as sustainable management of our water resources. For this reason, it is important to intensify the strategy of collecting energy data for future years, to guarantee regular monitoring of the country's energy trajectory, as well as the constitution of a solid database capable of transcending the difficulties we encountered in our study during the reference year, with a view to developing alternative future scenarios.

Acknowledgments

Our sincere thanks go to Professor Clément N'ZAU Umba-di-MBUDI, who agreed to co-supervise the work on energy system modelling. We would like to thank Mr Jean MUGANZA ANUNU ASWIBA, for his assistance and encouragement in research to provide the Democratic Republic of Congo with an energy policy that matches the Government's ambitions. We would also like to thank André KABWE BIBOMBE and the entire team at the International Energy Agency (IEA) for their support in mastering energy modelling tools.

Author Contributions: KIBUNGU HODIA Benjamin: Conceptualization, methodology, formal analysis, writing—original draft; NDAYE NKANKA Bernard: supervision, resources, project administration; NGONZO LUWESI Cush: writing—review and editing, project administration, validation; TSHIMANGA MUAMBA Raphaël: writing—review and editing, project administration, validation; ESAM Badr: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: The author(s) received no financial support for the research, authorship, and/or publication of this article.

Conflicts of Interest: The authors declare no conflict of interest.

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