

The Impact of Building or Not Building a Dam: Integrating River Conservation and Renewable Electricity Generation in Africa

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Abstract

The intertwined climate and biodiversity crises are among the most challenging threats to human well-being in the Anthropocene. The energy-supply sector (including electricity and heat production) is the largest source of greenhouse gas emissions that contribute to climate change. The global community recognizes the urgency of decarbonizing the global energy sector: The goals of Agenda 2030 include universal access to sustainable energy through a transition to renewable energy sources. Hydropower, the oldest and historically most cost-effective renewable energy, has expanded renewable capacity but at the cost of free-flowing rivers. Increasing fragmentation of rivers by dams threatens freshwater biodiversity. Solar and onshore wind power, while competitive, intensify land competition, with protected areas being frequently sacrificed to development needs. Consequently, a large part of the global population is challenged to align the decarbonization of electricity networks with the need to protect biodiversity. In Africa, where half of the population lacks basic electricity access, the renewable energy transition implies considerable capacity expansion. Simultaneously, Africa is home to the Congo forest and river systems, crucial global biodiversity centres. The aim of this thesis is to investigate the current status and future expansion of renewable electricity among African countries and its implications on ecosystems and society. The Renewable Power Plant Database (RePP) Africa presents harmonized in-depth information on the most important renewable technologies. It includes geographical coordinates, country information, construction status, and capacity (in megawatts) for 1074 hydro-, 1128 solar, and 276 wind power plant entries. The number of records surpasses corresponding information in other accessible databases and aligns closely with cumulative capacity data reported by international energy organizations, with discrepancies of less than 13% for hydro-, below 23% for wind, and below 32% for solar power plants. Building on RePP Africa, the ecological, social, and political impacts of 507 proposed hydropower plants, potentially operating with dam and reservoir storage, were systemically assessed. Selected impact indicators include River Regulation, Fragmentation, Potential Evaporation, Resettlement, Protected Area, Land Use Change, Sediment Entrapment, and affected Megafauna. A total of 104 hydropower plants were found to cause severe impacts. Surprisingly, both the ten top- and bottom-ranked projects exhibited relatively small capacity sizes (45.77 and 47.34 megawatts (MW); mean of 152.46 MW), underscoring that assessing hydropower plant impact solely on capacity size is inadequate. A sensitivity analysis demonstrated that the ranking is influenced by the number of included hydropower plants and the choice of indicators. In contrast to hydropower, solar and wind power have potential to lead sustainable renewable energy pathways in the future, while releasing the dam building pressure on freshwater ecosystems. Based on RePP Africa, 76% of Africa's electricity needs projected for 2040 could be met by renewable energy, with a remaining technical potential of >99% each for wind and solar photovoltaic systems, and 51% for hydropower. Considering the assessed impacts of future hydropower, efficiently combining existing hydropower with wind and solar will be more sustainable than constructing hydropower plants alone. As resource potential differs among regions, transnational electricity sharing can support a more efficient resource exploitation. Further options to optimize renewable electricity exploitation cover maintenance, co-use, and replacement. Past hydropower plant failure has diminished available capacity by 24%, pointing out that plant maintenance can optimize performance (maintenance potential). Covering 40% of each existing hydropower reservoir with floating photovoltaics could provide 22,596 terawatt hours (TWh) of electricity which equals 41 times the electricity from proposed hydropower capacity (co-use potential). In general, all 36 African countries could replace proposed hydroelectricity generation by fully exploiting feasible onshore wind and solar photovoltaic potential with a mean surplus of 371 TWh per year

(replacement potential). Yet, the effects of solar and wind infrastructure on environmental and social systems require improved understanding before their unhindered expansion can be promoted. In conclusion, the results of this thesis improve the evidence-based understanding on how renewable electricity generation and river conservation are linked. The findings can support discussions on future pathways to tackle the intertwined climate and biodiversity crises. In this regard, Africa possesses not just the capability to avoid an era of extensive reliance on fossil fuels by transitioning to renewable electricity generation but also to incorporate considerations of river conservation and trade-offs in renewable infrastructure into its renewable electricity planning.

Zusammenfassung

Die Klimakrise und die Biodiversitätskrise bedrohen das menschliche Wohlergehen im Anthropozän und sind gleichzeitig eng miteinander verknüpft. Der Energieversorgungssektor (einschließlich Strom- und Wärmeerzeugung) ist die größte Quelle von Treibhausgasemissionen, die zum Klimawandel beitragen. Die Weltgemeinschaft hat die Dringlichkeit der Dekarbonisierung des globalen Energiesektors erkannt: In der Agenda 2030 wird ein universeller Zugang zu nachhaltiger Energie durch einen Übergang zu erneuerbaren Energiequellen angestrebt. Die Wasserkraft, die älteste und für lange Zeit kosteneffizienteste erneuerbare Energiequelle, hat beträchtlich zum erneuerbaren Kapazitätsausbau beigetragen, allerdings auf Kosten von frei fließenden Flüssen. Dabei bedroht die zunehmende Fragmentierung durch Staudämme die biologische Vielfalt. Solar- und Windenergie sind aufstrebende Alternativen, die jedoch den Wettbewerb um Landnutzung zuspitzen. Letzteres führt dazu, dass die Etablierung und Erhaltung von Naturschutzgebieten häufig gegenüber anderen Entwicklungsbedarfen benachteiligt werden. Folglich steht der größte Teil der Weltbevölkerung vor der Herausforderung, die Dekarbonisierung von Stromnetzwerken mit dem Schutz der biologischen Vielfalt in Einklang zu bringen. In Afrika, wo die Hälfte der Bevölkerung keinen Zugang zu Elektrizität hat, impliziert die Energiewende einen erheblichen Kapazitätsausbau. Gleichzeitig befinden sich in der afrikanischen Kongoregion einige der weltweit wichtigsten Biodiversitätszentren. Ziel der vorliegenden Arbeit war es daher, den derzeitigen und künftigen Ausbau erneuerbarer Energien in den afrikanischen Ländern sowie dessen Auswirkungen auf Ökosysteme und Gesellschaft zu untersuchen. Die Renewable Power Plant Database (RePP) Africa bietet harmonisierte Informationen zu den wichtigsten erneuerbaren Technologien. Sie enthält geografische Koordinaten, Länderinformationen, Baustatus und Kapazität (in Megawatt) für 1074 Wasser-, 1128 Solar- und 276 Windkraftanlagen. Damit übertrifft die Anzahl der Einträge die in anderen zugänglichen Datenbanken und stimmt eng mit den von internationalen Energieorganisationen gemeldeten kumulierten Kapazitätsdaten überein, wobei die Abweichungen bei Wasserkraftwerken unter 13 %, bei Windkraftanlagen unter 23 % und bei Solarkraftwerken unter 32 % liegen. Aufbauend auf RePP Africa wurden die ökologischen, sozialen und politischen Auswirkungen von 507 geplanten Wasserkraftwerken, die potenziell mit Dämmen und Stauseen betrieben werden, systematisch bewertet. Zu den ausgewählten Wirkungsindikatoren gehören Flussregulierung, Fragmentierung, potenzielle Verdunstung, Umsiedlung, Verlust von Schutzgebieten, Landnutzungsänderung, Sedimenteintrag und betroffene Süßwassermegafauna. Insgesamt wurden für 104 Wasserkraftwerke schwerwiegende Auswirkungen abgeschätzt. Überraschenderweise wiesen sowohl die zehn am besten als auch die zehn am schlechtesten bewerteten Projekte eine relativ geringe Kapazität im Vergleich zum Mittelwert auf (45,77 und 47,34 MW; Mittelwert von 152,46 MW). Das unterstreicht, dass die Bewertung der Auswirkungen von Wasserkraftwerken allein anhand der Kapazitätsgröße unzureichend ist. Eine Sensitivitätsanalyse zeigte, dass das Ranking von der Anzahl der einbezogenen Wasserkraftwerke und der Wahl der Wirkungsindikatoren beeinflusst wird. Im Gegensatz zur Wasserkraft haben Solar- und Windenergie das Potenzial, eine führende Rolle bei der Entwicklung nachhaltiger erneuerbarer Energien zu spielen ohne die Flussfragmentierung voranzutreiben. Mit Blick auf die zukünftige Entwicklung kann festgehalten werden, dass laut RePP Africa 76 % des für 2040 prognostizierten afrikanischen Strombedarfs durch erneuerbare Energien gedeckt werden könnte, mit einem verbleibenden technischen Potenzial von jeweils mehr als 99 % für Wind- und Solarenergie und 51 % für Wasserkraft. In Anbetracht der bewerteten Auswirkungen zukünftiger Wasserkraft wird die effiziente Kombination von bestehender Wasserkraft mit Wind- und Solarenergie nachhaltiger sein als der Bau von

Wasserkraftwerken allein. Da das Ressourcenpotenzial innerhalb Afrikas stark variiert, kann die länderübergreifende Stromnutzung eine effizientere Ressourcennutzung unterstützen. Weitere Optionen zur Nutzungsoptimierung von erneuerbarer Stromproduktion sind Wartung, Mehrfachnutzung und Austausch. Vergangene Ausfälle von Wasserkraftwerken haben eine Kapazitätsminderung von 24 % verursacht, was die mögliche Anlagenleistungsoptimierung durch Wartung verdeutlicht (Wartungspotenzial). Die Bedeckung von 40 % jedes bestehenden Wasserkraftreservoirs mit schwimmender Photovoltaiktechnologie kann 22.596 TWh Strom liefern, was dem 41-fachen des Stroms aus der vorgeschlagenen Wasserkraftkapazität entspricht (Mitnutzungspotenzial). Im Allgemeinen könnten alle 36 afrikanischen Länder die vorgeschlagene Wasserkrafterzeugung durch die vollständige Ausschöpfung des realisierbaren Wind- und Solar-PV-Potenzials mit einem durchschnittlichen Überschuss von 371 TWh pro Jahr ersetzen (Austauschpotenzial). Dennoch sollten zunächst die Auswirkungen von Solar- und Windkraftinfrastruktur auf Ökosysteme und Gesellschaft umfassend verstanden werden, bevor ihr ungehinderter Ausbau gefördert wird. Es lässt sich zusammenfassen, dass die vorliegende Arbeit zu einem evidenzbasierten Verständnis der Zusammenhänge zwischen Stromerzeugung und Flussschutz beiträgt. Die Ergebnisse können Diskussionen über künftige Wege zur Bewältigung der miteinander verwobenen Klima- und Biodiversitätskrise unterstützen. In dieser Hinsicht ist Afrika nicht nur in der Lage, eine Ära weitgehender Abhängigkeit von fossilen Brennstoffen zu vermeiden und auf erneuerbare Stromerzeugung umzusteigen, sondern auch, Überlegungen zum Schutz der Flüsse und zu Kompromissen bei der Infrastruktur für erneuerbare Energien in seine Planung für erneuerbare Stromerzeugung einzubeziehen.

List of publications

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1.

Introduction and background

Climate change and biodiversity loss are among the most severe challenges humanity faces in the Anthropocene. The latest assessment report of the Intergovernmental Panel on Climate Change confirms that the total net anthropogenic greenhouse gas (GHG) emissions have continued to rise during 2010 – 2019, as have cumulative net CO₂ emissions since the 1850s (IPCC, 2022). The energy-supply sector (including electricity and heat production) is with 34% the largest source for anthropogenic GHG emissions, followed by industry (24%), agriculture (22%), transport (15%), and buildings (6%) (IPCC, 2022). The global community has acknowledged the urgency to decarbonize the global energy sector and sets in the Agenda 2030 the goal to “ensure access to affordable, reliable, sustainable, and modern energy for all” (Sustainable Development Goal (SDG) 7 (UN, 2016)).

While climate change is on everyone’s radar, biodiversity loss is (intentionally or not) less represented by national agendas. The last Global Assessment Report of Biodiversity and Ecosystems Services from 2019 states, that the “biodiversity – the diversity within species, between species and of ecosystems – is declining faster than at any time in human history” (IPBES, 2019). At present, biodiversity conservation is hardly understood as an approach to mitigate the climate crisis (Dobson et al., 2021). This is evident, for example, in the rapid expansion of renewable energy infrastructure with limited systemic and large-scale assessment of ecological trade-offs (Fuso Nerini et al., 2018). As such, the expansion of hydropower has diminished the global share of rivers flowing uninterrupted to the ocean to 23% (Grill et al., 2019).

Neither the recommendations to limit global warming set by the Intergovernmental Panel on Climate Change (IPCC) nor the Aichi targets set by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) were met by 2020; enhancing the pressure on the global community to find pathways that tackle the intertwined climate and biodiversity crises (Pörtner et al., 2023). The research community can support the discussion by providing evidence on how renewable energy systems and ecosystems interact and run scenarios to analyse which pathways serve to minimize trade-offs while guaranteeing renewable-energy expansion and biodiversity conservation.

1.1. Hydropower plant and dam building

The construction of the first dam anywhere in the world, the Sadd el-Kafara dam, began around 4675 years ago on the African continent in Cairo, Egypt. It was planned with a dam height of 14m and total reservoir capacity of around 570,000m³ (Garbrecht, 1985). The purpose of this dam was to control floods, but it never entered operation; most likely due to erosion on the downstream face of the incomplete dam and its lack of a spillway (Adamo et al., 2020). Thousands of years later, the first hydropower turbines were invented by James Francis (1849), Lester Allan Pelton (1880), and Viktor Kaplan (1913); ever since these three turbine types have shaped hydropower development and continue to be the three main turbine types in use (IHA, 2023a).

Most hydropower plants (HPPs) operate with dam and reservoir storage; other technologies implemented include run-of-river and pumped storage HPPs. HPPs operating with reservoir or pumped storage can hold back water and thus respond flexibly to peaks in electricity demand.

Pumped storage plants include two reservoirs and can pump water up into the upper reservoir during low-demand times and release it back during periods of high demand; this provides a large degree of flexibility to deal with changing electricity demand. Run-of-river HPPs operate with little or no storage and can have a small dam. The technology diverts some or most of the river flow through a channel or pipe fitted with hydroelectric turbines, before returning it to the main channel.

From the 1940s onwards, hydropower was increasingly developed as a low-cost power source (IHA, 2023a). The trend continued until the debates on environmental and social impact halted many projects around the world (IHA, 2023a; Schulz & Adams, 2019). As a response to the growing dam and hydropower opposition, the World Commission on Dams (WCD) was initiated by the World Bank in 1997; a global multi-stakeholder body that shared in 2000 a new framework for decision-making which critically reviewed benefits and impacts of dams worldwide (World Commission on Dams, 2000). At the same time, the International Hydropower Association (IHA) was formed under UNESCO in 1995 and, in 2010, presented the Hydropower Sustainability Assessment Protocol (IHA, 2010). This multi-stakeholder tool, which aims to assess hydropower projects at all phases of their lifecycle, was criticized by the environmental organization International Rivers to greenwash dams as it is not a standard, lacks transparency, and is built as a subjective scoring system (International Rivers, 2013). In addition, the critics argue that the IHA is not inclusive for civil society and people affected by dam building (International Rivers, 2013).

Despite the public discourse on dam building, hydropower development and dam construction boomed from 2010 onwards (Zarfl et al., 2015). The direct and indirect consequences of dam building and reservoir formation have since continued to be discussed critically. The alteration and disruption of the natural river course results in reduced water and sediment connectivity, which changes the fluvial geomorphology (Zarfl & Lucía, 2018) and truncates biogeochemical processes (Deemer et al., 2016). Dam building accelerates the biodiversity crisis with an 84% decline of freshwater species since 1970, and nearly one-third of all freshwater fish facing extinction (He et al., 2019). Causes for biodiversity loss include dam-induced habitat fragmentation, over-exploitation, pollution, species invasion, and inhibited animal migration (Carrizo et al., 2017; He et al., 2017; Wu et al., 2019). Globally, one-third of dams within protected areas were built after conservation was established, even though these areas have the purpose of protecting animal and plant species from anthropogenic pressures (Thieme et al., 2020). If a dam is constructed in settled areas, resettlement can provoke conflict, with resettled people remaining uninformed and not sufficiently compensated for the loss of their livelihoods (Abrampah, 2017; Albert, 2015; Bilson Obour et al., 2016). Reservoir inundation can favour the spreading of water-borne diseases and affect public health (Bianchi & Gianelli, 2018); and it may trigger earthquakes (Tuan et al., 2017). Hydropower development is often accompanied by project delays and cost-overruns, which result from inefficient risk management and wrong site selection and can cause major economic and political impacts (Azam et al., 2022; Kansal & Agarwal, 2022; Plummer Braeckman et al., 2019; Shaktawat & Vadhera, 2021). Dam construction and reservoir inundation alter landscapes and existing land use, affecting both the public's perception of landscape and livelihoods, and in turn influence political trust in governments and institutions (Ioannidis & Koutsoyiannis, 2020). Finally, as about 60% of global rivers are transboundary, conflicting demands on usage and an unbalanced distribution of benefits and impacts can cause conflict between riparian countries (de Bruin et al., 2023; Dombrowsky & Hensengerth, 2018; Llamosas & Sovacool, 2021).

Most of these effects are direct consequences of dam building and reservoir formation and can be linked to a certain HPP project. However, several effects have the characteristic to accumulate

over time and with a growing number of HPPs. As such, HPP development can cause long-term alterations in natural systems at a large scale. For example, sediment entrapment, river regulation and fragmentation, and evaporation cause indirect effects that cannot be associated directly with an individual HPP project but are assessable at a large scale (Grill et al., 2019; C Hauer et al., 2018; Pfister et al., 2020). Another indirect consequence is the resettlement resulting from reservoir formation, which exerts anthropogenic pressure on previously unsettled areas.

While hydropower strongly influences natural river courses, both directly and indirectly, it is not the only form of infrastructure that employs dams and reservoirs. Dams are built to create reservoirs for water supply, irrigation, and flood-control purposes; many of them even serve more than one purpose (Lehner, Liermann, et al., 2011). However, the development of dams for different water uses has been rather competitive than integrated, missing opportunities for shared development and benefits (Branche, 2017).

1.2. Sustainability in the context of hydropower development

Sustainability is a term that has shaped debates in the 21st century. The Brundtland Commission (the World Commission on Environment and Development) proposed in its report “Our Common Future” in 1987 the concept of sustainable development (Thomsen, 2013). Within this report, sustainability was defined as “development that meets the needs of the present [generation] without comprising the ability of future generations to meet their own needs”. Over time, the concept of sustainability has evolved to include three dimensions: social, economic, and environmental. However, this differentiation has been criticized, arguing that it conceals the true conflict between the goals of universal welfare and environmental conservation, jeopardizes the significance of the environmental dimension, and creates a division between the social and economic dimension, which in reality are interconnected (Kuhlman & Farrington, 2010).

The International Hydropower Association (IHA) claims that the construction of hydropower can be sustainable if local impacts on communities and environment are avoided, minimized or mitigated (IHA, 2023c). Within this thesis, impact is defined as an effect or consequence that is caused from the construction and operation of a hydropower project, without valuation. HPPs can cause impacts on a wide range of systems including environment, society, economics, energy production, governmental regulation, and climate. Kaunda et al. argue that if these impacts are anticipated and mitigated in planning and design, sustainable hydropower is feasible (Kaunda et al., 2012).

Within the Agenda 2030 the United Nations address various social, economic, and environmental challenges to achieve a more sustainable world by the years 2030 (UN, 2015). The core of Agenda 2030 is composed of the 17 Sustainable Development Goals (SDGs). While SDG 7 “affordable and clean energy” and SDG 13 “climate action” welcome hydropower development, SDG 6.6 “protect and restore water-related ecosystems” as well as SDG 15.1 “conserve and restore terrestrial and freshwater ecosystems” favour freshwater protection (UN, 2015). Consequently, the conflicts of interest shaping hydropower development and whether or not it can be declared as sustainable are already intrinsic in Agenda 2030 and the SDGs, giving rise to the need for careful, science-based guidance in hydropower development.

Attempts to integrate impacts in project planning are for example reflected in the Hydropower Sustainability Standard, a certification scheme for HPPs from 2021 that originates in the Hydropower Sustainability Assessment Protocol (IHA, 2021b). The standard advertises that it

helps a hydropower project to assure that it provides net benefits to local communities and environments. Thereby, it addresses a short-coming of HPP planning and design: project developers must guarantee that those who benefit from hydropower (and are often far away) compensate the local populations (Moran et al., 2018).

Nevertheless, the standard falls short when it comes to the integration of long-term and large-scale impacts that cannot directly be linked to the construction of a specific HPP. If people are resettled into a formerly unsettled area, a development process places environmental sustainability in opposition to society's resource-consumption habits (Sternberg, 2008). The consequences of sediment entrapment, river regulation and fragmentation, and evaporation accumulate over time and with the number of installed HPPs. Due to the difficulty in linking these indirect effects to specific projects, conflicts can emerge at a larger scale. For example, conflicting interests between the Floods Directive (river regulation), the Water Framework Directive (sediment continuity, river restoration), and the Renewable Energy Directive (increase in hydropower production) in the European Union underline the lack of guidance on how to balance sediment entrapment from hydropower damming and the need for sediment continuity (C Hauer et al., 2018).

Scientifically informed guidance is also lacking when hydropower development is discussed in the context of the opposing aims of SDG 7, SDG 13, SDG 6.6 and SDG 15.1. At a global scale, only 37% of rivers longer than 1,000 kilometres remain free-flowing and are restricted to remote areas such as the Congo river basin (Grill et al., 2019). Dams and reservoirs are the leading contributors to the loss of river connectivity, causing a rapid decline in biodiversity and essential ecosystem services (Cardinale et al., 2012; Grill et al., 2019). While SDG 6.6 and SDG 15.1 can be used to argue for a conservation of the Congo river basin, SDG 7 and SDG 13 support a hydropower development pathway to provide access from renewable resources.

Lastly, evaporation from reservoirs cannot be omitted and is a so far poorly considered part of an HPP's water footprint (the total volume of fresh water that is used to directly or indirectly to produce a particular product) (Demeke et al., 2013). The evaporation of greenhouse gases from reservoirs in particular described for the tropics further highlights that hydropower is not per-se a climate-neutral renewable resource (Lu et al., 2020). In that regard, SDG 13 could also support an argumentation against hydropower development.

Linking indirect, large-scale, and long-term effects of HPPs to the concept of sustainability demonstrates that current attempts to certify hydropower as sustainable fall short in the consideration of the following aspects: (1) the importance of intergenerational equity, and (2) the environmental dimension. If the integration of indirect, large-scale, and long-term impacts falls short, fails, or is entirely neglected, intergenerational equity can hardly be guaranteed. Global hydropower planning would need to be part of international river basin planning, but at state level even established international river basin organizations are confronted with groups with different interests inhibiting fair benefit-sharing and long-term planning of hydropower within shared river basins (Dombrowsky & Hensengerth, 2018; Opperman et al., 2023).

In terms of the environmental aspect, discussions on the concept of sustainability have highlighted that it obscures the underlying conflict between the objectives of universal well-being and environmental preservation, potentially undermining the importance of the environmental dimension (Kuhlman & Farrington, 2010). These concerns are manifested in hydropower development. The trade-offs between conservation and hydropower development have been described intensively in the scientific literature, yet the demand for energy has fuelled a continued development (Almeida, Schmitt, Castelletti, et al., 2022; Schulz & Adams, 2019; Thieme et al.,

2021; Zarfl et al., 2015). In this regard, the SDGs are not sufficient to guide a sustainable hydropower development.

1.3. The renewable energy transition in Africa

The global community has acknowledged the urgency to decarbonize the global energy sector and the Agenda 2030 sets the goal to “ensure access to affordable, reliable, sustainable, and modern energy for all” (UN, 2015). However, what transitioning to renewable energy systems means is determined strongly by the socioeconomic conditions and the national context. Some 91.4% of the global population has access to electricity; but in sub-Saharan Africa it is only 50.6% (census 2021) (World Bank, 2021a). Consequently, a renewable energy transition in Africa requires not only decarbonizing existing energy systems; it also means connecting 566 million people that currently lack access (World Bank, 2021b).

According to the International Energy Agency, the largest source of electricity in Africa is natural gas (41%), followed by coal (29%), and hydropower (18%) (IEA, 2023a). Minor shares are provided by oil (6%), wind power (2%), solar photovoltaics (1.4%), and nuclear power (1.2%); Geothermal energy (0.6%), solar thermal energy (0.3) and biofuels (0.2%) contribute only marginally to overall electricity generation (data from 2020). From 2010 to 2020, the share of renewables in the electricity mix increased from 17 to 22% (IEA, 2023a). Following goal of the African Union’s Agenda 2063 of “harnessing all African energy resources to ensure modern, efficient, reliable, cost-effective, renewable and environmentally friendly energy to all African households, businesses, industries and institutions”, the renewable sector has to grow much more quickly (African Union, 2015). While the goal is set by the African Union, the pathways remain unclear.

A lot of research has looked into the continent’s renewable energy potential and has investigated the potential for solar power (ESMAP, 2020), onshore and offshore wind power (Elsner, 2019; Mentis et al., 2015), and hydropower (Korkovelos et al., 2018; van Vliet et al., 2016). Other efforts have focused on specific regions or countries (Bouraiou et al., 2020; Hailu & Kumsa, 2021; Mutombo & Numbi, 2019; Shaaban & Petinrin, 2014; Winkler et al., 2017). However, Oyewo et al. found that studies on 100% renewable energy systems in Africa are restricted to certain countries such as Morocco, Nigeria and La Réunion, while 80% of countries are not covered (Oyewo et al., 2023). The majority of African countries lacks specific data and models on how to achieve and implement a transition to entirely renewable energy. These gaps need to be filled in order to guide evidenced-based pathways towards renewable electricity for all.

In Africa, hydropower is the major provider for renewable electricity. Some 355 HPPs exist, 46 are under construction and further 673 proposed (Peters et al., 2023). If all proposed HPPs were implemented and those currently under construction completed, the capacity would more than double from 49 to 132 GW (Peters et al., 2023). But 60% of the installed hydropower capacity is over 20 years old and needs maintenance and updates to avoid capacity reduction (IHA, 2023b).

Renewable energy resources, including hydropower, are technologies to reduce greenhouse gas emissions from the electricity sector and to mitigate climate change. However, hydropower as a renewable resource depends on the natural water cycle, which is in turn impacted by climate change. Climate change can have various effects on the total quantity of electricity produced from hydropower. Besides direct effects such as stream flow drought, hydroelectricity generation can be influenced by secondary effects including floods and landslides (Wasti et al., 2022). Another development is the increasing interannual precipitation variability, which causes extended periods of drought, an effect particularly severe in several African regions. Based on streamflow drought

simulations from 1975 to 2016 Wan et al. predicted that 12 countries face a risk of a high hydroelectricity reduction between 20 and 40% whereas nine are at risk of a severe hydroelectricity reduction of more than 40 to 100% (Wan et al., 2021). The countries at risk are located in northern, western, and southern Africa. In contrast, van Vliet et al. predicted that climate change will cause positive changes in central Africa and lead to an increasing hydropower potential (van Vliet et al., 2016). Consequently, climate change will affect hydropower performance and potential, but the direction is subject to location and varies within the African continent. Therefore, much more regionally specific research is needed to provide spatially explicit evidence and guidance on how climate change affects existing and future hydroelectricity production.

1.4. The impact of building or not building a dam

Dams along river courses are constructed due to various reasons, of which all are instrumental to human needs. Communities benefit from water supply, flood control, irrigation, and hydroelectricity. Increasing population and a rising demand for these services have promoted dam and reservoir development, with a total of 38,667 dams globally installed (Mulligan et al., 2020). In addition, the need for climate change mitigation has enlarged interests in hydropower as a renewable electricity resource. The momentum fuelling dam and reservoir development was temporarily slowed by debates on the negative effects of dam building and reservoir inundation that started in the 1980s (World Commission of Dams, 2000). However, the need for the services provided by dams and reservoirs overcame these concerns and led to their continued development.

In African countries, the impact of building or not building a dam is more pronounced than elsewhere: hydropower is an important source of renewable energy, and the continent not only needs to decarbonize its energy systems but also provide access to energy to almost half of its growing population. Simultaneously, river networks such as the Congo are among the last mainly free-flowing rivers worldwide and harbour important amounts of biodiversity. Developing hydropower within this field of conflicting needs requires careful and sustainable planning. In this regard, the concept of sustainability must be applied critically at system scale to avoid the “greenwashing” of dams. Therefore, implementers have to acknowledge that dams and reservoirs operate differently from conventional infrastructure. A design life-concept for hydropower needs to integrate the negative effects of the simultaneous construction of several HPPs at system scale.

At the state level, the African continent lacks scientific evidence including data, scenario modelling and potential analysis, to guide scientifically informed pathways towards renewable energy for all. Current guiding systems such as the Hydropower Sustainability Standard fall short when it comes to the integration of secondary, long-term and large-scale impacts. They can result in recommendations for seemingly sustainable HPPs, but history has shown that secondary effects occur with a spatial and temporal delay, resulting in, among other effects, sediment entrapment, river fragmentation, biodiversity decline, and protected area disturbance (Grill et al., 2019; Christoph Hauer et al., 2019; He et al., 2019; Thieme et al., 2020).

If hydropower is identified as unsustainable, the question arises whether renewable alternatives have the potential to step in. The African continent is shaped by a large diversity and range of climatic conditions and ecosystems. Climatic conditions shape each country’s potential for renewable resource exploitation, including hydro-, solar, and wind power. In addition, solar and wind power are variable renewable resources that require energy storage or a smart electricity system design to ensure a secured electricity supply (Sterl, 2021a; Sterl et al., 2020). For

hydropower-dependent countries located in central Africa, the joint use of renewable energies may become necessary. To adequately address each country's possibilities, data on wind and solar potential, as well as on projects already in the pipeline, are needed. An "access to affordable, reliable, sustainable, and modern energy for all" further implies the inclusion of the diverse starting points, from which African countries head off (UN, 2015). These starting points are shaped by population density, electricity access rates, fossil fuel dependency, and the geological and climatic conditions. In addition, scientifically informed pathways require context-specific data on future scenarios where the "energy for all" must fill the electricity needs of an increasing population.

More than any other continent, Africa holds the potential to avoid a phase of fossil fuel dependency. Yet, sustainable renewable pathways have to integrate the negative effects of building hydropower dams. Solar and wind power can be feasible options to supplement or replace hydropower, but a lack of openly accessible and harmonized data on the three main renewable types hydro-, solar, and wind power hampers research. Scientific research in renewable energy modelling has focused on just a few countries in the past, limiting recommendations to specific countries or to "one solution fits all" approaches (Mulugetta et al., 2022; Oyewo et al., 2023). As such, large-scale analyses that consider national contexts and conditions are of high relevance to provide scientific evidence on how Africa can provide sustainable renewable energy to all its citizens.

1.5. Research objectives

The overarching motivation of the present thesis is to provide insights in renewable energy development in Africa that integrates (1) the need to expand electricity generation, (2) the need to mitigate climate change and thus expand renewable electricity, and (3) the need to reduce river fragmentation. More specifically, the thesis provides insights on what is needed to provide renewable electricity for all, while avoiding the projected impacts from proposed hydropower, which are often considered to be negative. It therefore considers the renewable alternatives, solar and wind power.

In detail, this thesis aims to answer the following research questions:

- (1) How many hydro-, solar, and wind power plants exist in Africa and how many are under construction or proposed?
- (2) To which degree would proposed hydropower plants influence the natural environment and society at the river-basin and continental scale if implemented?
- (3) Has Africa the capacity to undertake the transition towards renewable energy-based systems that meet increasing demand for electricity?
- (4) Can the maintenance of existing hydropower infrastructure, the combination of existing hydropower with floating solar power, and the replacement of proposed hydropower with solar and wind power, avoid further hydropower development?

1.6. Outline of the thesis

The present thesis is a continental in-depth analysis that provides data-driven evidence on how renewable electricity generation and river protection are linked. It further investigates renewable alternatives that enable simultaneous renewable electricity expansion and river conservation.

In Chapter 2 the Renewable Power Plant Database (RePP) Africa, a georeferenced and curated database on existing and proposed wind, solar, and hydropower plants is presented (Figure 1.1).

RePP Africa is a compiled database that harmonizes in-depth information on existing and proposed renewable power plants for the most important technologies.

Based on the hydropower data in RePP Africa, an integrated impact assessment for all proposed HPPs on the African continent is implemented in Chapter 3 (Figure 1.1). Therefore, the impacts of proposed HPPs were calculated and ranked according to several ecological, socioeconomic and political indicators. The results were aggregated and analysed at different spatial scales, and tested for sensitivity under different scenarios.

Chapter 4 reviews and integrates the entire RePP Africa dataset to analyse the starting points that shape each country's pathway towards universal renewable electricity access (Figure 1.1). The chapter looks into the diversity in potentials and needs within the African continent and points out the context-specific evidence needed to guide a sustainable development.

In Chapter 5 the feasibility of a renewable electricity mix that avoids the increasing fragmentation of African rivers is investigated (Figure 1.1). The chapter analyses potentials for HPP maintenance, co-use, and replacement. HPP maintenance considers the historic development of available hydropower capacity, including the lost capacity due to times of no operation. HPP co-use potential assesses to which degree further electricity could be exploited from existing hydropower reservoirs by installing floating photovoltaics. HPP replacement potential investigates each country's capacity to replace proposed hydropower by exploiting economically feasible areas for solar and wind power.

In summary, the present thesis provides data and a large-scale analysis on the context specific pathways that must guide a sustainable renewable energy transition in African countries all over the continent. The need for renewable electricity generation is integrated with an in-depth analysis of hydropower as a renewable resource that is not *per se* sustainable.

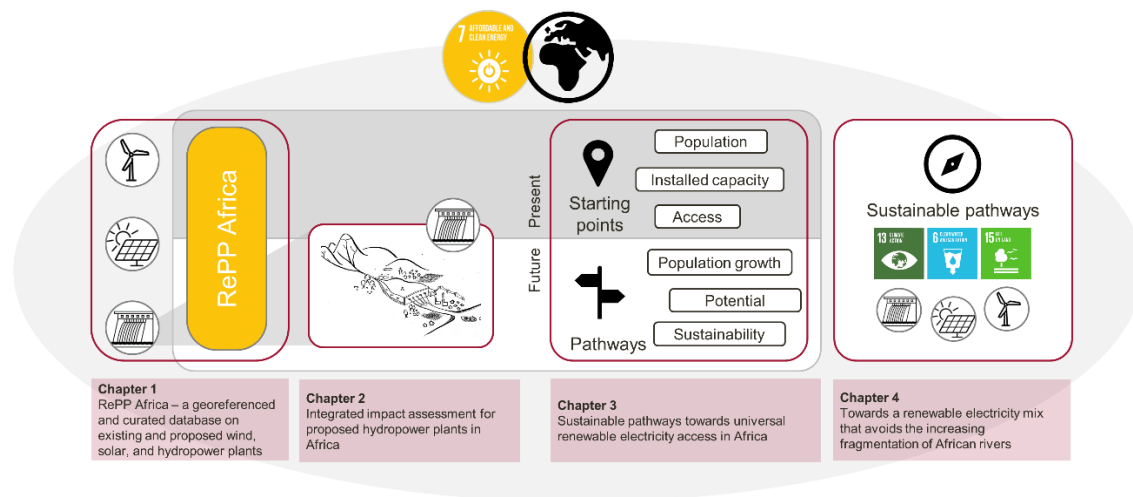


Figure 1.1. Structure of thesis. Chapter 2 “Integrated impact assessment for proposed hydropower plants in Africa” is intended for publication and its methodology has been adapted from Peters et al. (Sustainability, 2021). Chapter 3 “RePP Africa – a georeferenced and curated database on existing and proposed wind, solar, and hydropower plants” is published as Peters et al. (Scientific data, 2023). Chapter 4 “Sustainable pathways towards universal renewable electricity access in Africa” is published in Peters et al. (Nature Reviews Earth & Environment, 2023). Chapter 5 “Towards a renewable electricity mix that avoids the increasing fragmentation of African rivers” is intended for publication, but has not yet been submitted. Icons of four Sustainable Development Goals (SDG) of the Agenda 2030 are included: SDG 7 in yellow stands for “affordable and clean energy”. SDG 13 in dark green stands for “climate action”. SDG 6 in light blue stands for “clean water and sanitation”, as Chapter 5 specifically addresses SDG 6.6 which aims to “protect and restore water-related ecosystems”. SDG 15 in light green stands for “life on land”, as Chapter 5 specifically addresses SDG 15.1, which aims to “conserve and restore terrestrial and freshwater ecosystems”.

2.

RePP Africa – A georeferenced and curated database on existing and proposed wind, solar, and hydropower plants

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2.1. Abstract

Promoting a transition to low-carbon energy systems to mitigate climate change requires an optimization of renewable energy (RE) planning. However, curated data for the most promising RE technologies, hydro-, wind and solar power, are missing, which limits data-based decision-making support. Here, a spatially explicit database for existing and proposed renewable power plants is provided: The Renewable Power Plant Database for Africa (RePP Africa) encompasses 1074 hydro-, 1128 solar, and 276 wind power plant records. For each power plant, geographic coordinates, country, construction status, and capacity (in megawatt) are reported. The number of RePP Africa records exceeds the respective values in other existing open-access databases and matches available cumulative capacity data reported by international energy organizations best with deviations <13% for hydro-, <23% for wind, and <32% for solar power plants. This contemporary database is the most harmonized open-accessible reference source on RE power plants across Africa for stakeholders from science, (non-)governmental organizations, consulting, and industry; providing a fundamental data basis for the development of an integrated sustainable RE mix.

2.2. Background & summary

African countries face the challenge of providing electricity for 596 million people that currently lack access (i.e. 43% of actual population (1373 million); census: 2021) (IEA, 2020b). Concurrently, for advancing climate change mitigation and achieving long-term objectives of the Paris Agreement, the electricity sector needs to be climate-neutral by mid-century (Kuramochi et al., 2018). While many developed countries are dealing with the environmental impacts caused by a long history of fossil fuel energy dependence, African countries could leapfrog the transition to renewable, low-carbon energy supply systems (Momodu et al., 2022; Mutezo & Mulopo, 2021). In Africa, hydropower remains the primary renewable electricity resource, accounting for 70% of the renewable electricity share, which corresponds to 16% of total electricity production

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(2020) (Mutezo & Mulopo, 2021). At the same time, the continent has the highest untapped hydropower potential worldwide, with actually 11% utilized (IHA, 2021a). An estimation of remaining potential for Africa amounts to 2.3 petawatt hours (PWh) per year, at costs of more than 0.5 US\$ per kilowatt hour (kWh) (Gernaat et al., 2017). Electricity generation from hydropower is considered renewable and one that can support climate change mitigation. However, costs and risks of large hydropower plants (HPPs) have often been underestimated while their benefits were overestimated (Moran et al., 2018). HPPs operating with dams truncate natural river flows and may cause unexpected ecological, socioeconomic, and political ramifications on different temporal and spatial scales (de Faria et al., 2017; Peters et al., 2021; Thieme et al., 2021; Zarfl et al., 2019). These changes are often irreversible. Furthermore, not only does dam building impact natural river systems, but dam removal can also cause unknown costs and ecological impacts on the formerly dammed river regimes (Bellmore et al., 2019; Habel et al., 2020). Regarding the future performance of HPPs, climate change induced runoff changes (e.g., floods, prolonged droughts) are likely to jeopardize hydroelectricity generation in several African regions (van Vliet et al., 2016). Other technologies to generate electricity from hydropower are run-of-river and pumped storage schemes. While run-of-river is a decade-old technology, with limited capacity for energy storage, pumped storage technology has gained increasing attention only very recently (Hunt et al., 2020). Consistent databases reporting and distinguishing the three technology types are still lacking. As a consequence, the opportunities for and impacts of these technology types on a national or continental level are poorly studied, constraining advanced hydropower energy planning (Kuriqi et al., 2021).

During recent years, solar and wind power have exhibited the highest growth rates among Africa's renewable energy (RE) resources, yet they still contribute marginally to Africa's energy resource mix (i.e. solar: 1.2%; wind: 1.5% share of total electricity generation in 2019 (IRENA, 2022d)). Given the dependence of solar and wind power on meteorological variables, power generation from these RE resources is variable and intermittent, from short (sub-hourly) to long (seasonal and interannual) timescales (Engeland et al., 2017). In order to address this challenge, increased research attention has been given to approaches that investigate integrated RE storage options, to thereby exploit the complementary spatiotemporal properties of RE resources (Solomon et al., 2020; Sterl, 2021a).

Various databases on renewable power plants have been published. On a global scale, the Global Energy Observatory (Global Energy Observatory (GEO), 2022), the Open Infrastructure Map (OpenStreetMap, 2004), and the Global Power Plant Database (Byers et al., 2018) provide georeferenced information on fossil fuel and renewable power plants. Up to now, however, these open source databases lack information for Africa, in particular in the fast-developing domains of solar and wind power. The Global Reservoir and Dam Database (GRanD) and the Future Hydropower Reservoirs and Dams Database (FHReD) are frequently cited as established databases reporting existing and future HPPs (Lehner, Liermann, et al., 2011; Zarfl et al., 2015); yet only HPPs operating with a dam and a reservoir are included. Published in 2021, the African Hydropower Atlas (AHA) presents a harmonized dataset on existing and planned hydropower plants to facilitate modelling of power systems across Africa (Sterl, Devillers, et al., 2021). At the same time, its restriction to hydropower plants limits renewable power plant modelling. In order to implement integrated modelling approaches on the (potential) electricity mix, and its implications in Africa, the African Energy Live Data database, provided by the African Energy company, has been increasingly used as a reliable source by the science community in the past (African Energy, 2022; Alova et al., 2021; Mahmood et al., 2020). However, the London based consultancy company only provides small shares of their data to the public and charges for further downloads for analysis processing (African Energy, 2022). The Wind Power is one of a few global

databases that provides information on existing and proposed wind farms in Africa, but similar to African Energy Live Data, only parts of it are freely accessible (Pierrot, 2022). For solar power plants the Wiki solar database (WolfeWare, 2022) provides a similar service and covers globally more than 10,000 power plants. Again, data usage and replication are restricted and not available under a creative common license. The scientific use of renewable energy datasets without creative common license conflicts with the need that research published in scientific journals and including accessible datasets is reproducible. This lack of harmonized, open-access, and reliable datasets with georeferenced information on existing and proposed HPPs, solar power plants (SPPs), and wind power plants (WPPs) limits ongoing research efforts on the sustainable development of the energy resource mix and constrains a science-based discussion among stakeholders in the decision process.

In summary, two main approaches are currently used for renewable energy analyses on a continental or global scale: (1) Analyses are performed for one RE type, using a corresponding database (Thieme et al., 2020) or (2) integrated analyses for different RE types are performed and data is compiled from various databases (de Angelis et al., 2021; Sterl et al., 2020) or databases are behind paywalls (Alova et al., 2021). The lack of a comprehensive and up-to-date database covering comparable information of existing and proposed HPPs, SPPs, and WPPs limits integrated renewable energy planning worldwide, in particular for Africa.

Here, the comprehensive, curated and georeferenced Renewable Power Plant Database for Africa (RePP Africa) is presented (last revision: 16.11.2022) (Peters et al., 2022). Data records were compiled and processed from various sources for all African countries. The establishment of the database included four steps: compilation, georeferencing, completion, and revision (Figure 2.1).

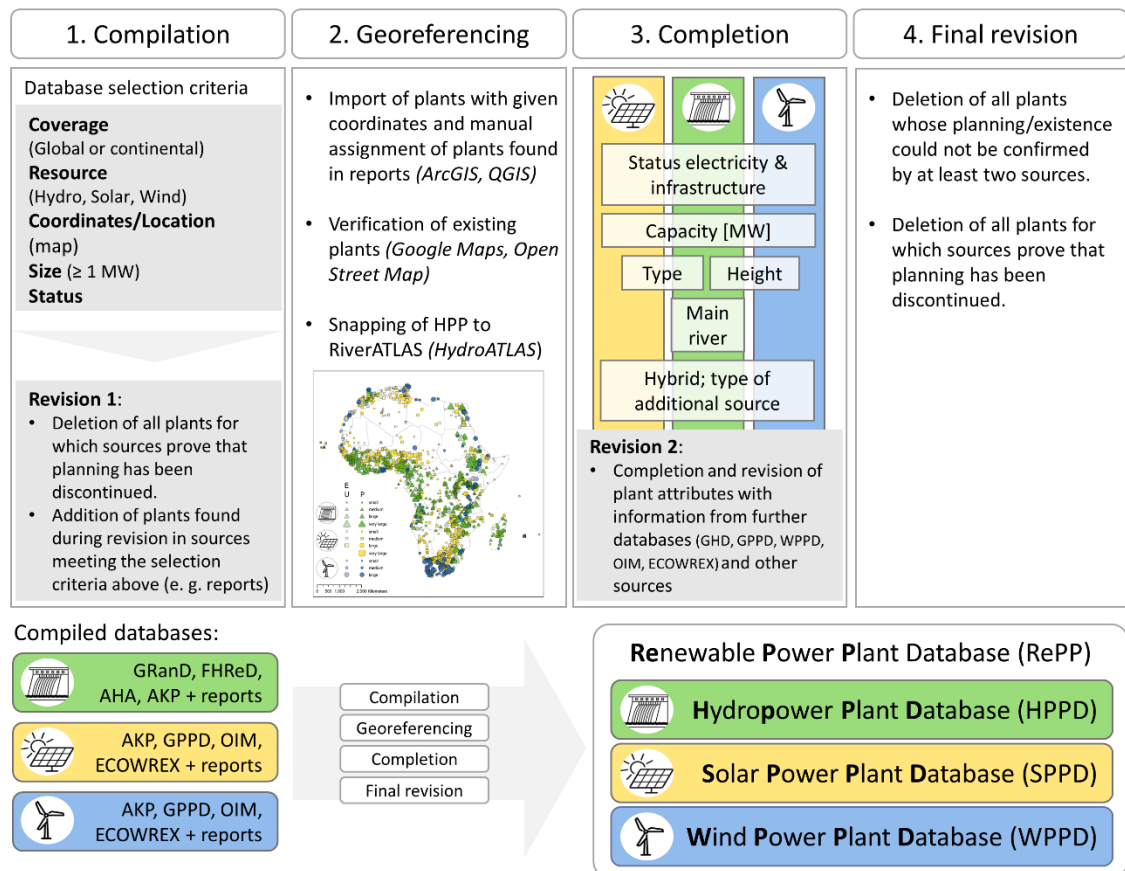


Figure 2.1: The four steps of the database generation process. 1. Compilation: Databases were selected based on five criteria: i. The database (DB) has a global or continental coverage; ii. The DB contains information on hydro, solar

and/or wind power plants; iii. The DB provides coordinates or maps the location of power plants; iv. Power plants with a capacity of ≥ 1 megawatt (MW) are included; v. A status of the electricity production or plant facility is indicated (e. g. proposed/planned; under construction; existing). During revision 1 all compiled plants were revised to delete plants for which sources prove that planning has been discontinued and to add plants that were identified in sources meeting the database selection criteria. 2. Georeferencing: All data records were georeferenced. 3. Completion: Summary of attributes that were checked for each plant to fill missing information. Background colours indicate if an attribute is given for all three RE types (green = hydropower, yellow = solar power, blue = wind power) or only for one or two RE types. 4. Final revision: Data records with status cancelled or insufficient proof were deleted. The final product is the Renewable Power Plant Database (RePP) Africa which consists of the Hydropower Plant Database (HPPD), Solar Power Plant Database (SPPD), and Wind Power Plant Database (WPPD) for Africa.

The first openly-accessible and harmonized renewable power plant database covering entire Africa includes georeferenced information on a total of 1074 HPPs, 1128 SPPs, and 276 WPPs. 401 HPPs, 411 SPPs, and 127 WPPs are existing or under construction, with a total capacity of 58.36 gigawatts (GW), 10.56 GW, and 10.53 GW respectively (Table 2.1). As of November 2022, 673 HPPs, 717 SPPs, and 149 WPPs are proposed with a total respective capacity of 132.05 GW, 53.32 GW, and 16.87 GW.

RePP lists three types of power plant facility status (attribute label in database: stat_inf): existing (E), under construction (U), and proposed (P). Proposed plants include potential sites where feasibility studies were realized. Once the construction has started, the status changes to under construction. If a plant is officially inaugurated, its status turns to existing. Each data entry is provided with a time stamp indicating when the status was last checked.

Table 2.1: Summary of number and capacity (MW) of hydro-, solar, and wind power plants according to four size categories. Summaries are given for the status of the power plant facility (stat_inf) distinguishing existing plants (E), plants under construction (U) and proposed plants (P). Numbers in brackets: Percentage [%] of the total.

			Hydropower		
			E	U	P
Number of plants	Total		355	46	673
	Small	1 - 10 MW	152 (43)	12 (26)	202 (30)
	Medium	>10 - 100 MW	124 (35)	15 (33)	283 (42)
	Large	>100 - 1000 MW	70 (20)	14 (30)	166 (25)
	Very large	>1000 MW	9 (2)	5 (11)	22 (3)
Capacity [MW]	Total		39175.97	19188.40	132049.68
	Small	1 - 10 MW	650.75 (2)	49.40 (0)	946.02 (1)
	Medium	>10 - 100 MW	4772.32 (12)	575.00 (3)	11412.01 (9)
	Large	>100 - 1000 MW	20641.90 (53)	4203.00 (22)	53567.65 (41)
	Very large	>1000 MW	13111.00 (33)	14361.00 (75)	66124.00 (50)
			Solar power		
			E	U	P
Number of plants	Total		361	50	717
	Small	1 - 10 MW	192 (53)	19 (38)	200 (28)
	Medium	>10 - 100 MW	164 (45)	31 (62)	429 (60)
	Large	>100 - 1000 MW	5 (1)	1 (2)	85 (12)
	Very large	>1000 MW	0	0	3 (0)
Capacity [MW]	Total		8636.46	1923.12	53316.31
	Small	1 - 10 MW	673.51 (8)	96.42 (5)	1217.93 (2)
	Medium	>10 - 100 MW	7097.95 (82)	1326.70 (96)	23732.73 (44)
	Large	>100 - 1000 MW	865.00 (10)	500.00 (26)	18815.65 (35)

	Very large	>1000 MW	0	0	9550.00 (19)
			Wind power		
			E	U	P
Number of plants	Total		119	8	149
	Small	1 - 10 MW	26 (22)	0	10 (7)
	Medium	>10 - 100 MW	53 (44)	2 (25)	78 (52)
	Large	>100 - 1000 MW	40 (34)	6 (75)	61 (41)
	Very large	>1000 MW	0	0	0
Capacity [MW]	Total		9032.21	1495.91	16869.45
	Small	1 - 10 MW	133.23 (1)	0	64.00 (0)
	Medium	>10 - 100 MW	2617.24 (29)	158.91 (11)	4379.75 (26)
	Large	>100 - 1000 MW	6281.74 (70)	1337.00 (89)	12425.70 (74)
	Very large	>1000 MW	0	0	0

Power plant facilities might exist but not generate electricity for uncertain time periods due to damage or other reasons. However, the searched databases do not distinguish operating and temporarily not operating existing plants. In order to enable RePP Africa users to consider this issue when using RePP Africa data (Peters et al., 2022), we include the status of electricity generation (status_ele). It gives information on the status of power generation and distinguishes between operating (O), under construction (U), proposed (P), and not operating (NO). Since in the last case, the infrastructure of the power plant facility is existing, not operating plants could be rehabilitated and operate again.

For HPPs and SPPs, different operating systems are distinguished. Some 446 HPPs operate with reservoir storage, 286 as run-of-river HPPs, and 17 HPPs with a pumped-storage system. No adequate information could be provided for 325 HPPs (30% of total), with 86% of these categorized as proposed (281 HPPs). Most SPPs (1072) are operating or proposed as photovoltaic (PV), 47 as concentrated solar power (CSP), and 9 as concentrator photovoltaic (CPV) type plants.

As of November 2022, all 54 African countries have installed or proposed energy generation capacity from RE resources. Solar power and wind power are playing an increasingly important role in the total RE resource mix, with shifts between installed and proposed total capacity differing among countries (Figure 2.2).

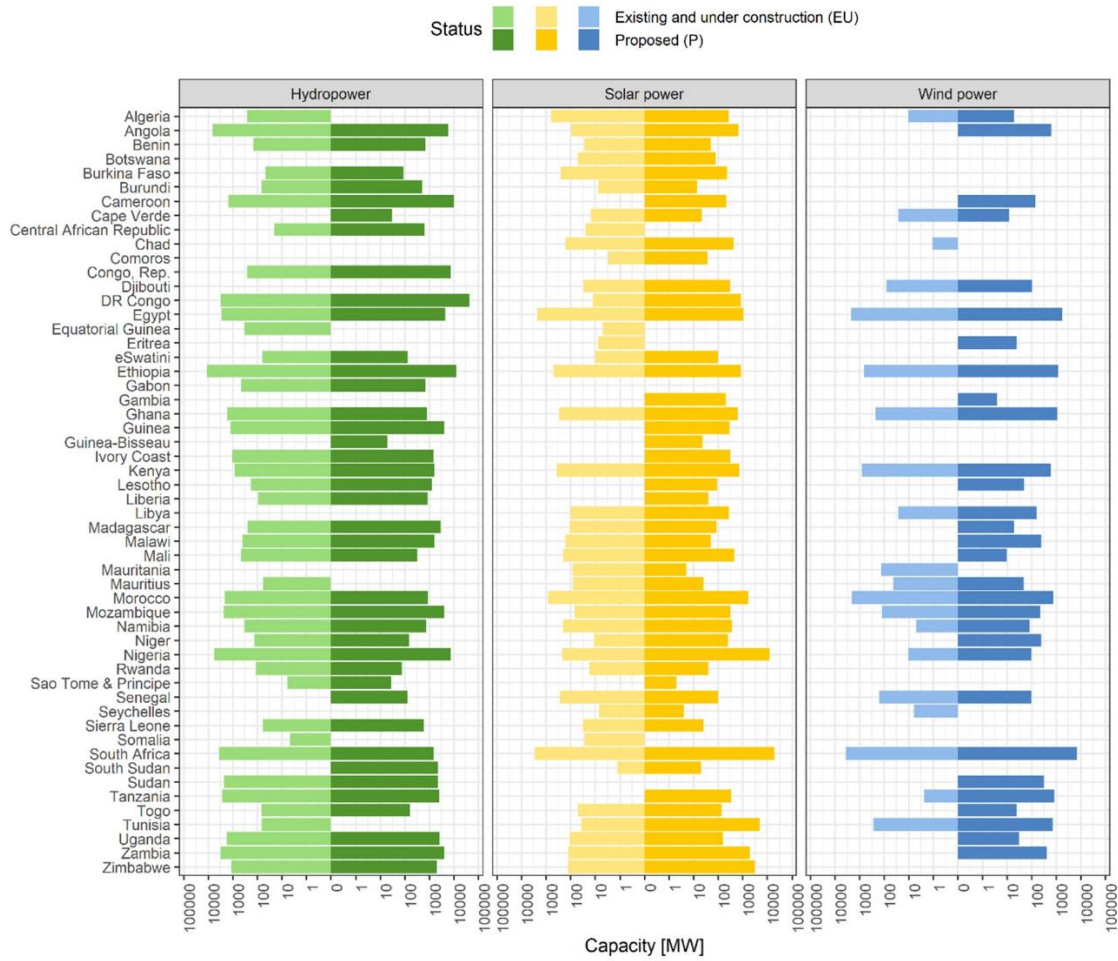


Figure 2.2: Cumulated capacity in megawatts (MW) by country for hydropower, wind power, and solar power plants. In this figure, the Sahrawi Arab Democratic Republic (Western Sahara) is geographically aggregated with Morocco. No statements on the political situation are intended.

The contemporary, curated database on renewable power plants (existing, under construction, proposed) in African countries will enable the research community to address and fill current research gaps and to advance integrated renewable energy modelling. Openly accessible data on renewable energy plants vary in quality among countries. The RePP Africa (Peters et al., 2022) intends to stimulate integrated research and large-scale assessments at a continental level as well as to foster case studies and research activities in data-poor regions of less-studied African countries.

2.3. Methods

The spatially-explicit, Renewable Power Plant Database (RePP) Africa (Peters et al., 2022) aims to advance existing efforts in the field of open-accessible renewable energy data. By harmonizing, reviewing, and updating information on power plants from established databases (Byers et al., 2018; Global Energy Observatory (GEO), 2022) and adding information from other sources, RePP Africa (Peters et al., 2022) is a coherent database on the current key technologies hydro-, solar and wind power for the African continent. RePP was created to respond to an increasing demand for datasets that allow integrated electricity planning and impact assessment modelling on renewable power technologies. RePP Africa (Peters et al., 2022) is composed of three sub-datasets, containing information for hydropower, solar power and wind power. This approach enables the user to apply the database either for a specific energy source or across RE sources.

RePP Africa (Peters et al., 2022) covers all African countries and includes existing power plants (E), plants under construction (U) and proposed power plants (P). It further indicates the status of electricity production, because existing power plant facilities might be temporarily out of operation (operating (O), under construction (U), proposed (P), not operating (NO)). Data collection started in March 2021. The last revision was finished in November 2022. Power plants scheduled to go into operation in 2022 are kept in the categories “under construction” or “proposed” if no source indicating inauguration or construction start is given. However, continuous revisions will be performed in order to update the database and to adjust information if necessary or justified.

2.3.1. Compilation

Data was collected from a wide array of available information sources. First, data records on existing and proposed projects were compiled from available databases with creative common license (Figure 2.1). Databases had to match the following criteria: (1) Coverage of the database is global or continental (Africa). Due to limited availability of freely accessible databases for wind and solar power plants we optionally accepted the ECOWAS observatory for Renewable Energy and Energy Efficiency (ECOWREX) (ECREE, 2022) covering West Africa. (2) The database includes information on hydropower, solar power, or wind power plants: The database contains information on all RE resources or, in selected cases, only on a specific energy source. (3) The database includes precise geographic information on the power plant location, ideally coordinates (latitude, longitude), or is displayed in form of a freely-accessible map that indicates plant location. In the latter case, coordinates were manually derived using ArcGIS Pro (ESRI, 2022) and QGIS (QGIS, 2021). (4) The database provides the capacity of the respective plant in megawatts (MW), at least for the majority of the power plant projects. Reservoir size data in million cubic meters (million m³) from the Global Reservoir and Dam Database (GRanD) (Lehner, Liermann, et al., 2011) was optionally accepted. (5) Information on the status of electricity production (not operating, operating, under construction, proposed) or the power plant facility (existing, under construction, proposed) is provided. The Africa Knowledge Platform (AKP) (European Commission, 2020) provides capacity values in megawatts only for existing plants, which was optionally accepted because AKP was the database with the highest number of data records for all renewable resources. Data entries were combined with further information found during the following revision steps.

Four databases were used to compile information of power plants for each renewable source: For hydropower plants we used information from the Global Reservoir and Dams Database v1.3 (GRanD) (Lehner, Liermann, et al., 2011), the Future Hydropower Reservoirs and Dams Database (FHReD) (Zarfl et al., 2015), the African Hydropower Atlas v2.0 (AHA) (Sterl, Devillers, et al., 2021), and Power Plants by the Africa Knowledge Platform (European Commission, 2020). For solar and wind power we used information from Power Plants by the Africa Knowledge Platform (European Commission, 2020), the Global Power Plant Database v1.3.0 (GPPD) (Byers et al., 2018), ECOWAS observatory for Renewable Energy and Energy Efficiency (ECOWREX) (ECREE, 2022), and Open Infrastructure Map (OpenStreetMap, 2004). After collection and harmonizing power plant information for each resource in an Excel sheet, all data entries were checked using the Google Search Engine (Revision 1). Entries of power plants for which sources prove that planning has been discontinued were deleted. If the database compilation revealed inconsistent information, we consulted further sources in order to assure providing a correct information for each plant. Therefore, we prioritized (1) information from individual, specific project reports and (2) information from up-to-date sources (referring to the current timestamp of the data entry). Inconsistent information was mainly found for proposed

power plants, because feasibility studies and project proposals do not confirm a single capacity value to be installed but may present different capacity values. For the attribute `g_cap_mw` (given capacity in megawatts (MW)), we selected the capacity indicated by the majority of sources and saved further information in the field “other capacity” (`other_cap_mw`). Additional power plants found during revision 1 in other literature sources matching criteria (3), (4), and (5) were added. Only openly accessible information from databases with creative common license was included. All licences that apply to the searched databases are listed in RePP Africa (Peters et al., 2023).

2.3.2. Georeferencing

All plants with given coordinates were imported to ArcGIS Pro (ESRI, 2022) and QGIS (QGIS, 2021) software. All plants with locations indicated or described by reports or other sources were added manually and coordinates checked for plausibility. Existing plant locations were cross-checked using Google Maps and Open Street Map and, if necessary, corrected. All HPPs were snapped to river lines of the RiverATLAS (HydroATLAS (Linke et al., 2019)) to facilitate further processing.

2.3.3. Completion

In order to complete information, all plants were checked (revision 2) using Google search engine and information from further databases (Hydropower: Global Hydropower Database (Wan et al., 2021), Global Power Plant Database (GPPD) (Byers et al., 2018), World Power Plant Database (WPPD) (Global Energy Observatory (GEO), 2022), Open Infrastructure Map (OpenStreetMap, 2004), and ECOWAS observatory for Renewable Energy and Energy Efficiency (ECOWREX) (ECREE, 2022); Solar and Wind Power: World Power Plant Database (WPPD) (Global Energy Observatory (GEO), 2022). The database Power Africa from the African Development Bank was excluded during the last revision in November 2022, because the database is no longer accessible due to unknown reasons. Table 2.2 summarizes all available attributes and the relative proportion [%] of plants for which the information is available. In addition, RePP Africa (Peters et al., 2022) indicates for each plant if it is listed in one of the consulted databases and specifies further used sources. Such additional data sources can be divided into three categories: (1) summary reports and books that list power plants on a regional/national scale, including all three power types or on a continental/global level for a specific power source; (2) information pertaining to individual projects, from technical project fact sheets, environmental impact assessments, peer-reviewed papers, and project summaries or presentations from engineering companies; and (3) online newspaper articles and social media announcements.

Table 2.2: Overview of attributes (metadata) provided in the African Renewable Power Plant Database (RePP Africa). Attribute (column name) and a description are given. For each renewable type (Hydropower Plant Database (HPPD), Solar Power Plant Database (SPPD), and Wind Power Plant Database (WPPD)) the share of records that have a data entry for this attribute is indicated as percentage [%] of the total number of records (i.e., 100% indicates that the attribute is given for all plants). If attributes are not available for all data records (<100%), the relative proportion of available records is given in percent [%] for all plants; and for existing and under construction/proposed plants separately (in brackets).

Column name	Description	HPPD	SPPD	WPPD
<i>Total number of records:</i>		1074 (355/46/673)	1128 (361/50/717)	276 (119/8/149)
		Total of available data records in percent [%]		
		(Existing (E)/under construction (U)/proposed (P))		

ID	Identification number for each power plant by source	100	100	100
Lon/Lat [Degree]	Longitude and Latitude	100	100	100
Country	Country name	100	100	100
Name	Power plant name	100	100	100
Several phases	Existing and proposed database entries with exact same location (presumably capacity update of existing power plant)	8 (12/4/5)	2 (2/2/2)	14 (32/13/1)
Status electricity	Status of electricity generation (Not operating (NO), Operating (O), Under construction (U), Proposed (P))	100	100	100
Status infrastructure	Status of infrastructure of plant facility (Existing (E), Under construction (U), Proposed (P))	100	100	100
Capacity [MW]	Given capacity in megawatts (MW)	100	100	100
Type	Run-of-river (RoR), reservoir or pumped storage for HPP; photovoltaic (PV), concentrator photovoltaics (CPV), concentrated solar power (CSP) for SPP	70 (89/89/58)	100	-
Main river	Main river for hydropower plants	91 (92/89/90)	-	-
Height [m]	Dam height for HPP (type reservoir); wind turbine height for WPP	20 (36/37/11)	-	20 (37/13/7)
Construction start [year]	Indicates year of construction start	9 (19/46/2)	10 (12/54/6)	13 (20/75/3)
First operating start [year]	Indicates (proposed) year of plant commission / first operation start	61 (99/54/42)	41 (96/50/13)	55 (100/75/18)
Operating stop [year]	Indicates year of temporary operation stop	2 (7/0/0)	0	1 (3/0/0)
Operating at full capacity [year]	Indicates first year where plant operates at full capacity (in particular for large plants this year can differ from the year of commission)	5 (15/2/0)	0	0
Hybrid	Indicates if power plant operates with additional energy sources	1 (0/2/2)	13 (19/14/10)	5 (4/0/6)
Additional capacity	Energy source(s) that provide(s) the additional capacity	1 (0/2/2)	13 (19/14/10)	5 (4/0/6)
Last edit [DD.MM.YYYY; HH:MM]	Date and time of last edit (UTC +1)	100	100	100

2.3.4. Final revision

Each plant record was revised by the authors and specifically checked on plant existence or proposal. To increase data quality and exclude outdated and incorrect data records, each entry is confirmed by two or more references. In order to assure the latter, we consulted sources found via the Google search engine and freely accessible data from African Energy Live Data (African Energy, 2022), The Wind Power (Pierrot, 2022), and Wiki-Solar (WolfeWare, 2022). The consultation of these databases was in agreements with their respective terms of use: No information was downloaded or copied and only freely accessible information was consulted to confirm information collated for RePP Africa (Peters et al., 2023). Collected data records were excluded when (1) a second source was not found during final revision or (2) when the proposed plant was irreversibly cancelled. Date of last revision and edit is indicated for each plant and for the complete database. Last revision of the complete current version was November 2022. Just before RePP Africa (Peters et al., 2022) database submission, 5% of all database entries were randomly selected (49 HPPs, 67 SPPs, and 8 WPPs) and carefully checked again against the defined selection criteria as mentioned above to provide a most updated database version and get an idea about the potential error in the data (e.g. due to typos or invalid links to online references). This final check was conducted between November 16 and 17, 2022, and did not show any errors in the selected entries.

2.3.5. Data records

RePP Africa (Peters et al., 2022) is collated in a single spreadsheet-based file and consists of the Hydropower Plant Database (HPPD), Solar Power Plant database (SPPD), and Wind Power Plant Database (WPPD). Figure 2.3 maps all data records according to resource type (symbol colour, symbol shape) and capacity, i.e. size in megawatts (symbol size).

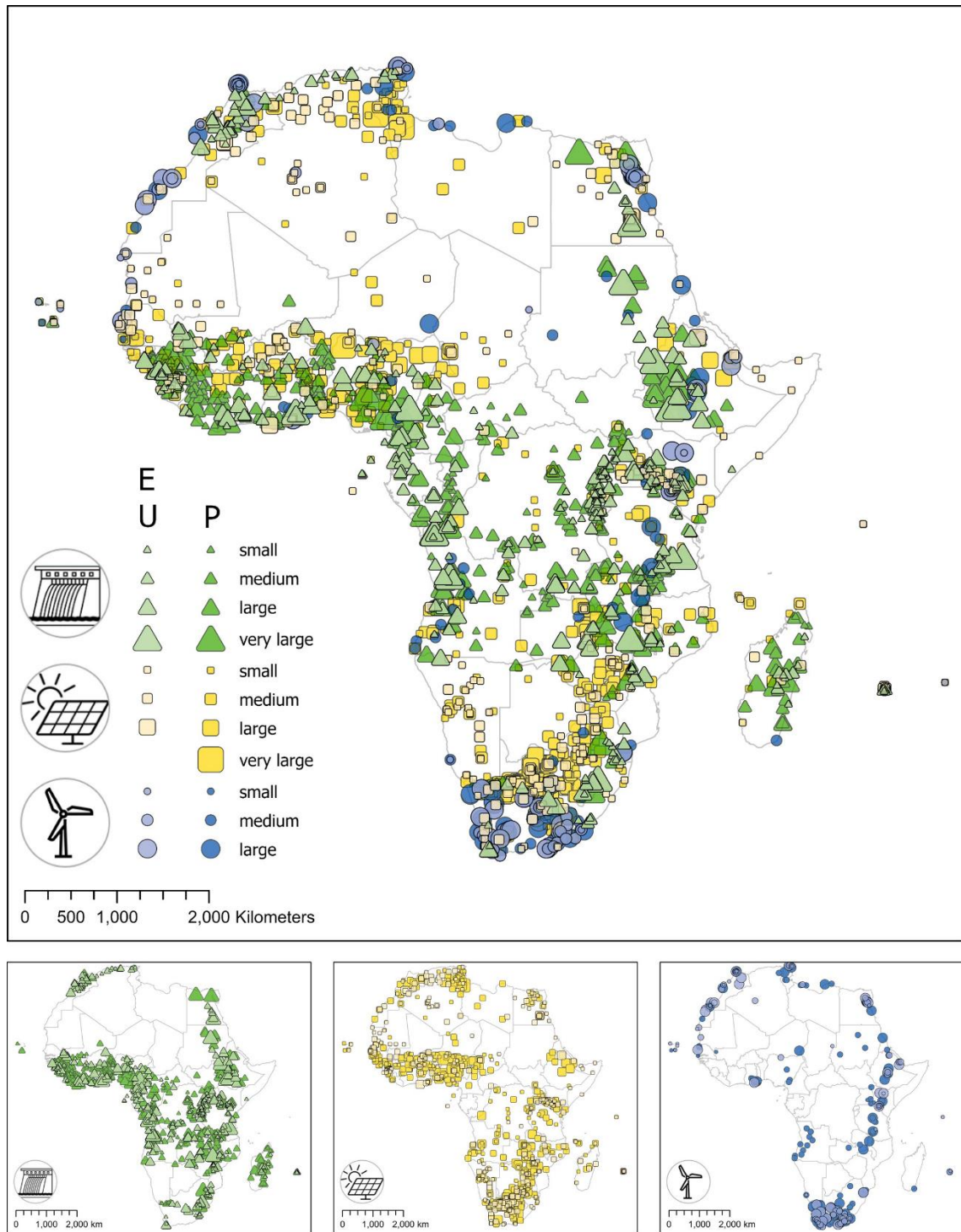


Figure 2.3: Map of all hydropower, solar power and wind power plants as compiled in the African Renewable Power Plant Database (RePP Africa). Symbol colour and shape indicate renewable energy type; colour intensity indicates status (E - existing and U - under construction, P - proposed); symbol size indicates capacity in megawatts [MW] with small 1-10 MW, medium >10-100 MW, large >100-1000 MW, and very large >1000 MW. No plants are located on open water; all facilities not located on the mainland are located on islands.

RePP Africa (Peters et al., 2022) provides data records for hydropower, solar power, and wind power plants in all African countries (Figure 2.3). The database is hosted on figshare (Peters et al., 2022). The repository includes one Excel file with eleven sheets containing one information sheet on the general structure of the file and the sheets included (Info), one overarching sheet with metadata (S1) and, for each of the three RE resources (hydro, solar-, wind power), three specific sheets that provide (1) the RE specific metadata (S2, S5, S8), (2) the respective dataset (S3, S6, S9), and (3) the data sources (S4, S7, S10). The overarching table with metadata gives an

overview on all attributes including descriptions of attributes and the number of plants for which an attribute is reported (Table 2.2). Figure 2.4 summarizes the distribution of RePP Africa data entries by installed capacity for existing plants and plants under construction, and proposed plants.

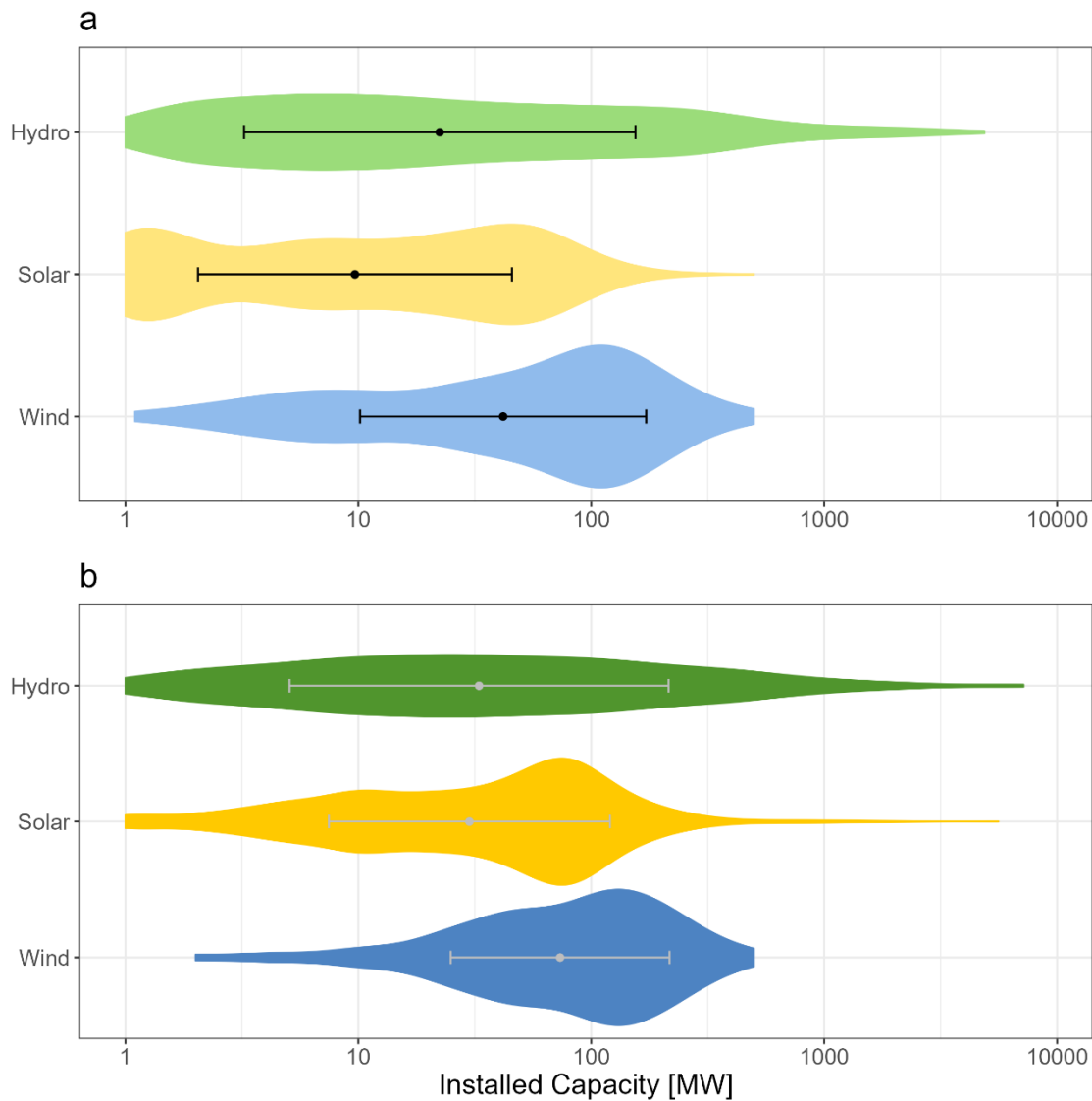


Figure 2.4: Distribution of RePP data entries by installed capacity in megawatts (MW) and status (stat_inf) for hydropower (green), solar power (pink) and wind power (blue). a. Existing plants and plants under construction. b. Proposed plants.

RePP Africa (Peters et al., 2022) data entries were further aggregated for each resource type in four capacity size categories to illustrate differences between share of capacity and number of existing and proposed power plants (Figure 2.5). We differentiated between small (1-10 MW), medium (>10-100 MW), large (>100-1000 MW), and very large (>1000 MW) sized power plants.

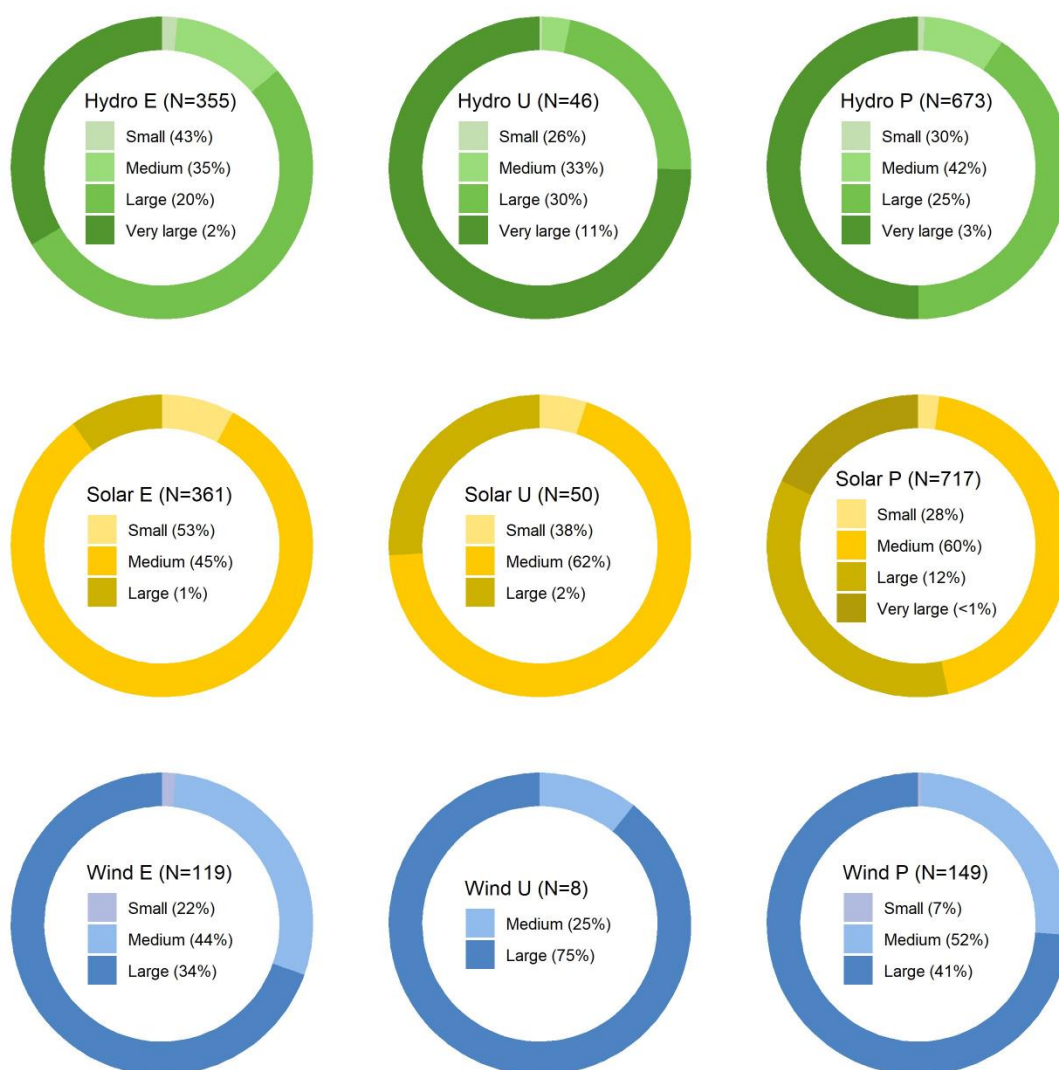


Figure 2.5: Share of total capacity in megawatts (donut plots) for existing plants, plants under construction (EU) and proposed plants (P) for hydropower (green), solar power (pink), and wind power (blue). Number of plants (N) and shares in percent (%) of N are annotated.

During the first step of data compilation (Figure 2.1), several plants of the searched databases were rejected and not compiled due to varying reasons: (1) The capacity was below 1 MW. (2) No location was indicated. (3) Power plant only occurred in one of the databases that were searched and no further information was found (including sources used for revision only). (4) No capacity was indicated. (5) No name was indicated (occurred only for plants compiled from open infrastructure map (OpenStreetMap, 2004)). Table 2.3 gives an overview on the number of plants that were disregarded after the first search of the databases.

Table 2.3: Total number (no.) of power plants of the searched databases for each resource type. The number of rejected power plants are indicated per country and database for each resource type (hydropower, solar power, wind power). The total number of rejected power plants is indicated. ‘-’ indicates that the database has no data entry for the respective country. Grey coloured columns indicate that RePP Africa does not list any power plants for the respective resource. The approximate number of included power plants was calculated as the difference between total number of power plants and total number of rejected power plants per database and renewable resource. The absolute number of plants in RePP Africa can differ from the calculated value due to differences (e. g. duplications or different counting of plant phases) between RePP Africa and searched databases. Database abbreviations: AKP – Africa knowledge platform (European Commission, 2020); AHA – African Hydropower Atlas (Sterl, Devillers, et al., 2021); FHReD – Future Hydropower Reservoirs and Dams Database (Zarfl et al., 2015); GRanD – Global Reservoir and Dam Database (main purpose: hydroelectricity) (Lehner, Liermann, et al., 2011); GPPD – Global Power Plant Database (Byers et al., 2018); ECOWREX – ECOWAS observatory for Renewable Energy and Energy Efficiency (ECREE, 2022); OIM – Open

Infrastructure Map (OpenStreetMap, 2004). In this figure, the Sahrawi Arab Democratic Republic (Western Sahara) is geographically aggregated with Morocco. No statements on the political situation are intended.

	Hydropower				Solar Power				Wind Power			
	AKP	AHA	FHReD	GRanD	AKP	GPPD	ECOWREX	OIM	AKP	GPPD	ECOWREX	OIM
Total No. of plants	868	634	200	66	318	120	51	263	138	41	14	35
<i>No. of rejected plants per country and database:</i>												
Algeria	8	2	0	1	15	8	-	3	1	-	-	1
Angola	27	2	1	0	-	-	-	1	-	-	-	-
Benin	1	2	0	0	-	-	4	0	-	-	-	-
Botswana					1	-	-	0	-	-	-	-
Burkina Faso	3	3	0	0	1	0	0	2	-	-	-	-
Burundi	25	1	0	0	-	0	-	-	-	-	-	-
Cameroon	4	7	0	2	3	-	-	8	-	-	-	-
Cape Verde	-	-	-	-	1	0	1	6	14	-	2	0
Central African Republic	5	4	0	-	-	-	-	-	-	-	-	-
Chad	-	-	-	-	-	-	-	-	0	-	-	-
Comoros	2	-	-	-	2	-	-	-	-	-	-	-
Congo, Rep.	2	1	0	0	-	-	-	-	-	-	-	-
Djibouti	-	-	-	-	0	-	-	1	0	-	-	0
DR Congo	32	3	-	0	-	-	-	-	-	-	-	-
Egypt	3	0	0	0	5	5	-	6	0	0	-	1
Equatorial Guinea	1	1	-	-	0	-	-	4	-	-	-	-
Eritrea	-	-	-	-	-	-	-	-	2	-	-	-
Eswatini	4	0	-	0	2	-	-	2	-	-	-	-
Ethiopia	5	4	3	0	2	-	-	-	0	-	-	0
Gabon	5	1	1	0	1	-	1	-	-	-	-	-
Gambia	-	-	-	-	-	-	1	-	2	-	2	-
Ghana	-	4	1	0	2	0	-	-	0	-	0	-
Guinea	3	3	3	1	-	-	-	-	-	-	-	-
Guinea-Bissau	0	1	-	-	1	-	0	-	-	-	-	-
Ivory Coast	2	3	2	0	-	-	0	-	-	-	-	-
Kenya	27	0	1	0	10	0	-	1	7	0	-	0
Lesotho	7	0	0	0	-	-	-	-	1	-	-	-
Liberia	2	3	0	0	0	-	-	-	-	-	-	-
Libya	-	-	-	-	1	-	-	-	0	-	-	-
Madagascar	11	0	-	1	1	1	-	2	1	-	-	-
Malawi	5	1	0	-	-	-	-	0	-	-	-	-
Mali	3	2	2	-	3	-	1	4	1	-	-	-
Mauritania	-	-	-	-	5	0	-	5	0	0	-	0
Mauritius	9	-	-	-	2	2	-	4	1	-	-	-
Morocco	15	3	0	0	1	0	-	4	2	1	-	0
Mozambique	5	0	0	0	0	-	-	-	-	-	-	-
Namibia	0	0	0	-	1	1	-	12	3	-	-	-
Niger	0	1	0	-	-	0	0	1	-	-	-	-
Nigeria	6	16	0	1	11	0	2	2	1	-	0	0
Rwanda	23	0	0	-	1	0	-	3	-	-	-	-
Sao Tomé e Príncipe	2	-	-	-	1	-	-	-	-	-	-	-
Senegal	0	0	-	-	3	1	-	2	0	-	0	0
Seychelles	-	-	-	-	-	-	-	-	1	-	-	-
Sierra Leone	5	20	1	0	0	-	-	2	-	-	-	-
Somalia	0	-	-	-	0	-	-	6	1	-	-	-
South Africa	22	0	2	0	37	3	-	56	2	0	-	0
South Sudan	0	1	1	-	-	-	-	3	-	-	-	-
Sudan	0	0	0	0	1	-	-	-	1	-	-	-

Tanzania	50	2	0	0	5	-	-	1	1	-	-	-
Togo	1	2	0	-	-	-	1	-	0	-	0	-
Tunisia	2	2	-	-	1	-	-	1	1	0	-	0
Uganda	9	0	2	0	2	0	-	0	-	-	-	-
Zambia	5	4	0	0	3	1	-	-	-	-	-	-
Zimbabwe	17	0	1	0	1	-	-	1	-	-	-	-
Total no. of rejected plants	358	99	21	6	126	22	11	143	43	1	4	2
Approx. no. of included plants	510	535	179	60	192	98	40	120	95	40	10	33
No of plants <1 MW	230	16	-	-	100	0	50	-	19	0	3	-

2.3.6. Technical validation

RePP Africa (Peters et al., 2022) compiles and revises existing data on hydropower, solar power and wind power for the entire African continent. The presented openly accessible and curated database is an attempt to meet the demand of the renewable energy modelling science community for free, accurate, and harmonized scientific data. All data and related information have been checked several times and are confirmed by at least two references each. Limitations in the accuracy of locations and other attributes might occur in particular for proposed power plants. We performed a technical validation for RePP Africa (Peters et al., 2022) by randomly selecting 5% of all data entries after the last full revision, which ended on 16 November 2022. The random selection resulted in a dataset of 128 data entries (49 hydro-, 67 solar, and 8 wind power plants). We checked all attributes and sources. All data entries were consistent with all or the majority of provided sources. We did not find inconsistent or missing data entries or non-functioning links. Each reported status (stat_inf) was in line with given sources and all indicated databases were correct. For 6%, minor discrepancies were found: duplicate source (1), one source refers to a different plant (5), majority of sources indicates a slightly different capacity (2). However, despite these discrepancies, the majority of sources still confirmed the given information and in case of differing capacity values the difference was acceptable (<5%).

Outstanding in comparison to other databases is the number of references cited for each data record: 36% of all hydro-, 77% of all solar, and 59% of all wind power plant records are validated by two or three sources, the rest is validated by up to 15 references (Table 2.4).

Table 2.4: Total number of data entries for all sources (summary databases & additional sources) and for the different data generation process steps (Figure 2.1): Compilation databases for 1. Compilation; Completion databases for 3. Completion, Revision 2; Further sources for 1. Compilation, Revision 1; Revision databases for 4. Final revision. Percentages refer to the total number of power plants per resource (Hydropower N=1074, Solar power N=1128, Wind power N=276).

		Hydropower		Solar power		Wind power	
		number of data entries	percent	number of data entries	percent	number of data entries	percent
Summary (databases & additional sources)	Total number of sources						
	2 or 3	383	36%	867	77%	164	59%
	4 or 5	360	34%	195	17%	67	24%
	6 or 7	165	15%	64	6%	41	15%
	8 or 9	101	9%	2	0.2%	3	1%
	10 or 11	40	4%			1	0%
	12 or 13	17	2%				
	14 or 15	8	1%				

Sources							
Compilation databases	GReD	115	11%				
	FHReD	167	16%				
	AHA (license CC BY)	550	51%				
	AKP (license CC BY 4.0)	461	43%	130	12%	104	38%
	GPPD (license CC BY 4.0)			103	9%	55	20%
	Ecowrex (license: CC BY-SA 4.0)			35	3%	10	4%
	OIM (license CC BY)			140	12%	50	18%
Completion databases	GHD (license CC0)	114	11%				
	GPPD (license CC BY 4.0)	117	11%				
	WPPD (license CC BY)	102	9%	1	0.1%	19	7%
	OIM (license CC BY)	119	11%				
	Ecowrex (license: CC BY-SA 4.0)	20	2%				
Further sources	source_1	1020	95%	1123	100%	276	100%
	source_2	688	64%	382	34%	157	57%
	source_3	343	32%	74	7%	39	14%
	source_4	147	14%	23	2%	8	3%
	source_5	50	5%	2	0.2%	3	1%
	source_6	23	2%				
	source_7	5	0.5%				
Revision databases	African Energy Live Data (for revision purposes only)	1019	95%	192	97%	157	57%
	International Journal of Hydropower and Dams (for revision purposes only)	140	13%				
	Wiki Solar (for revision purposes only)			197	17%		
	The Wind Power (for revision purposes only)					157	57%

In total, 1172 different references are provided for HPPs, 1134 for SPPs, and 432 for WPPs. One-third (33%) were collected from website and newspaper articles, 20% from development or environmental reports, company or government Power Point presentations, and fact-sheets, 16% from other databases, 14% from company websites, and 10% from encyclopaedia records. Less frequently, information was obtained from peer-reviewed articles (3%), United Nations, development bank and government websites (2%), social media (1%), and books or theses (1%).

Compiled total numbers and capacities of the different renewable power plant types have been cross-checked with available cumulated continent-related data (Table 2.3).

In comparison to other currently existing open-access databases, RePP Africa (Peters et al., 2022) lists more renewable power plants with cumulated capacity, better matching the respective values reported by IHA (IHA, 2022), IEA (IEA, 2021a), and IRENA (IRENA, 2022e) (Table 2.5). It highlights that we could enhance quality and completeness of RePP Africa (Peters et al., 2022) by not only searching existing databases but also including plants from additional sources (compilation, revision 1). The latter applies in particular to wind and solar power plants. In general, the cumulated capacities of existing power plants included in the RePP Africa (Peters et

al., 2022) differ by a minimum +3.07% (hydropower) and maximum -31.82% (solar power) from data reported by IHA, IEA, IRENA, and Hydropower & DAMS (Hydropower and DAMS, 2021) for 2020 and 2021 (Table 2.5, HPPD: +3.07% (IHA 2021), +3,98% (IRENA 2021), +12.81% (H&D 2020); SPPD: -27.31% (IEA 2021), -31.82% (IRENA 2021); WPPD: +12.86% (IEA 2021) +23.19 (IRENA 2021)). The largest discrepancy is between reported cumulated capacity of proposed HPPs with 132.05 GW according to the here presented database (HPPD) and 49 – 115 GW in the available literature (Hydropower & DAMS). The following reasons may be explanations for the discrepancies in the hydropower data: (1) The HPPD contains data records on HPPs not covered by IHA or Hydropower & DAMS; (2) The HPPD includes up-to-date data (2021) which is so far not included in IHA or Hydropower & DAMS datasets from 2020; (3) The implementation of the proposed HPP is subject to uncertainty. Different organizations use different definitions when including proposed or planned power plants in cumulative capacity calculations. Underestimation of the cumulated solar power capacity in RePP Africa (Peters et al., 2022) in comparison to IEA and IRENA might result from neglecting all solar power plants <1 MW. Another discrepancy comes up when taking a look at the details of the different solar power plant types. IEA further differentiates between solar power from photovoltaics (PV) and concentrated solar power (CSP). According to them, in 2021, 9.4 GW is installed as PV and 1.4 as CSP versus 7 GW as PV and 3 GW as CSP, respectively, in the SPPD of RePP Africa (Peters et al., 2023).

At present, wind and solar energy outpace hydropower and other renewable sectors with their growth rates. Although the IEA provides forecasts for cumulative capacities for 2021 and 2022, these analyses are based on data from 2020, making the presented database RePP Africa (Peters et al., 2022) the most up-to-date open-access database on renewable power plants in Africa.

Table 2.5: Comparison of data from all searched databases (compilation databases) to the here presented African Renewable Power Plant Database (RePP Africa) and to other established data sources for renewable energy assessment (validation databases, year of census in brackets). Number of plants and cumulated capacities for the whole African continent are given in gigawatts (GW) for the specific renewable resources (hydropower, solar power, wind power) and the specific construction status (existing (E), under construction (U), proposed (P)). AKP – Africa Knowledge Platform; AHA v2.0 – African Hydropower Atlas Version 2.0; GReD v1.3 – Global Reservoir and Dam Database Version 1.3; FHReD – Future Hydropower Reservoirs and Dams Database; GPPD v1.3.0 – Global Power Plant Database Version 1.3.0; ECOWREX – ECOWAS observatory for Renewable Energy and Energy Efficiency; OIM – Open Infrastructure Map; IHA – The International Hydropower Association; IEA – The International Energy Agency; IRENA – The International Renewable Energy Agency; GWED – The Global Wind Energy Council. Empty fields: No data.

Existing (E)		Compilation databases				RePP (2022)	Validation databases		
Hydropower	Database Name	<i>AKP (2019) *</i>	<i>AHA v2.0 (2021)</i>	<i>GReD v1.3 (2019)**</i>	<i>FHReD (2015)</i>	<i>HPPD (2022)</i>	<i>IHA (2021)</i>	<i>IRENA (2021)</i>	<i>H & D Atlas 2021 (2020)</i>
	Capacity	30.16 GW	31.91 GW			39.17 GW	38 GW	37.68 GW	34.72 GW
	Number	529	368	66		355	-	-	-
Solar power	Database Name	<i>AKP (2019) *</i>	<i>GPPD v1.3.0 (2021)</i>	<i>ECOWRE X (2016)</i>	<i>OIM (2022)</i>	<i>SPPD (2022)</i>	<i>IEA (2021/22)</i>	<i>IRENA (2021)</i>	
	Capacity	2.42 GW	4.89 GW	0.214 GW	3.83 GW	8.64 GW	11/16 GW	11.39 GW	
	Number	202	129	18	263	361	-	-	
Wind power	Database Name	<i>AKP (2019) *</i>	<i>GPPD v1.3.0 (2021)</i>	<i>ECOWRE X (2016)</i>	<i>OIM (2022)</i>	<i>WPPD (2022)</i>	<i>IEA (2021/22)</i>	<i>IRENA (2020)</i>	<i>GWEC (2020)</i>
	Capacity	3.29 GW	4.29 GW	0.077 GW	3.06 GW	9.03 GW	8/11 GW	7.33 GW	7 GW
	Number	74	41	8	35	119	-	-	-

*All plants with capacity >0 MW **Purpose Hydroelectricity

Under construction (U)		Compilation databases				RePP (2022)	Validation databases
Hydro-power	Database Name	AKP (2019)	AHA v2.0 (2021)	GRanD v1.3 (2019)	FHRe D (2015)	HPPD (2022)	H & D Atlas 2021 (2020)
	Capacity					13.89 GW	16.62 GW
	Number					21	-
Solar power	Database Name	AKP (2019)	GPPD v1.3.0 (2021)	ECOWRE X (2016)	OIM (2022)	SPPD (2022)	
	Capacity					0 GW	1.92 GW
	Number					0	50
Wind power	Database Name	AKP (2019)	GPPD v1.3.0 (2021)	ECOWRE X (2016)	OIM (2022)	WPPD (2022)	
	Capacity					0 GW	1.50 GW
	Number					0	8

Planned (P)		Compilation databases				RePP (2022)	Validation databases
Hydro-power	Database Name	AKP (2019) *	AHA v2.0 (2021)**	GRanD v1.3 (2019)	FHRe D (2015)	HPPD (2022)	H & D Atlas 2021 (2020)
	Capacity		100.00 GW		97.10 GW	132.05 GW	48.75 - 114.98 GW
	Number	339	266		179	673	-
Solar power	Database Name	AKP (2019) *	GPPD v1.3.0 (2021)	ECOWRE X (2016)	OIM (2022)	SPPD (2022)	
	Capacity			1.06 GW	0 GW	53.32 GW	
	Number	116		33	0	717	
Wind power	Database Name	AKP (2019) *	GPPD v1.3.0 (2021)	ECOWRE X (2016)	OIM (2022)	WPPD (2022)	
	Capacity			1.10 GW	0 GW	16.87 GW	
	Number	66		6	0	149	

*All plants with capacity of 0 MW **Status Candidate/Planned/Committed

2.3.7. Acknowledgements

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3.

Integrated impact assessment for proposed hydropower plants in Africa

3.1. Abstract

Mitigating climate change, while human population and economy are globally growing, requires a bold shift to renewable energy sources. This shift entails specific needs and challenges for Africa, as it is the least-electrified continent with the fastest growing population. Among renewables, hydropower has been the most economic and established technique for decades. Due to a lack of impact assessments at the basin scale in the planning process, the construction of hydropower plants (HPPs) may have (unexpected) ecological, socioeconomic, and political ramifications in the short and long term. In Africa, 673 proposed HPPs will alter current river courses via dam construction and reservoir inundation if implemented. In order to address the continent's need for renewable electricity expansion, but also the urgency to protect the world's last free-flowing rivers as important providers for societal and economic services, this study carries out an integrated impact assessment covering all proposed HPPs. Therefore, projected reservoir areas were estimated and overlapped with spatially explicit datasets on megafauna abundance, protected areas, land cover, and settlement. We further calculated river regulation and fragmentation indices and assess potential sediment entrapment and potential evaporation from projected reservoirs. By exemplarily integrating the selected impact indicators River Regulation, Fragmentation, Sediment Entrapment, Megafauna, Protected Area, Land Use Change, Resettlement, and Potential Evaporation, a total of 104 HPPs was assessed to end up in the highest impact category. The highest and lowest ranked HPPs based on impact indicators showed comparably low capacity sizes (45.77 and 47.34 megawatts (MW); mean capacity size of 152.46 MW), highlighting that capacity size alone is not adequate to assess an HPP's impact. A sensitivity analysis revealed that the ranking depends upon the number of HPPs included in the ranking analysis and the selection of indicators. This study provides scientific data that can serve as discussion support when balancing renewable electricity needs and HPP impact at basin and continent scale.

3.2. Introduction

During the past decades, the dominance of fossil fuels in meeting increasing energy demands has generated stress on Earth's natural systems. Hence, mitigating global warming is part of the Agenda 2030 within the Sustainable Development Goals 7 "Affordable Energy" and 13 "Climate Action". According to the International Energy Agency (IEA), the renewable sectors hydro-, solar, and wind power need to expand in order to meet long-term climate goals as well as increasing energy demands (IEA, 2023b). In sub-Saharan Africa, 80% of newly installed capacity is to come from renewable resources by 2030; one main driver is China's announcement to end support for coal-fired power plants once all plants under construction are fully completed (IEA, 2022a). However, African countries are not only challenged to phase out fossil fuels but also to

provide access to a continuously growing population. Hydropower has the highest share among renewables and accounts for 17% of overall electricity generation in Africa; this share is likely to increase to more than 23% by 2040 (IEA, 2020a). Its contribution to the electricity mix varies largely between African countries and exceeds 80% in the tropics (Democratic Republic of Congo, Ethiopia, Malawi, Mozambique, Uganda, and Zambia) (IEA, 2020a). Hydropower is the renewable resource with the longest history, both globally and in Africa: the first plants on the continent were built at the beginning of the 20th century (Peters et al., 2023). Despite hydropower counting as a renewable electricity resource, it is not per se climate-neutral; furthermore, it has multiple ecological, socioeconomic, and political ramifications (Figure 3.1).

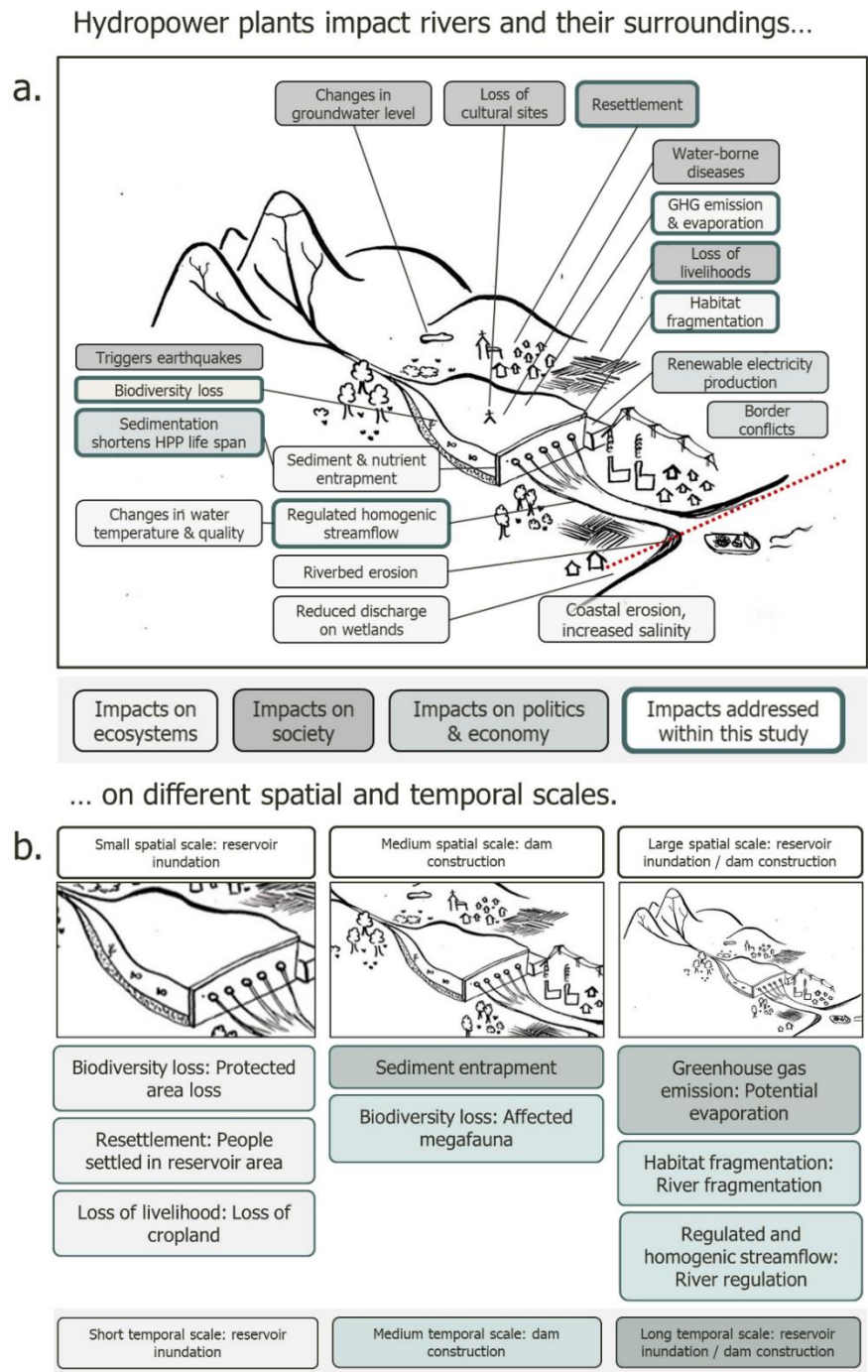


Figure 3.1: Ecological, social, political, and economic impacts induced by hydropower construction. a. Overview of which hydropower plant component induces which impact. Bold-framed impacts are addressed in the present study. GHG: greenhouse gas. b. Different spatial and temporal scales on which these impacts can be observed and measured. Spatial scale differs with column, temporal scale with colour (short: grey, medium: light blue; long: dark grey-blue).

Global debates on these negative effects have shaped the development of hydropower since the 1980s (Schulz & Adams, 2019; Thieme et al., 2021), but the need for renewable energy results in continuous dam construction and reservoir inundation (Zarfl et al., 2015). Both impact the functioning of freshwater ecosystems: water and sediment connectivity are reduced, fluvial geomorphology altered (Zarfl & Lucía, 2018), biogeochemical processes truncated (Deemer et al., 2016), and biodiversity threatened due to habitat fragmentation, over-exploitation, pollution, species invasion, and inhibited animal migration (Carrizo et al., 2017; Thieme et al., 2021; Zarfl et al., 2019). Dam-induced resettlement can provoke social conflicts leaving resettled people uninformed and not sufficiently compensated for livelihood losses (Adovor Tsikudo, 2023; Schulz & Skinner, 2022). Reservoir inundation may increase disease diffusion. At the River Zambezi, the spread of malaria has been monitored around Kariba HPP (Bianchi & Gianelli, 2018). Insufficient planning and wrong site selection have caused project cost and timeline exceedances in the past, which may in turn have in major economic and political impacts (Shaktawat & Vadhera, 2021). Wrong site selection can even trigger earthquakes (Tuan et al., 2017). Hydropower facilities alter existing landscapes, and the change in landscape aesthetics can result in public resistance, which influences national and international politics (Ioannidis & Koutsoyiannis, 2020). Finally, as about 60% of large rivers cross country borders, international conflicts may emerge (de Bruin et al., 2023; del Bene et al., 2018; Llamosas & Sovacool, 2021).

The ecological, socioeconomic, and political ramifications of hydropower plants (HPPs) are diverse and vary with time and space (Figure 3.1) (Moldoveanu et al., 2023; Williams, 2020). The interruption of the water course and the creation of a new water body cause cumulative effects within the river system as each barrier adds to the disturbance of the natural river course (Chen et al., 2015) and the creation of new water bodies can add to greenhouse gas emissions (Ai et al., 2022). Globally, only 37% of rivers longer than 1,000 kilometres remain free-flowing (Grill et al., 2019). At the same time, climate change increasingly affects existing and proposed hydroelectricity production both positively and negatively (van Vliet et al., 2016; Wan et al., 2021; Yalaw et al., 2020). Climate change impact can alter the proposed electricity outcome of HPPs, making hydroelectricity unprofitable in regions affected by increased drought (Falchetta et al., 2019). On top of that, 60% of the installed African hydropower capacity is over 20 years old and in need of maintenance and updates to avoid capacity reduction (IHA, 2023b).

While the construction of HPPs continues to be the subject of controversial scientific debates (Schulz & Adams, 2019), the International Hydropower Association has continued its efforts to develop guidance for project implementors on how to include environmental and socioeconomic effects in the planning process. As such, the Hydropower Sustainability Standard (HSS) is a further developed version of the already established Hydropower Sustainability Assessment Protocol (HSAP) and aims to enable an independent rating of hydropower projects (IHA, 2010, 2021b). In contrast to the HSAP of 2010, the 2021 HSS goes one step further by not only rating but also certifying a project's sustainability performance (IHA, 2010, 2021b). While it successfully integrates diverse ecological and socioeconomic indicators, it is still restricted to one project and cannot account for impacts on river connectivity at basin-scale caused by the implementation of several HPPs in the same river basin. In that regard, researchers continue to outline the importance of moving from individual plant-based project assessment to integrated renewable-energy planning at system scale in order to adequately integrate benefits as well as environmental and socioeconomic costs (Almeida, Schmitt, Castelletti, et al., 2022; Opperman et al., 2023). River basin organizations (RBOs) are institutional bodies established in many transboundary river basins to govern the different interests in water resources; still, even if such RBOs are established, power dynamics and diverging interests often lead to decisions in favour of HPP construction while (unintentionally) neglecting the negative (cumulative) impacts at a

system scale (Kouangpalath & Meijer, 2015). Therefore, further research on socioeconomic and environmental impacts of proposed HPPs at system scale is needed to provide data-driven evidence that underlines the necessity of system-scale hydropower planning.

In Africa, 673 new HPPs are proposed (≥ 1 megawatt (MW) in capacity): 243 of these are confirmed to operate with dam and reservoir and an additional 281 have an uncertain operational type (Peters et al., 2023). Thus, in the present study an integrated impact assessment approach introduced by Peters et al. on HPP construction is applied and further developed on a system scale to the major river basins on the African continent (Peters et al., 2021). The aims are to (1) assess and integrate impacts for potential dam locations across Africa; (2) based on the outcome, derive rankings of all proposed HPP on two spatial levels, for major basins each and for the entire continent; and (3) to test the effect of the selection of indicators on the total ranking. Results are designed to provide discussion support on location decision making for HPP construction in Africa by integrating a set of ecological, social, economic and political indicators.

3.3. Materials and methods

3.3.1. Underlying hydropower plant data

Data on existing and proposed HPPs in Africa was obtained from the Renewable Power Plant Database for Africa (RePP Africa) (Peters et al., 2023). This database includes HPPs with a capacity larger than one megawatt (MW) and differentiates between the operating types reservoir, run-of-river, and pumped storage. The present analysis focuses on proposed HPPs of type reservoir and type unknown (dataset 1 with a total of 507 data entries). We tested sensitivity by running all calculations excluding HPPs of type unknown (dataset 2 with total of 236 data entries). For complementing the HPP characteristics, projected reservoir areas for the proposed HPPs were estimated with the Python Toolbox DamTools for ArcGIS Pro (Bürger & Berlekamp, 2022). For the reservoir estimation, the flooding of the upstream digital elevation model (DEM) at a dam position is simulated up to the reservoir water level that is limited by the dam height. The simulation uses data on river segments from the RiverATLAS (Linke et al., 2019), major river basins from the HydroBASINS database (Lehner, 2014), simulated annual mean natural discharge data with 15'' resolution from the Water GAP 2.2 model (Döll et al., 2003), and the SRTMGL3 3'' DEM (JPL, 2013).

Since impact estimations are to be conducted on river system scale, some of the selected impacts indicators as outlined below require details on dam location and reservoir area also for already existing HPPs and existing other dam infrastructure (e.g. for irrigation or drinking water purposes). RePP Africa includes information on reservoir areas for HPPs only, which is why we additionally used data on other existing dams and reservoirs from the Global Reservoir and Dam Database (GRanD) (Grill et al., 2015).

3.3.2. Indicator selection

Indicators for potential HPP impacts were selected based an approach introduced by Peters et al. (Peters et al., 2023): First, the set of selected indicators represented measurable ecological, social, and economic impacts to underpin the idea of assessing dam locations in the frame of sustainability. Second, comprehensive and high-resolution spatial data were available via open access platforms to ensure reproducibility.

Therefore, exemplarily, the following eight indicators were selected for this study:

1. River Regulation – change in average river flow due to dam building; given by an index in % (ecological indicator)
2. River Fragmentation – degree of fragmentation of the river network into smaller river stretches due to dam building; given by an index in % (ecological indicator)
3. Sediment Entrapment – retention of sediments that are transported along the river in the reservoir due to the dam and the reduced water flow velocity in the reservoir (compared to a river); the indicator value is given in tons of sediment per year. We further indicate the resulting lifespan in years (ecological and economic indicator)
4. Megafauna – overlap of projected HPP reservoir with megafauna species dispersal as an indicator for the potential threat of dam construction and reservoir inundation on biodiversity; given in species number (ecological indicator)
5. Protected Area – overlap of the projected HPP reservoir with protected areas as an indicator for potential HPP impacts on areas of “high ecological value”; given in square kilometres (ecological indicator)
6. Land Use Change – overlap of the HPP reservoir with cropland to indicate a potential conflict with food production; given in square kilometres (social and economic indicator)
7. Resettlement – potential resettlement of people living in the area of the HPP reservoir to be flooded; given in number of people (social indicator)
8. Potential Evaporation – change in potential evaporation due to turning a flowing river into a (almost) standing water with a large water-atmosphere interface that favours evaporation; given in cubic kilometres per year (ecological indicator)

While the indicators River Regulation, River Fragmentation and Sediment Entrapment measure effects that can be traced back directly to the construction of an HPP (including a dam wall), the indicators Megafauna, Protected Area, Land Use Change, Resettlement and Potential Evaporation depict indirect effects that are caused by the flooding of an area (projected reservoir area).

Depending on the indicator, alterations accumulate and/or are delayed in time, causing synergistic effects on larger spatial and temporal scales. All calculations to quantify the selected impact indicators for each proposed HPP in both datasets were carried out and their results visualized with ArcGIS Pro 2.9.4 (ESRI, 2022).

3.3.3. Quantification of potential impacts of proposed hydropower plants according to selected indicators

For the indicators River Regulation and Fragmentation, the River Regulation Index (RRI) and the River Fragmentation Index (RFI) were calculated, respectively. RRI and RFI include the current degree of regulation and fragmentation caused by existing HPPs and other dam infrastructure. Both indices were calculated by applying a methodology developed by Grill et al. (Grill et al., 2014). The basis for these calculations is data from the HydroSHEDS database (Lehner et al., 2008) and the HydroBASINS dataset (Level 3, Level 4) (Lehner, 2014). Discharge data is obtained from the WaterGAP model (Döll et al., 2003). To calculate the number of years until the reservoir area would be fully filled with eroded sediment (Sediment Entrapment), a revised version of the Universal Soil Loss Equation (USLE) considering the entire basin with existing reservoirs of all purposes and projected hydropower reservoirs (Renard et al., 1994; Wischmeier & Smith, 1978) was used. The USLE, an empirical model designed to predict the annual average soil erosion from runoff using information on soil properties, rainfall, topography and land use, is used in combination with a connectivity index to estimate how much of the eroded soil would

arrive to the fluvial network and be trapped behind the dam wall (Grill et al., 2019; Zarfl & Lucía, 2018).

Impact calculations of all other single indicators were based on projected reservoir areas and considered only proposed HPPs. To estimate the number of megafauna freshwater species (≥ 30 kg, Megafauna) including reptiles, amphibians and mammals that might be affected by dam construction, we overlapped data on presence of freshwater megafauna with projected reservoir areas (Carrizo et al., 2017; Zarfl et al., 2019). For the indicator Protected Area, projected reservoir areas were intersected with protected areas using a polygon layer of the World Database on Protected Areas (UNEP-WCMC and IUCN, 2020). For the indicator Land Use Change, we used land cover maps from 2015 (Land Cover Maps v2.0.7) provided by the European Space Agency's Climate Change Initiative with a resolution of $300\text{m} \times 300\text{m}$ (ESA, 2017). We extracted cropland as an indicator for food production and overlaid it with the projected reservoir areas.

In order to estimate the number of people that must be resettled from potentially inundated reservoir areas (Resettlement), we overlapped projected reservoir areas with a population raster dataset obtained by the WorldPop Project with a resolution of 3 arc seconds (WorldPop, 2022). For the indicator Potential Evaporation, the potential evaporation values [mm/year] were obtained by the FAO GeoNetwork database with a resolution of 10 arc minutes (Jippe Hoogeveen (FAO), 2004). Evaporation values of the raster feature were bound to reservoir points, and potential evaporation [m^3/year] was calculated by multiplying each reservoir area [m^2] with its respective evaporation value [mm/year].

Correlation between independent indicators and projected reservoir areas was tested with R using the rank correlation coefficient Spearman's rho.

3.3.4. Ranking of proposed hydropower plants considering all indicators and indicator compositions

The impacts of proposed HPPs in Africa were assessed for dataset 1 (HPPs of type reservoir and type unknown), and dataset 2 (HPPs of type reservoir) following the methodological approach summarized in Figure 3.2. First, indicators of ecological, social, and economic relevance were selected and analysed separately. The proposed HPPs were ranked for one indicator at a time according to their calculated impact. Second, following the ranking of each single indicator and the resulting quartile values, every HPP was given the value of the respective quarter they belonged to: from one representing low impact; two, moderate impact; three, heavy impact; to four, severe impact. Third, quarter values were summed for each proposed HPP. Every proposed HPP was ranked according to its overall impact (sum of quarters) (1) for the entire continent and (2) within major basins (Congo, Niger, Nile, Volta, Zambezi) and. Because impacts of large environmental projects occur in various sectors on different spatial scales and across time, it can be crucial to test if a change of a certain input parameter or an input parameter composition changes the outcome (Saltelli et al., 2004). In order to test the sensitivity of the model to the composition of the indicators, analyses were re-run in a "leave-one-out" fashion (one indicator was excluded at a time, local sensitivity approach (Middendorf, 2018; Saltelli et al., 2004)), and then again through excluding several indicators by creating different scenarios. After the exclusion of one or more indicators at a time, rankings for both spatial scales, (1) continental and (2) major basins, were created. Results of the impact assessment considering single indicators, all indicators and indicator compositions were compared among each other (Figure 3.2) and visualized with ArcGIS Pro (ESRI, 2022).

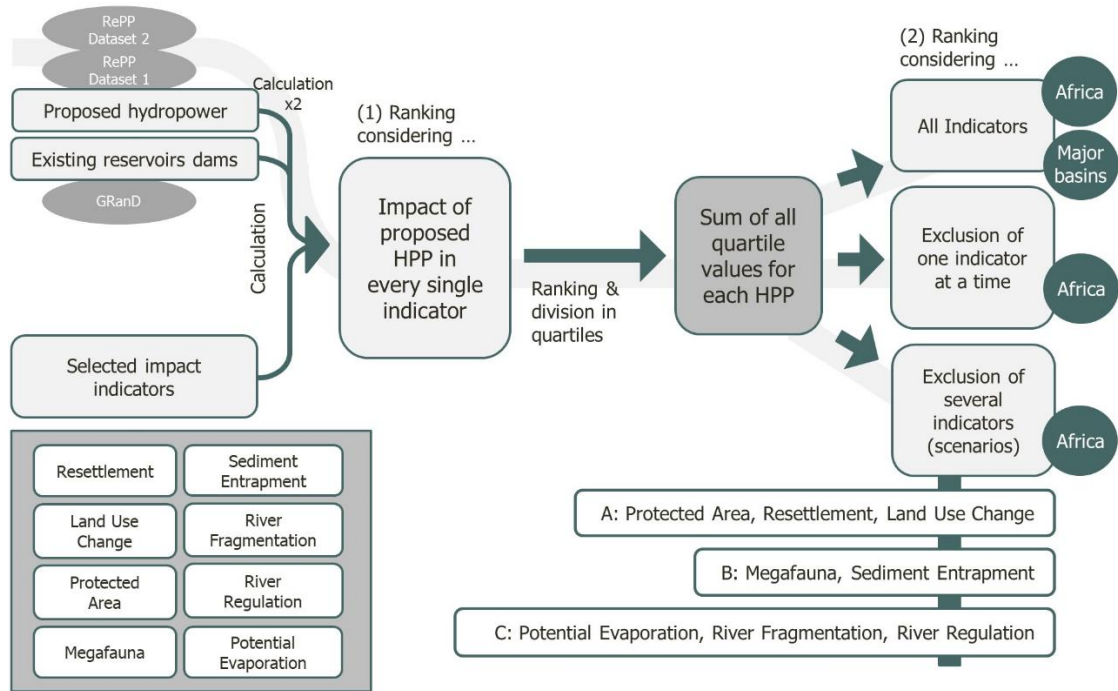


Figure 3.2: Methodological approach: Impact assessment of proposed hydropower plants and ranking for every single indicator (1) and for different indicator compositions (2). All calculations were run twice: Dataset 1 includes all proposed hydropower plants (HPPs) of type reservoir, and dataset 2 all proposed hydropower plants of type reservoir and type unknown. Data was obtained from the Renewable Power Plant Database (RePP) Africa (Peters et al., 2023). Additionally, we used data on existing dam and reservoir infrastructure for hydropower and other purposes from the Global Dam and Reservoir Database (GRanD) (Lehner, Liermann, et al., 2011).

We created three different indicator-composition scenarios to better understand if and how the selection of indicators might change the ranking of proposed HPPs. Scenario A includes the indicators Protected Area, Resettlement, and Land Use Change, which assess the direct effect of reservoir inundation on a small spatial scale. Scenario B includes the indicators Megafauna and Sediment Entrapment, which emphasize how dam construction impacts megafauna dispersal and sediment transport and thus emphasizes effects at a medium spatial scale. Scenario C includes the indicators River Regulation and Fragmentation, both consequences of dam construction, as well as Potential Evaporation, which is a consequence of reservoir creation. All three indicators assess impacts that cause cumulative system alterations at a large scale. The created scenarios are examples that intend to show that rankings at basin or continental level generally depend on the selection of indicators.

3.4. Results

3.4.1. Impact assessment and ranking for selected indicators

Dataset 1 includes 507 HPPs of type reservoir and type unknown for which reservoir delineation was successful. 17 plants were excluded due to failed reservoir delineation. Most of the latter are projects with capacity updates or other HPPs that operate at existing reservoirs and will not cause an inundation of new ones. For dataset 2, only the 236 HPPs of type reservoir were included and a further seven excluded due to the aforementioned reasons (Table A.1).

The degree of regulation (River Regulation Index: RRI) would range between 0.004% and 1265% for dataset 1 (0.8% and 1226% for dataset 2; results for dataset 2 from here on in brackets), if all proposed HPPs were constructed. The degree of fragmentation (River Fragmentation Index: RFI) of sub-catchments ranged from 0.04% to 92% (0.04% to 81%). RRI and RFI values peaked in the

upper Niger, Nile, and Zambezi basins (Figures A.1, A.2; Tables A.2, A.4). Without management activities such as sediment flushing, a total of 2,191 million tons of sediment would be trapped behind dam walls annually (1,490 million tons per year, Figure A.3), which would reduce the lifetime of the HPPs (time until the reservoir would be completely filled with sediments) to up to one year. 17 HPPs with a calculated lifespan of <1 year for a proposed capacity of >10 MW were excluded. Full sedimentation of a reservoir of this size within less than one year is unlikely and probably consequence of imprecise coordinates of the future dam location.

The area flooded by all HPPs combined (i.e., total reservoir area) was estimated to be 46,389 km² (34,721 km²); with a total reservoir volume of 969 km³ (826 km³). For both datasets, reservoir inundation and dam construction would impact between one and 11 freshwater megafauna species (Figure A.4) and between one and eight protected areas (Figure A.5). In total, 168 projected reservoirs (84) would affect in total 297 protected areas (167) and potentially inundate a total area of 24,092 km² (22,310 km²). Projected reservoirs would flood 13,039 km² of cropland (8,186 km², Figure A.6) and 4.9 million people currently living in potentially flooded areas would need to be resettled (2.7 million people, Figure A.7). The projected inundated reservoir area would potentially cause an additional evaporation of 6 km³ per year; an increase of 12% over the present evaporation from existing reservoirs and lakes (Figure A.6).

Calculated impacts of proposed HPPs and the rankings of proposed HPPs per indicator and in sum are listed for both datasets in A. Supporting information – Chapter 3 (Tables A.2, A.4; Figures A.1 – A.8).

3.4.2. Impact assessment and ranking considering all indicators for the entire continent and for major basins

If the impact calculation was successful for all indicators, the respective HPP was included in the integrated impact assessments and rankings. Some 448 proposed HPPs of type reservoir and unknown type were included (dataset 1; 211 for dataset 2).

Based on the eight indicators selected, the aggregated impact value could potentially range from eight (i.e., all indicators reflect lowest impact values) to 32 (i.e., all indicators reflect highest impact values). For Africa as a whole, the calculated total value (all indicators combined) varied between 9 and 29 (dataset 1, mean: 19.3 ± 4.1 ; dataset 2: 9 and 27, mean: 18.9 ± 3.9 ; Figures 3.3, A.9).

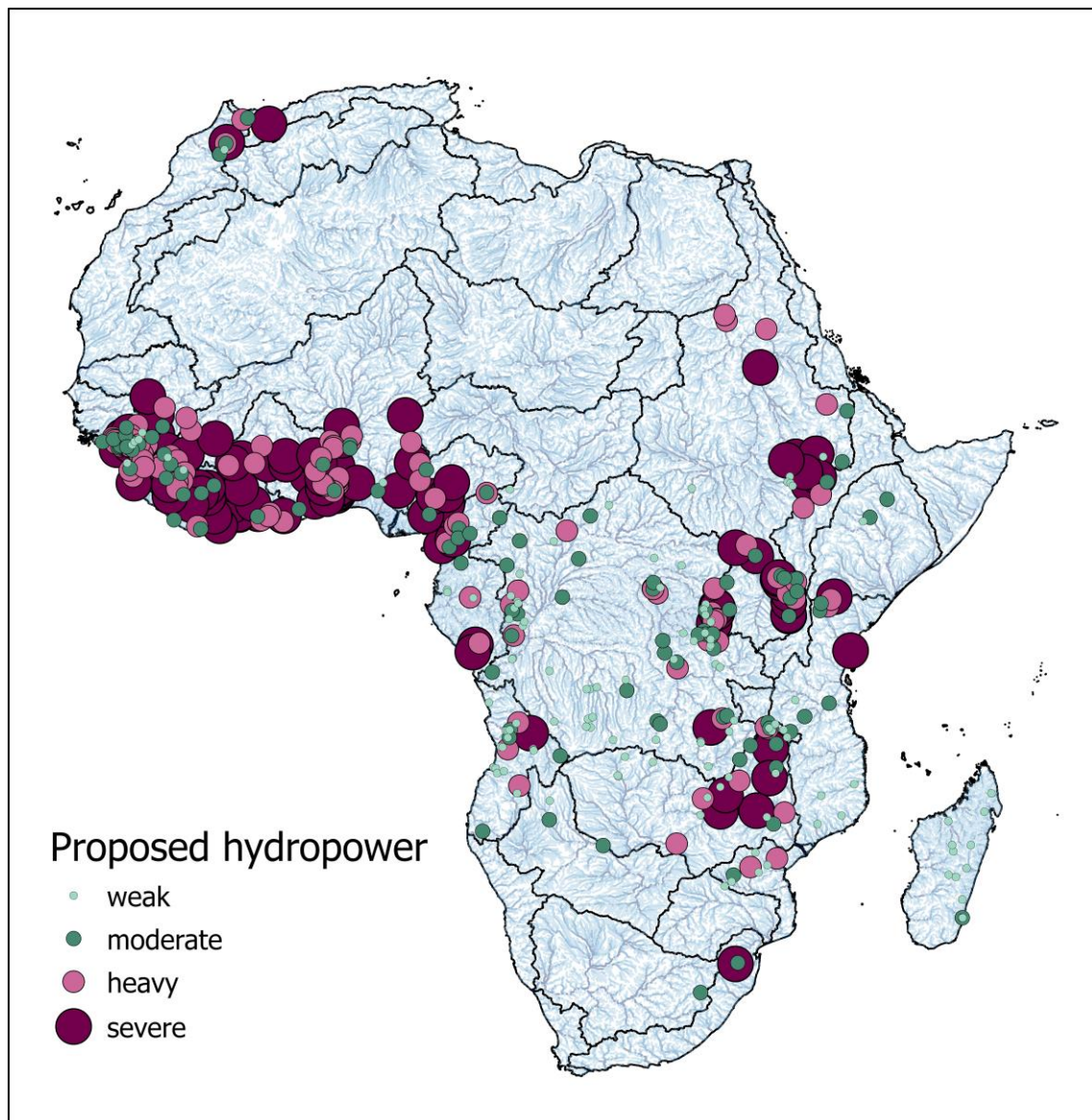


Figure 3.3: Results of the continental impact assessment including all indicators for hydropower plants of type reservoir and type unknown (dataset 1): Circles indicate proposed hydropower plants and size increases with indicated quarter value from weak ($< \text{Quartile}(Q) 1$), moderate ($Q1-Q2$), heavy ($Q2-Q3$) to severe ($> Q4$). Boundaries represent major river basins (HydroBASIN Level 3).

104 (41) HPPs proposed on the African continent were assessed to cause severe and 124 (61) low impact (Figure 3.4). In the continental comparison, 23 (21) countries have proposed HPPs that were assessed to cause severe impact.

The mean capacity of the top-ranked HPPs in dataset 1 is 45.77 MW and for the ten lowest-ranked, 47.34 MW. Comparing these figures with the mean capacity of the complete dataset of 152.46 MW, these numbers suggest that capacity size alone is not an adequate factor to assess for an HPP's impact. Dataset 2 excludes HPPs of type unknown, which affects in particular HPPs of small and medium size and results in a medium capacity size of 214.16 MW. The difference of this value from ten top- and ten lowest-ranked HPPs was not as pronounced as for dataset 1, but were remarkable with a mean capacity size of 132.28 MW for the ten top ranked and a medium capacity size of 179.60 for the ten lowest-ranked HPPs.

Overall rankings of each proposed HPP (i.e., sum of the assigned quarter value per indicator) are listed in A. Supporting information – Chapter 3 (Tables A.3, A.5). Spearman's correlation

coefficients did not yield strong or very strong relationships among individual indicators ($r_s > 0.6$, $r_s < -0.6$), with few exceptions (Table A.6).

We performed an integrated impact assessment for the major African basins, because for international river basins in particular, conflict between countries may emerge when it comes to sharing water resources for water supply, hydroelectricity generation, or irrigation needs. Our assessment, which includes the Congo, Niger, Nile, Volta, and Zambezi basins, highlights the proposed HPPs that were assessed to cause severe impact at basin scale (Figure 3.4). In comparison to the continental assessment where 87% (83%) of HPPs proposed in the Congo basin were assessed to cause low to medium impact, an assessment at basin scale reveals that 36 of 84 HPPs (5 of 12) may cause high and severe impact relative to all proposed HPPs in that basin. Results for the impact assessment at basin-scale for dataset 2 are visualized in A. Supporting information – Chapter 3 (Figure A.10).

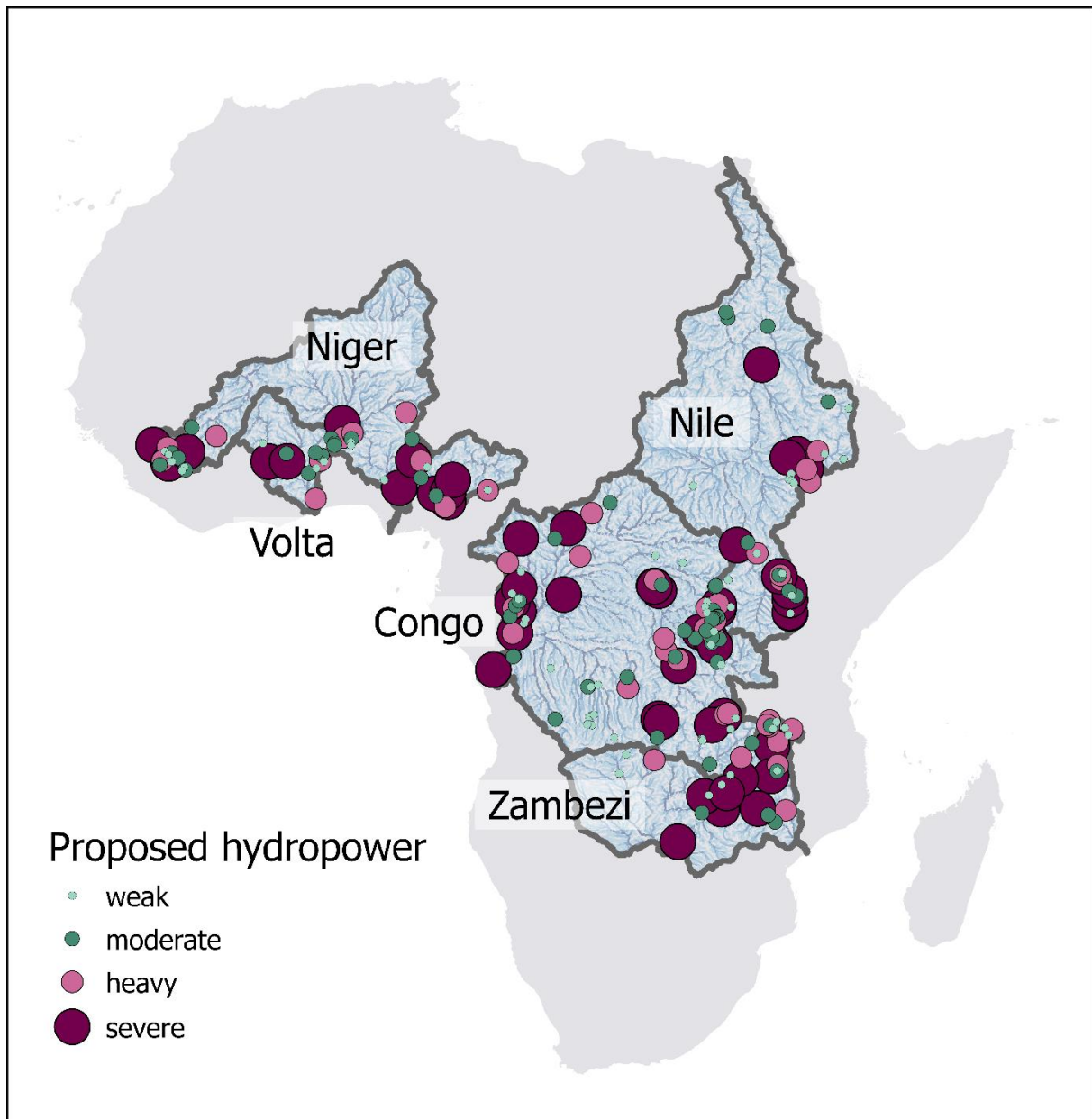


Figure 3.4: Results of the impact assessment at basin-scale including all indicators for hydropower plants of type reservoir and type unknown (dataset 1). Basin-scale assessments were conducted for the Congo, Niger, Nile, Volta, and Zambezi river basins (HydroBASIN Level 3). Circles indicate proposed hydropower plants and circle size increases from weak ($< \text{Quartile}(Q) 1$), moderate ($Q1-Q2$), heavy ($Q2-Q3$) to severe ($> Q4$) cumulative impact.

3.4.3. Impact assessment and ranking considering different indicator compositions

Not all proposed top-ranked HPPs shared the same outcome for the single indicator impact assessment. Leaving one indicator out at a time assigned 54 (25) proposed HPPs to the same quarter, while 50 (17) proposed HPPs were assessed to be in the third quarter in up to 50% of the eight leaving-one-indicator-out scenarios (Tables A.3, A.5).

Three scenarios were created to assess the impact of different indicator compositions on the total ranking. Scenario A includes the indicators Protected Area, Resettlement, and Land Use Change, which serve as a proxy to assess direct effects caused by reservoir inundation (Figure 3.1). Applying this scenario, HPPs proposed in the Niger and Volta as well as in the Zambezi catchment area were assessed to cause severe impact (i.e., located in top quarter, Figure 3.4). Scenario B covers the indicators Megafauna and Sediment Entrapment, which emphasize effects caused by dam construction at a medium spatial scale, i. e. changes in megafauna dispersal and sediment transport. High-ranked HPPs are located in the Niger, Volta, and Congo catchments. Scenario C includes the indicators River Regulation, River Fragmentation, and Potential Evaporation. These indicators are proxies for effects measurable at a large spatial scale: River Regulation and Fragmentation indicate the effects of dam construction on river networks at a basin scale while Potential Evaporation from reservoirs changes the greenhouse-gas emission budget. High-ranked HPPs of Scenario C are located in West Africa in and the Nile basin. The Manya HPP proposed with 136 MW in Nigeria, the Beterou HPP proposed with 30 MW in Benin, and the Aderci Tiassalé HPP proposed with 15 MW in Ivory Coast were assessed to cause severe impact within all three indicator composition scenarios. For dataset 2, which includes HPPs of type reservoir only, the Sabaloka HPP proposed with 205 MW in Sudan was assessed as potentially having severe-impacts under all scenarios. Results for dataset 2 can be found in the A. Supporting information – Chapter 3 (Figure A.11). The comparison confirms that not only the selection of indicators, but also the number of included HPPs in the analysis affects the ranking.

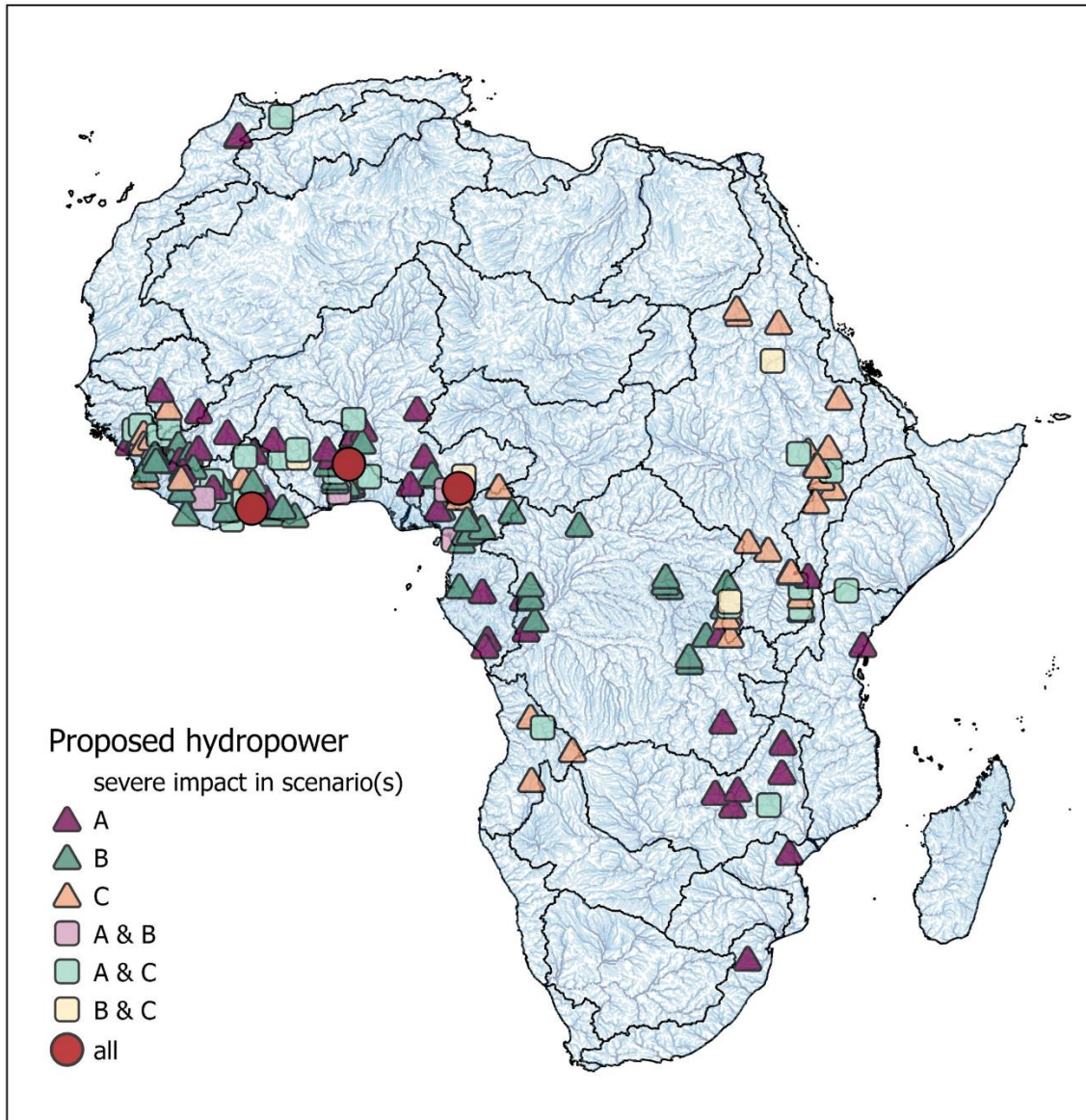


Figure 3.5: Results of the impact assessment for dataset 1 by applying three different scenarios of indicator consideration (Scenario A: Protected Area, Resettlement, Land Use Change; Scenario B: Megafauna, Sediment Entrapment; Scenario C: River Regulation, River Fragmentation, Potential Evaporation): Symbols indicate proposed hydropower plants (HPPs). Proposed HPPs located in the top quarter (>Quartile 4; severe impact) of one (triangle), two (square), or all scenario(s) (circle) are of different shape and colour.

3.5. Discussion

Although hydropower has historically been favoured as a low-cost source of base-load power for renewable electricity generation (Gernaat et al., 2017), its development remains subject to major discussions (Schulz & Adams, 2019). Standardized impact assessments to assess ecological, social, and economic impacts of proposed HPPs are normally – if legally mandatory at all – restricted to the impact of individual HPPs. Furthermore, the rapid expansion of hydropower is making it increasingly difficult to implement the necessary Environmental Impact Assessments (EIAs) in time (Erlewein, 2013). Another shortcoming outlined by researches is the spatial and temporal extent covered by EIAs: the diverse and (potentially) synergistic impacts of several existing and proposed HPPs operating within one connected river system cannot be captured by an individual plant-based assessment (Almeida, Schmitt, Castelletti, et al., 2022; Opperman et al., 2023; Thieme et al., 2021). To that point, the present study provides in-depth information on what

impacts the simultaneous implementation of all proposed HPPs may produce at a basin and continental scale.

Current policies favour hydropower development and expansion (Peters et al., 2023; Zarfl et al., 2015). It is further claimed that Africa's unused profitable hydropower potential is 6,000 TWh per year, four times larger than its developed hydropower (Xu et al., 2023). The International Renewable Energy Agency (IRENA) highlights that meeting the climate goals set in the Paris Agreement calls for a complete decarbonization, which is according to IRENA only feasible if the globally installed hydropower capacity more than doubles by 2050 (IRENA, 2023). In contrast, a recent economic study by Carlino et al. on the economic feasibility of hydropower under climate change suggests that hardly any new hydropower will be economically feasible in Africa after 2030 (Carlino et al., 2023). Still, 673 HPPs are currently proposed on the continent (Peters et al., 2023). In particular, tropical countries depend on hydropower, as it provides up to 80% of the total electricity in the Democratic Republic of Congo, Ethiopia, Malawi, Mozambique, Uganda, and Zambia. Addressing the need for renewable electricity generation, our study reveals that high capacity does not necessarily result in high impact when HPPs are ranked at a continental or basin scale. The average cumulative impact of the 30 HPPs proposed with a capacity between 500 and 7180 MW was assessed as high (20.6 ± 3.9), while the impact of the 116 HPPs proposed with a capacity from one to 10 MW was assessed as medium (18.6 ± 3.7). To that point, all 30 proposed HPPs with capacity sizes above 500 MW would provide 60 times the installed capacity of all 116 HPPs with a proposed capacity size below 10 MW. As such, comparable impacts can result from both small and large capacity sizes. Both cause comparable physical alterations to the river, underlining the importance to consider the site-specific context and to link capacity generation to HPP impact (Kelly et al., 2017).

The results of the impact assessment considering different indicator compositions highlight that an overall ranking is dependent upon the selection and composition of indicators. The created scenarios support a trend that real-life scenarios are showing. Individual plant-based impact assessments such as EIAs fall short when it comes to assess impacts at larger scales of multiple HPPs to be implemented simultaneously. An evaluation of results at basin-scale shows that proposed severe-impact HPPs within the Congo basin were ranked lower in the continental comparison. One reason is the selection of indicators, which is also shown by the results of Scenario B: this scenario includes the indicators Sediment Entrapment and Megafauna. According to the continental ranking, only one HPP proposed in the Congo river basin was assessed to cause severe impact ($N=448$). In contrast, the ranking of scenario B assigned a total of 12 proposed HPPs to the highest impact category ($N=448$). Considering only HPPs within the Congo basin, a total of 20 HPPs were assessed to cause severe impact ($N=84$). The Congo river basin has large regions that are sparsely populated leading to less impact in resettlement and land use change (cropland) compared to the Nile, Niger, Volta and Zambezi catchments. At the same time, the Congo counts globally as one of the last very large free-flowing rivers (Grill et al., 2019) and harbours a great biodiversity (Archer et al., 2018). Furthermore, advocates often overestimate benefits and underestimate the far-reaching effects on biodiversity and critically important fish species (Winemiller et al., 2016). As such, implementation of the 84 proposed HPPs along the Congo and its tributaries must be critically evaluated within the water-energy-food-biodiversity nexus. If alternatives are exploited and electricity shared across borders, the Congo river system could be protected as largely free-flowing.

Even though it is important to consider that our study is restricted to certain indicators and datasets, our results outline the challenges that emerge when moving from individual plant-based EIAs to large-scale assessments. First, the inclusion or exclusion of impact indicators might

change a ranking. If impact assessments are not standardized, stakeholders with different interests might consciously or unconsciously prioritize and include specific indicators in their assessments, which is likely to have a pronounced effect on the overall impact assessment and ranking of proposed HPPs. Second, the ranking is dependent on the number of proposed HPPs included in the ranking analysis. Additionally, it is unlikely that all proposed plants will be implemented as described in their proposals. However, the inclusion of several proposed HPPs reveals, for example, the synergistic effects on connectivity, river regulation, and sediment entrapment; factors that remain overlooked in regular EIAs. To account for the uncertainty in the database, we advise to test sensitivity by running all calculations and assessments for different datasets, as done in this study via excluding HPPs with uncertain operating type (dataset 2).

3.6. Conclusions

In Africa, the number of HPPs operating with dams and reservoirs will increase from 247 (2022, including 29 plants under construction) to 771 if all proposed HPP are constructed (from 203 to 446 for dataset 2, excluding HPPs where the operation type is uncertain). The total capacity would even increase from 29 GW to 159 GW. Hence, the proposed dams and inundated reservoirs will alter the major river systems they extract energy from. At the state level, research has claimed that electricity planning needs to move from individual plant-based hydropower impact assessment to integrative basin-scale planning in order to assess basin-wide future alterations. RBOs are institutional bodies for overseeing the water-resource management and development in particular for transnational rivers, but they are not comprehensively established and fall short on standardized methods to assess how the construction of multiple proposed HPPs would alter the river network.

To avoid stakeholders with different interests selecting a set of indicators that may lead to their most favoured outcomes (i.e., self-fulfilling results), standardized and comparable impact-assessment procedures are of utmost importance. In conclusion, the following recommendations to support discussions can be made:

- Impact assessments, applying a comparable set of criteria, should be carried out for both small and large HPPs at a basin scale. Indicators should include measures and scenarios on how the implementation of several proposed HPPs would change the large-scale river connectivity and greenhouse-gas emissions from reservoirs;
- Impact assessments should include a sensitivity analysis because the ranking of proposed HPPs might change depending on the impact indicators and proposed HPPs included in the ranking analysis. Policy discussions should reflect on the role of power dynamics and how indicator selection impacts the ranking;
- When deciding for small or large HPPs, future capacity potential should be considered and linked to the projected impact.
- Continental assessments allow for comparisons between basins and can support discussions on potential alternatives to hydropower exploitation: river conservation and protection can be supported if renewable electricity is shared across locations and countries.

Hydropower continues to be the renewable resource of choice in many African countries. Hydropower capacity additions of 48% surpassed wind and solar additions in 2019 and 2020 by 24% (IRENA, 2022d). However, wind and solar power are increasingly competitive, as the resource potential is large while the costs are continuously decreasing.

To favour simultaneously resilient renewable energy development and the protection of rivers in Africa, future research (and management actions) should not only focus on sustainable planning

of hydropower as a well-established technology, but also consider alternative renewable energy resources to broaden the regional energy portfolio. This includes a better understanding of how other renewable resources, such as wind and solar power, alter the natural systems they extract energy from. A sustainable renewable energy development needs to integrate infrastructure effects and renewable energy benefits, while balancing it with food production, conservation, and human living conditions. Therefore, future development requires a shift from individual plant-based EIAs to large scale assessments that integrate basin-scale energy and conservation planning and are based on international cooperation.

4.

Sustainable pathways towards universal renewable electricity access in Africa

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4.1. Abstract

Reaching Sustainable Development Goal (SDG) 7 means to “ensure access to affordable, reliable, sustainable and modern energy for all”, but currently half of the African population lacks electricity access. Expectations that Africa could avoid a phase of fossil fuel dependency and move directly to electricity systems entirely based on renewable energy (RE) shape the global RE debate. A multidisciplinary approach is needed to address the complexities of developing RE across nations with differing national starting points, global interests in their resources, and local and regional environmental and socioeconomic conditions. In this perspective, we present trends in RE development and access, and discuss Africa's capacity to lead the continent's transition towards RE-based electricity systems that meet the increasing electricity demand. Based on a quantitative analysis of georeferenced data for all 54 African countries on existing and proposed renewable power plants, 76% of Africa's electricity needs projected for 2040 could be met by RE, with a remaining technical potential of >99% each for wind and solar PV, and 51% for hydropower. Efficiently combining the advantages of hydropower with exploitation of wind and solar potential will be a more sustainable alternative to hydropower plant construction alone. Integrated science needs to build on georeferenced and open-accessible data to comprehensively investigate the optimal outcome of (hybrid) renewable electricity systems, track plant failures, and monitor socioeconomic, political and ecological impacts.

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4.2. Key points

- Human population and economic growth in Africa lead to increasing electricity demand, while Nationally Determined Contributions (NDC) ask for “climate-neutral” renewable electricity production. African countries are challenged to integrate both issues in national policies and strategies.
- About half of the human population in Africa still lacks electricity access: in rural areas, where no grid connection is available, renewable off-grid and mini-grid solutions are more feasible and economic than grid expansion; in urban areas, where capacity does not match demand, capacity updates need to ensure that supply meets demand and makes energy affordable (electricity access lack in 2020: 46% on average; 24% in urban areas, 65% in rural areas; IEA (IEA, 2021b)).
- Hydropower has been the main renewable energy resource for electricity developed to date, but declining costs for solar photovoltaic (90% decline since 2009, IRENA (2022)) and wind turbines (55-60% decline since 2010, IRENA (2022)) have led to steeper growth rates compared to hydropower and, therefore, both technologies have potential to lead to sustainable pathways for renewable electricity.
- If all existing wind, solar and hydropower plants operate on full capacity and all proposed plants are implemented, 76% of Africa's electricity needs projected for 2040 could be met by renewable energy without additional RE project development.
- If all proposed plants are implemented, the most technically feasible potential remains for wind and solar PV power (each >99%; hydropower: 51% (Hydropower and DAMS, 2021; Sterl et al., 2022)). Shifting from hydropower to wind and solar power would protect freshwater ecosystems and pave the path towards a sustainable renewable energy development. Because resource potential differs among countries, transnational electricity sharing helps to exploit resource potential and fully use nationally produced peak capacity.
- Renewable power plant infrastructure is not without impact; impacts need to be assessed and harmful infrastructure avoided. Assessments should include alternatives for action and value assignment and policymakers need to be aware that interests are often not considered equally when deciding for or against renewable power plant construction. For a sustainable transition, power plants need to operate efficiently and be smartly combined via hybrid systems.

4.3. Introduction

About 626 million Africans lack access to electricity (46% of current human population in 2020) (IEA, 2021b; UN, 2022), with Africa's population expected to nearly double by 2050 (2.5 billion people) (IEA, 2022a). After a sustained decline since 2014, the share of people without access recently recorded an increase (+4%, 2019-2021) (IEA, 2022a). Financial difficulties of power providers cause blackouts, electricity rationing and financing backlogs for an urgently needed renewable capacity expansion (IEA, 2022a). African countries account for less than 3% of the world's energy-related carbon dioxide emissions, but are already disproportionately experiencing the negative effects of climate stress (AfDB, 2022; IEA, 2022a; IPCC, 2022). While the continent is facing these challenges, climate commitments from 27th Conference of the Parties of the United Nations Framework Convention on Climate Change (COP) outline Africa's commitment to low carbon development pathways (UN Climate, 2022). To “ensure access to affordable, reliable, sustainable and modern energy for all” (Sustainable Development Goal (SDG) 7 (UN, 2015)), capacity for electricity production needs not only to increase but also to come from renewable

resources to meet each country's Nationally Determined Contributions (NDCs). There is an existing narrative that, in contrast to other continents, Africa can avoid a phase of fossil fuel dependency (Batinge et al., 2017; Ram et al., 2022; van der Zwaan et al., 2018): providing renewable electricity systems with high renewable share is technically and economically feasible (Barasa et al., 2018; IEA, 2021b; IRENA, 2022f; van der Zwaan et al., 2018), offers high growth and job-creation potential (Barasa et al., 2018; Lema et al., 2021; Ram et al., 2020), improves climate-change resilience (IRENA, 2022f), and minimizes negative impacts of emissions on the environment and human health (Tiba & Belaid, 2021). However, current pathways have strongly determined current electricity generation and access in each country and are most likely inadequate to fulfil SDG 7 by 2030. Countries with low electricity generation and/or few fossil fuel shares do indeed have the capacity to avoid a phase of high fossil fuel dependence and directly transit to clean renewable electricity systems. Countries with high electrification rates that build on fossil fuel-based electricity production will have to gradually reduce their dependence. As a result, there is an urgent need for context-specific evidence that guides national pathways towards 100% renewable electricity systems considering electricity access rates, fossil fuel and renewable shares in electricity system, and population growth rates for each country (Mulugetta et al., 2022). Building on that evidence, data on existing and proposed renewable power plants can indicate each country's state-of-the-art and near future RE capacity, while data on remaining feasible RE potential highlights what could be exploited additionally. Georeferenced power plant data can further support the understanding of how a transition towards 100% renewable electricity systems will affect the natural resource systems that the respective RE depends on and provide quantified and site-specific information on proposed infrastructure impacts. These results can support the future discussion on what is needed for a transition to renewable electricity that is environmentally, socially, and economically sustainable.

Currently, African countries tremendously differ in electricity access rates. Nearly 100% of people living in Morocco, Algeria, Tunisia, and Egypt have at least four hours of access per day, while less than 20% in Burkina Faso, Niger, Chad, the Central African Republic, the Democratic Republic of Congo, Malawi, and South Sudan have such access (Ritchie et al., 2020). Depending on climatic conditions, current fossil fuel dependence, and investment risk for renewable energy (RE) projects, the natural and economic RE potential may be limited, or exploitation not attractive, which determines the feasible capacity of a country to transition to entirely renewable electricity systems (Mulugetta et al., 2022; Sterl et al., 2023). The International Renewable Energy Agency (IRENA) states that 23.1% of the total electricity capacity installed in 2021 in Africa came from renewables, which is 15.2% less than the worldwide renewable capacity share for electricity (IRENA, 2022e). To date, hydropower provides the greatest share of renewable electricity in African countries (63.8%, 2021) (IRENA, 2022e). Since the emergence of the first hydroelectric power plants, the construction of dams has been accompanied by a debate on their negative impact on environment and society (Kuriqi et al., 2021; Schulz & Adams, 2019; Thieme et al., 2021). Falling prices and large technical resource potential fuelled the emerging role of wind and solar power in the African renewable resource mix, but impact and potential also in combination with hydropower remain poorly quantified on a larger scale due to a lack of openly accessible and spatially explicit plant data (Adenle, 2020; Danso et al., 2021; Sterl, 2021a; Timilsina, 2021). Increasing Africa's RE capacity sustainably includes manifold, site-specific solutions: Updating centralized capacity can offer affordable electricity to the grid-connected population in urban areas, while decentralized off-grid and mini-grid solutions serve for rural locations, where grid extensions are not profitable (Dagnachew et al., 2017; Ulsrud, 2020). Minimization of chronic plant failure (Kumar & Saini, 2022; Wan et al., 2021), avoidance of harmful infrastructure (Peters et al., 2021), combinations of renewables via hybrid systems

(Solomon et al., 2020; Sterl, 2021a; Sterl et al., 2020), and electricity sharing across borders (Gonzalez et al., 2021; Llamosas & Sovacool, 2021; McCluskey et al., 2022) are possibilities to ensure efficient and diversified RE systems to sustainably combat climate change and protect highly valuable ecosystems.

In order to drive the transition to 100% renewable electricity systems that provide access for all, it is indispensable that different scientific disciplines and engineers cooperate on providing integrated insights and openly accessible data to support local research, and guide decision support and investments via scientific scenario analysis (Carlino et al., 2023; H. Li et al., 2022). Sustainable renewable power plant and electricity system planning must build on good national practice options from the past and consider management and planning mistakes (O'Brien et al., 2021; Opperman et al., 2023). It is further crucial to learn from the examples of environmental impacts of RE on other continents and avoid impairing infrastructure. As an example, Europe is spending millions to remove former hydroelectric and other dams to restore free-flowing rivers (Schiermeier, 2018). In African countries located within the Congo Basin, where (very) long free-flowing and biodiverse rivers associated with rich cultural traditions still remain (Grill et al., 2019), these costs could be considered when planning electricity sources and fragmenting infrastructure could be weighed against alternative solutions.

In this review, we summarize past, current, and future trends in the fast-growing RE development sector in Africa. We discuss trends and drivers that shape the debate on different renewable resource types, their impacts, and electricity access strategies for the entire continent. We analyse national data on electricity access, population growth, as well as fossil fuel and renewable electricity shares to determine national starting points and future challenges related to a continental transition towards 100% renewable electricity systems. We further use georeferenced data on existing and proposed renewable power plants as an indicator to estimate each country's renewable capacity and electricity generation. Using these site-specific data, we elaborate on potential alterations that might occur as renewable infrastructure is likely to alter the system it derives electricity from. Our analysis provides new scientific insights on the starting points and near-future prospects of a transition towards 100% renewable electricity for all-Africa and what is needed to realize the African Union's Agenda 2063 vision to build "environmentally sustainable and climate resilient economies and communities" (African Union, 2015).

4.4. Past developments

Past development of electricity access and renewable power plant implementation determine the initial conditions from which African countries start to align development and climate goals. These developments are often overlooked in global debates on Africa's potential to leapfrog to an RE transition, bypassing fossil fuels, but are crucial to provide context-relevant evidence for a clean energy future (Mulugetta et al., 2022).

4.4.1. Development of electricity access in Africa

The status quo of energy systems and electricity per capita rates highly differs between countries, and in 2021 more than half of the population without electricity access lived in countries where an enabling policy environment is still at an early or middle stage (Dagnachew et al., 2020; ESMAP, 2022). Only three out of 54 countries have a higher electrification rate than the world average (Seychelles, Libya, South Africa; Figure B.1). Concurrently, the three countries with the largest population lacking access worldwide are located in Africa: In 2020 Nigeria counted 66 million, the Democratic Republic of Congo 82 million, and Ethiopia 59 million unserved people, which represents 35% of the worldwide population without access (584 million people without

electricity access in 2020, Figure B.2) (Ritchie et al., 2020; UN, 2022). Elsewhere, several countries including Ivory Coast, Ghana, Kenya, Rwanda, and Senegal were able to reduce or stabilize the number of people without access between 2020 and 2021 despite the delays in making new connections due to the pandemic (IEA, 2022a). Major disparities in access exist between urban and rural areas. While the share of people with access is still higher in urban areas (83% vs. 36% in rural areas), rural access rates improved faster than in urban settings mainly due to the development of mini-grid and off-grid systems (IEA, 2021b, 2022a).

4.4.2. Development of renewable energy in Africa

Electricity in Africa is mainly generated by natural gas (41%), coal (29%), and hydropower (18%; total of 840,819 GWh for Africa in 2020) (IEA, 2021b). Gas and oil (6% of total in Africa) dominate in north African countries, while coal is exploited mainly in South Africa. Nuclear (2% of total in Africa) and geothermal power (1% of total in Africa) play a minor role in the continental electricity generation mix.

Hydropower plants are the longest established infrastructure for renewable electricity generation in African countries, and globally, in terms of number and installed capacity (MW). In Africa, the construction of hydropower plants boomed until 1990, followed by slower development until 2010 (Figure 4.1) (Peters et al., 2023). The hydropower boom up to the 1990s led to global debates on hydropower plant impacts, which caused a stagnation until 2010. However, the need for RE and the large hydropower potential fuelled a second boom from 2010 onwards (Figure 4.1) (WB, 2021).

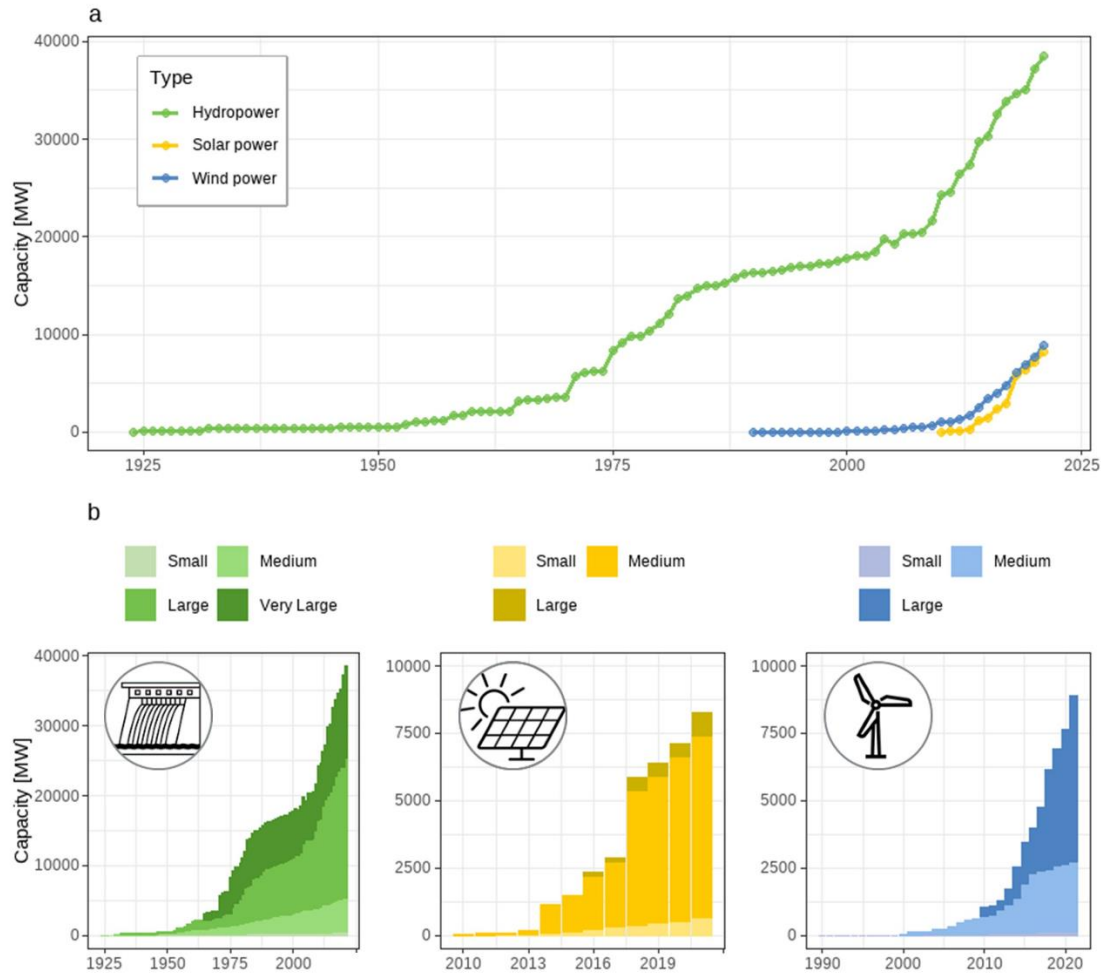


Figure 4.1: Development of renewable energy implementation in Africa. Annual cumulated installed capacity in megawatts (MW) for hydro- (green), solar (yellow), and wind power plants (blue). Each year capacity of newly commissioned plants is added. a. Comparison of the overall implemented capacity of the three renewables in time. b. Composition of capacity for each renewable type (hydro, solar, wind) by plants of different size (small: 1 to 10 megawatts (MW); medium: >10 to 100 MW; large: >100 to 1000 MW; very large: >1000 MW). Data: RePP Africa (Peters et al., 2023).

To date, hydropower has been the main RE of choice not only in Africa, because running costs are considered to be low, and for hydropower plants operating with reservoir storage, electricity production can be tailored on demand (Cole et al., 2014). Wind power (4% of total in Africa), solar photovoltaics (PV, 1% of total in Africa) and solar thermal power (<1% of total in Africa) experience ongoing increases in the continental electricity mix due to a strong decline of levelized costs of electricity for power plant facilities (Figure B.1) (Timilsina, 2021). In comparison to the global average, where RE was mainly financed by the private sector (86%), most African countries are not able to attract private capital due to high political, legal, and economic risks, and mainly public investments drive the RE development (IRENA, 2022d).

Between 2000 and 2019, Africa's RE sector received 15% of the global public investment (US\$ 64 billion) into the RE sector, i.e. in all RE related infrastructure, which is the lowest share in comparison to other emerging economies in Latin America, the Caribbean, and Asia. Large hydropower (>50 MW) received 78% of investment commitments in Africa, mainly from China (51%) (Brautigam & Hwang, 2019; Tan-Mullins et al., 2017). Continental investments are distributed to the disadvantage of those who do not effectively attract private investors due to fragile security conditions: While South Africa, Egypt, Nigeria, Morocco and Kenya receive more

than half of the investment, the 33 least-developed countries in Africa with globally greatest deficits in access to energy and electricity received only 37% of the globally committed investment for RE (2010-2019) (IRENA, 2022d). Local investments become more important with African companies increasingly diversifying the economy and promoting a sustainable growth path (AfDB, 2018). The Continental Free Trade Area set out by the African Union aims to facilitate transnational investments by African companies. However, the Zimbabwean economist and general secretary of the Common Market for Eastern and Southern Africa Sindiso Ngweyina points out that the disparity between the treatment of foreign and national investors still inhibits local investment flows: investors carrying non-African passports can move easily and get better incentives than national or regional investors (AfDB, 2018). In order to attract and support local investment, national policies must continue to create an enabling environment that fosters intra-African investment.

Despite hydropower plants being still the most established RE technique in Africa and worldwide, a global debate on pros and cons of hydropower plants continues (Schulz & Adams, 2019). Particularly controversial are the negative impacts caused by hydropower plants operating with impoundment and dams, because the created reservoir can result in short- and long-term ecological, socioeconomic, and political ramifications and irreversibly alter the natural flow, sediment and thermal regime of a river (Peters et al., 2021; Schulz & Adams, 2019; Thieme et al., 2020, 2021; Zarfl et al., 2019). Less considered in this debate, but of equal importance, is that climate change (Falchetta et al., 2019; Gernaat et al., 2021; Turner et al., 2017; van Vliet et al., 2016), inadequate plant maintenance (Kumar & Saini, 2022), and damage or (wanton) destruction of plants due to wars (e. g. in Liberia during the civil war) (Bartle, 2002) have in the past led to reduced plant output or failure of plants and lower hydropower electricity generation, a trend that is also likely to affect future power plants and thus reduce efficiency.

4.5. Current trends

Population size, population growth, access to electricity, share of renewables, and current status of power plants and grid characterize the different starting conditions and future challenges each African country faces on the path towards reliable and renewable electricity access for all. Conflicts of use including water-energy-food nexus problems emerge and need to be addressed and integrated in future pathways (X. Zhang et al., 2018).

4.5.1. Access to electricity in Africa

Africa has more than sufficient energy resources to meet domestic electricity demands; however, almost half of its population does not have access to electricity (IEA, 2021b; UN, 2022). To “ensure access to affordable, reliable, sustainable and modern energy for all” by 2030 (Sustainable Development Goal (SDG) 7), in sub-Saharan Africa alone, around 85 million people would need to be connected each year from 2020 to 2030 (UN, 2015; WB, 2021). Different countries face different challenges in order to achieve SDG 7. Most important factors determining the different starting points are current human population size, projected human population growth, and current access to electricity (Figure B.2).

The most populated countries - Nigeria, Democratic Republic of Congo, and Ethiopia - still need to provide electricity access for 207 million people and these countries are predicted to (almost) double their population by 2050 (UN, 2022). The Central African Republic, South Sudan, and Chad are the African countries with the highest proportional electricity access deficits; 95%, 93%, and 94%, respectively, of the national population remains unserved in 2020. In other countries, major shares of the population have access, but due to energy crises, electricity is rationed: in

South Africa, 95% of the total population is connected, but parts of the national grid go offline for hours every day. An ageing fleet of coal plants that supplies 90% of the country's electricity, too little short-term capacity in the pipeline, and cash scarcity of the power supplier Eskom led the country into a severe electricity crisis (Butgereit, 2015; Du Venage, 2020; Madiba et al., 2022). Zambia experienced enormous electricity failing and rationing because of a drop in hydropower generation brought on by drought (Anfom et al., 2023). These examples show that even countries with seemingly high access rates must consider the need for electricity rationing. By contrast, most Global North countries with similarly high electricity access rates do not have to handle planned blackouts on an everyday basis.

4.5.2. Current energy systems in Africa

The current human population size, projected population growth, and current access to electricity (Figure B.2) determine the national starting points and future targets for the implementation of electricity access for all as envisioned by SDG 7 (UN, 2015). Current share of renewables, the current electricity per capita rate, and the resource potential determine the national feasibility of a country to provide access for via RE-based electricity systems (Figure 4.2). In 2022, some 401 hydro-, 411 solar, and 127 wind power plants are in place or under construction with a combined installed capacity of 58.36 gigawatts (GW) hydro-, 10.56 GW solar, and 10.53 GW wind power (Figure 4.2).

The total electricity generation from renewables in Africa in 2021 was 23% and differs significantly between countries (Figure 4.2; mean=40%, standard deviation=35%) (Ritchie et al., 2020). In 12 countries, the current renewable share in electricity is $\geq 75\%$; in most of these countries (e. g. Guinea, Central African Republic, DR Congo, Zambia, Mozambique) electricity is mainly produced from hydropower.

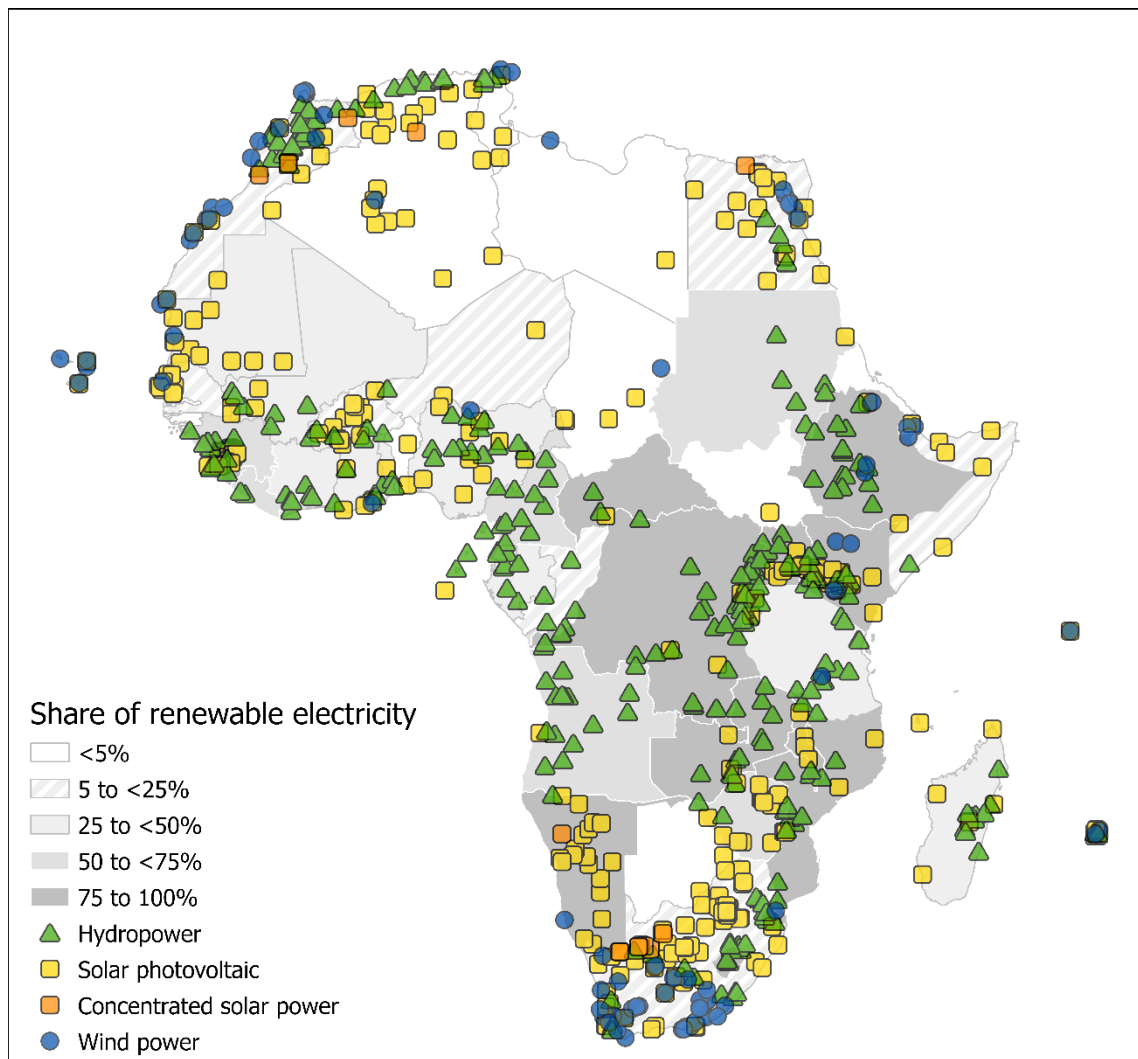


Figure 4.2: Existing renewable power plants and share of renewables for electricity generation. Country polygons are coloured according to the share of renewables for national electricity generation for 2021. Symbols indicate existing power plants and power plants under construction and include hydropower (green), solar photovoltaic (yellow), concentrated solar power (orange), and wind power (blue). No plants are located on open water; all facilities not located on the mainland are located on islands. Data: Our World in Data (Ritchie et al., 2020), RePP Africa (Peters et al., 2023).

Just 11 countries generate 5% or less of their electricity from renewable resources and are coal- (e.g. South Africa) or oil- and gas- (e.g. Algeria, Libya, Egypt) dependent. Although national determined contributions outline that all African countries envision comprehensive clean and sustainable energy systems, recent research has pointed out the high carbon lock-in risk for the continent, unless African countries and partners realize a large-scale cancellation of fossil fuel plants currently in the pipeline (Alova et al., 2021). The overall demand for fossil fuels is also driven by exports: Russia's invasion in Ukraine instigated an energy crisis in European countries and has increased the demand for African gas. However, following Agenda 2030 goals, development strategies that rely on natural gas production and exports are risky, as the world aims to transition to zero emissions and future gas demand is subject to large uncertainties. Jobs in the fossil fuel industry are not secure and sectoral employment is estimated to fall by around 75% by 2050 under a well-below-2°C scenario (CAT, 2022).

At the same time, the continent holds the key ingredient to facilitate the global energy transition: 30% of all worldwide mineral reserves are located in Africa and include graphite, lithium, cobalt, copper, manganese, and rare earth metals (AfDB, 2016); the production of these would need to increase by 500% if the worldwide investment in RE increases to levels required for a clean

energy transition (World Bank, 2017). However, at the state level national economies barely benefit from their mineral resources: value chains are generally outsourced and mineral ores are exported to foreign countries (e. g. China, North America, Europe) for further processing (Ericsson et al., 2020). International civil society must support the African civil society in its commitment to economic prospects and local value creation. A joint commitment can increase pressure on governments, international corporations, and financial institutions to avoid exploitation and ensure fair benefit-sharing. Host governments of foreign mining operations must create binding policy frameworks that attract investors but also maximize national benefits from foreign mining investment (Hilson, 2019). Some countries already have adopted policies that emphasize the need to attract investors to the mining sector, as for example, in Rwanda (Crawford & Bliss, 2017; Yakovleva et al., 2017). Multidisciplinary approaches can provide the context-specific evidence that supports civil society and policy makers in their work. This context-specific evidence includes, for example, socioeconomic analyses on value chain dynamics in Africa (Andreoni, 2019), but also research on the environmental impacts of mining as done for gold mines in Burkina Faso (Porgo & Gokyay, 2017). Bridging scientific disciplines and making research results openly available for policy makers is key to provide informed discussion support and shape discussions on a sustainable transition to 100% renewable electricity systems.

While Africans still lack benefits from their mineral resources, several established sharing mechanisms increase continental co-benefits on renewable resource exploitation and electricity production. On a large regional scale, five established power pools enhance cross-border trade of electric power and create a cost-effective way of connecting excess capacity in one country with demand in another (Box 1). On a smaller scale, multiple countries share transboundary renewable power plants. While solar and wind power plants are normally not built at border locations, hydropower plants may sit in international rivers and operate with a transboundary dam, causing catchment-wide impacts. Transboundary tensions or conflicts may also arise if a hydropower plant located in one country causes flow regulation problems in a neighbouring downstream country (de Bruin et al., 2023). In particular for hydropower plants, benefit-sharing arrangements are needed to positively impact an optimal outcome and diminish conflict between different riparian parties (Llamosas & Sovacool, 2021).

Box 1 | **Renewable power plant operating types and energy distribution systems**

Hydro-, solar, and wind power are the main RE power plant types used for electricity production. Power from wind, solar, and water diversion is variable, especially in contrast to fossil fuel and controllable RE resources (such as impoundment hydroelectricity). Because these technologies are not dispatchable due to their fluctuating nature, increasing the share of variable RE requires technological development and well-designed regulations for grid management and operation (IRENA, 2016).

Hydropower. Three hydropower plant technology types can be distinguished: impoundment, diversion, and pumped storage. Impoundment facilities are most common and use a dam to store river water in a reservoir. When water is released, it flows through a turbine and activates a generator to produce electricity. Impoundment facilities allow for flexible water release to meet changing electricity needs. Diversion or run-of-river facilities utilize the natural decline of the river bed elevation and channel a portion of a river through a canal and/or penstock; usually a small dam ensures that enough water enters the penstock pipes that lead to the turbines at a lower elevation. The water is then redirected to the main river flow. Reservoir storage is minimal. Pumped storage facilities operate with impoundment, but they use two reservoirs. In times of low

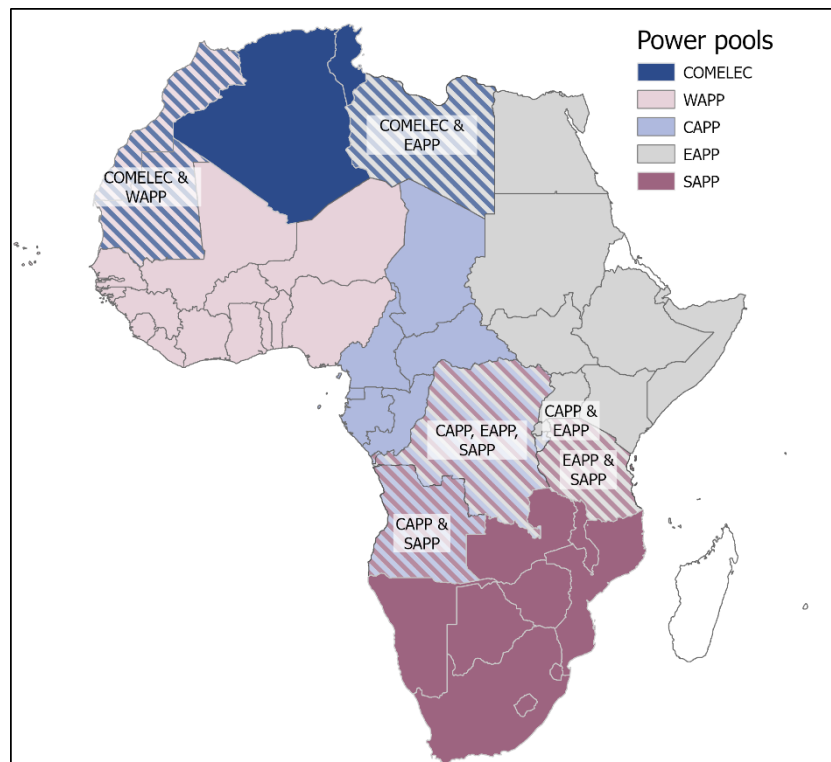
electricity demand, water is pumped from a lower to an upper reservoir, and released back when electricity demand is high.

Solar power. Photovoltaics (PV) and concentrating solar power (CSP) are the main solar power technology types. PV cells are utilized in solar panels and absorb the sunlight to transform it into electricity. CSP facilities use mirrors to concentrate sunlight into a central receiver. The concentrated sunlight heats a fluid, which transfers the thermal energy to a heat exchanger. The heat exchanger converts the thermal energy into steam, which can be used to drive a turbine and generate electricity. Concentrator photovoltaics (CPV) are a PV technology that uses curved mirrors to focus sunlight onto small multi-junction solar cells which reach far greater efficiencies than flat-plate PV cells.

Wind power. Wind farms harness kinetic energy from the wind using wind turbines. These turbines have rotor blades that spin when wind blows. The spinning blades are connected to a generator, which produces electricity. Onshore wind farms are located on land and feed on terrestrial air currents. Nearshore wind farms are sited on land less than three kilometres from the coast. They harness both terrestrial and sea winds to produce energy. Offshore wind farms are built on open sea where the wind's force is greater at a lower altitude, and more regular than on land. Hybrid renewable power plants combine two or more technologies and can also include energy storage.

Regional power pools.

Five collaborative initiatives have been established to manage and develop regional electricity networks, infrastructure, and power generation resources across the African continent (see the figure). They are established to facilitate cross-border trade and create a cost-effective way of evacuating excess capacity between countries to offset peak demands: The Maghreb Electricity Committee or Northern African Power



Pool (COMELEC), the Western African Power Pool (WAPP), the Central African Power Pool (CAPP), the Eastern African Power Pool (EAPP), and the Southern African Power Pool (SAPP).

4.6. Future supply and demand

The potential for each African country to cover the future electricity demand of a growing population with renewables depends on the current reliance on fossil fuels and the number of renewable power plants in pipeline. In particular for low- and middle-income countries, the need

to provide electricity access to major parts of the population adds pressure on the renewable capacity expansion.

4.6.1. Shift from fossil fuels to renewable energy

A transition to entirely RE systems requires not only the replacement of polluting fossil fuels for electricity generation, but also a future in which the growing electricity demand is met with renewables (IRENA, 2020b). A transition to hydro-, solar, and wind power systems would reduce global energy needs by 57%, energy costs by 61% and social (private, health, climate, environment) costs by 91% while avoiding blackouts, creating millions more jobs than lost, and requiring little land (Jacobson et al., 2019). However, for many countries that are highly dependent on fossil fuels, this means that fossil fuels have to be eliminated on a large scale, including projects already at the planning stage (Alova et al., 2021; Ganswindt et al., 2022). Because many African economies rely on fossil fuel, a transition will create winners and losers. Justice consideration must be part of transition strategies incorporating the needs of affected communities (Carley & Konisky, 2020). For example, in Mpumalanga, a region in South Africa with an economy exclusively relying on coal, a just transition implies the empowerment of citizens and their communities to address risks and social disturbances created with a turn away from coal, and to create enabling framework conditions for investments and economic diversification from which communities will benefit (Nel et al., 2023). Pathways that can put fossil-fuel-dependent countries on track for an RE transition should include long-term green-growth strategies and support schemes for business and workers in the fossil fuel industry (Mulugetta et al., 2022).

The shift to RE-based systems is a particular multilevel challenge for upper-middle income countries that not only rely on fossil fuels but also have high electrification rates (highest sum of upper quartiles: Algeria, Botswana, Libya, Seychelles, South Africa). To overcome these challenges, countries outside Africa could consider phasing out of the import of fossil fuels from Africa while supporting the respective countries in finding feasible alternatives to earn revenue and simultaneously transit towards RE systems. The phase-out must include the cancellation of fossil-fuel power plants proposed by foreign investors that are currently in the pipeline (Alova et al., 2021). Open trade policies can further stimulate intracontinental and global investments in RE expansion (AfDB, 2018; Murshed, 2020).

In contrast, countries with low electricity generation (lowest quartile: Niger, Chad, Benin, Somalia, Burundi, Central African Republic, Guinea-Bissau, South Sudan, Djibouti, Togo, Rwanda, Burkina Faso, Madagascar) and/or few dependences on fossil fuels (lowest quartile: Lesotho, Central African Republic, Ethiopia, Democratic Republic of Congo, Namibia, Eswatini, Uganda, Kenya, Sierra Leone, Zambia, Malawi, Mozambique, Guinea, Burundi) could avoid a phase of fossil fuel dependency and aim for 100% renewable electricity systems by up-scaling installed and implementing proposed renewable capacity. National policies must facilitate national and international investment in African RE development; simultaneously European and US-American banks need to stop financing fossil fuel expansion. Twenty of the top 23 investors accounting for 50% of total investments in African fossil fuel extraction are headquartered in the United States of America and Europe, while only one is headquartered on the continent (South Africa) (Ganswindt et al., 2022). The expansion of RE systems can further provide decent work opportunities and career perspectives, in particular for young people. In Nigeria and Kenya, the expansion of decentralized RE systems increases the need for skilled local work staff and creates employment and capacity building in rural areas (Shirley et al., 2020).

Finally, the global covid-19 crisis and Russia's invasion in Ukraine threaten a decades-long trend of cost decline for minerals and metals that are essential for clean energy technologies (IEA, 2022b); in addition, new investments in fossil fuels are being made and new supply routes created for European countries to have alternative sources to Russian energy (Renewal, 2022). The UN COP 27 fell short on efforts to reduce emissions from fossil fuels, and African leaders argued that countries need to exploit gas reservoirs to help generate universal electricity access, while African activists were claiming the opposite (Khadka, 2022). To facilitate a pan-African RE transition and reach climate goals, more finance needs to be unlocked and energy investments to be doubled to 2030 (IEA, 2022a); to access a universal electricity access in sub-Saharan Africa US\$ 30 billion are annually needed on top of the baseline Investment (US\$ 20 billion, +150%) (Falchetta et al., 2021). Finance conditions for RE have greatly improved (Egli et al., 2018), but renewable technologies are still disadvantaged by today's financial practices in Africa (Sweerts et al., 2019). For example, technological improvements alone will not suffice to make CSP competitive. Policies for de-risking to Organization for Economic Cooperation and Development risk levels are needed to assure that this RE technology is competitive throughout sub-Saharan Africa (Labordena et al., 2017).

4.6.2. Proposed renewable energy demand and supply

If all proposed plants were implemented, Africa would generate 1225 terawatt hours (TWh) from renewable resources (hydro-, solar, and wind power, Figure 4.3) (Peters et al., 2023). The International Energy Agency projects for 2040 a continental electricity demand of 1,614 TWh (the Stated Policies Scenario) to 2,321 TWh (Africa case) (IEA, 2019). The Stated Policies Scenario assesses the electricity demand by combining existing and announced policy frameworks with the continues evolution of known technologies. The African case scenario builds on the African Union's Agenda 2063 and presents a pathway to attain inclusive and sustainable economic growth and development. Assuming that existing plants operated at full capacity and all proposed plants were implemented, 76% (the Stated Policies Scenario) or 53% (Africa case) on average of Africa's energy needs projected for 2040 would be met by RE. This underlines the point that the RE capacity currently in the pipeline is – even if it is fully implemented – far from being enough to achieve the goals of Agenda 2030 and Agenda 2063.

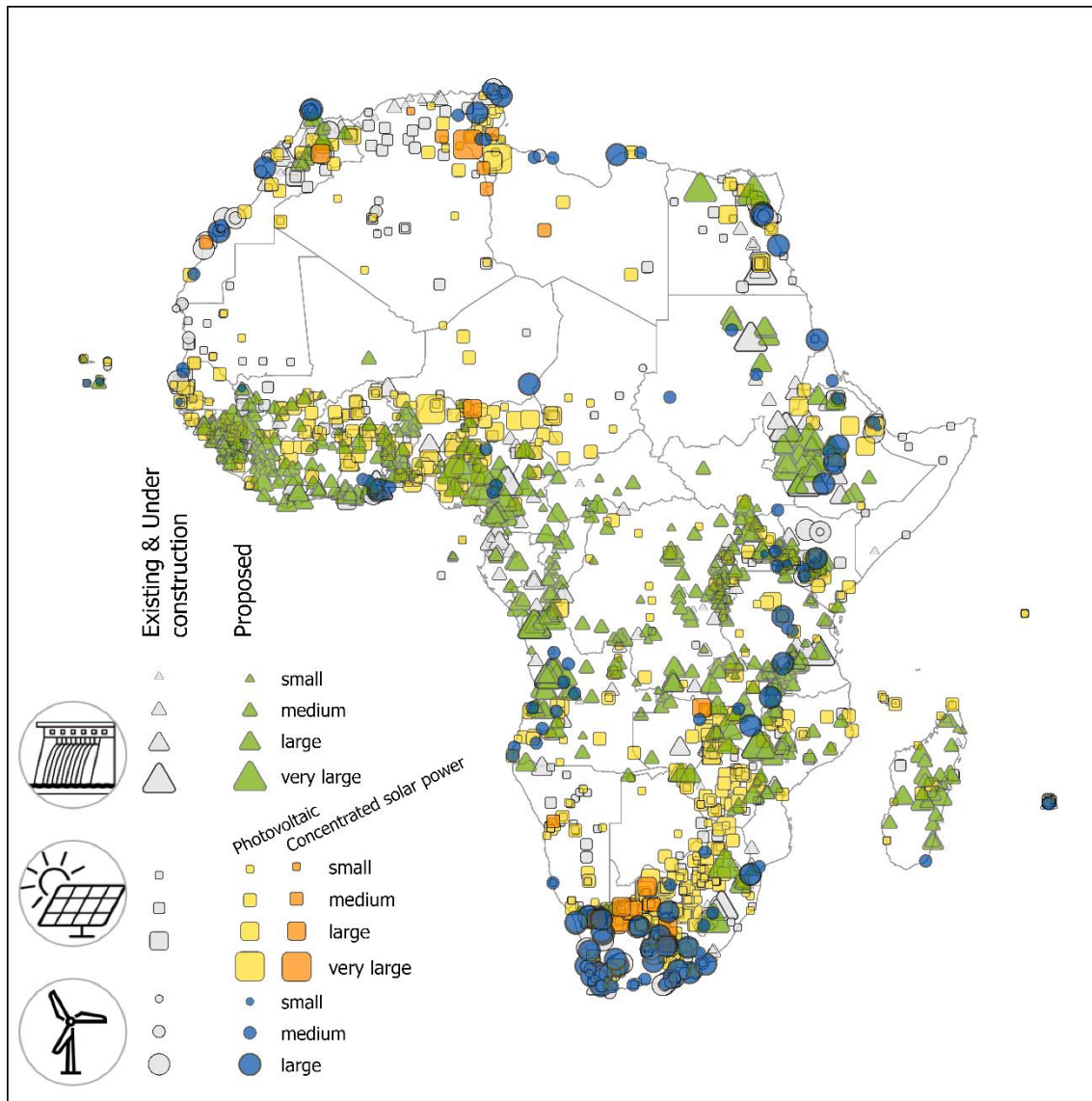


Figure 4.3: Existing and proposed renewable power plants differentiated by capacity size. Symbols indicate existing/under construction (grey colour) and proposed RE power plants and include hydropower (green), solar photovoltaic (yellow), concentrated solar power (orange), and wind power (blue) from RePP Africa (Peters et al., 2023). Symbol size increases with capacity (small: 1 to 10 megawatts (MW); medium: >10 to 100 MW; large: >100 to 1000 MW; very large: >1000 MW)

The two different scenarios of the International Energy Agency highlight that future electricity demand will be 44% higher if the RE transition “ensure[s] access to affordable, reliable, sustainable and modern energy for all” (SDG 7 (WB, 2021)) in order to build “environmentally sustainable and climate resilient economies and communities” (Agenda 2063 (African Union, 2015)). Nevertheless, there are national differences that need to be considered when talking about “Africa going renewable”. Taking the number of existing and proposed RE power plants as an indicator how African countries are concurrently positioned for a transition towards renewable electricity (Figure 4.3), some countries have enough RE projects in the pipeline to perform a transition, while others are locked in fossil-fuel dependency (Figure 4.4).

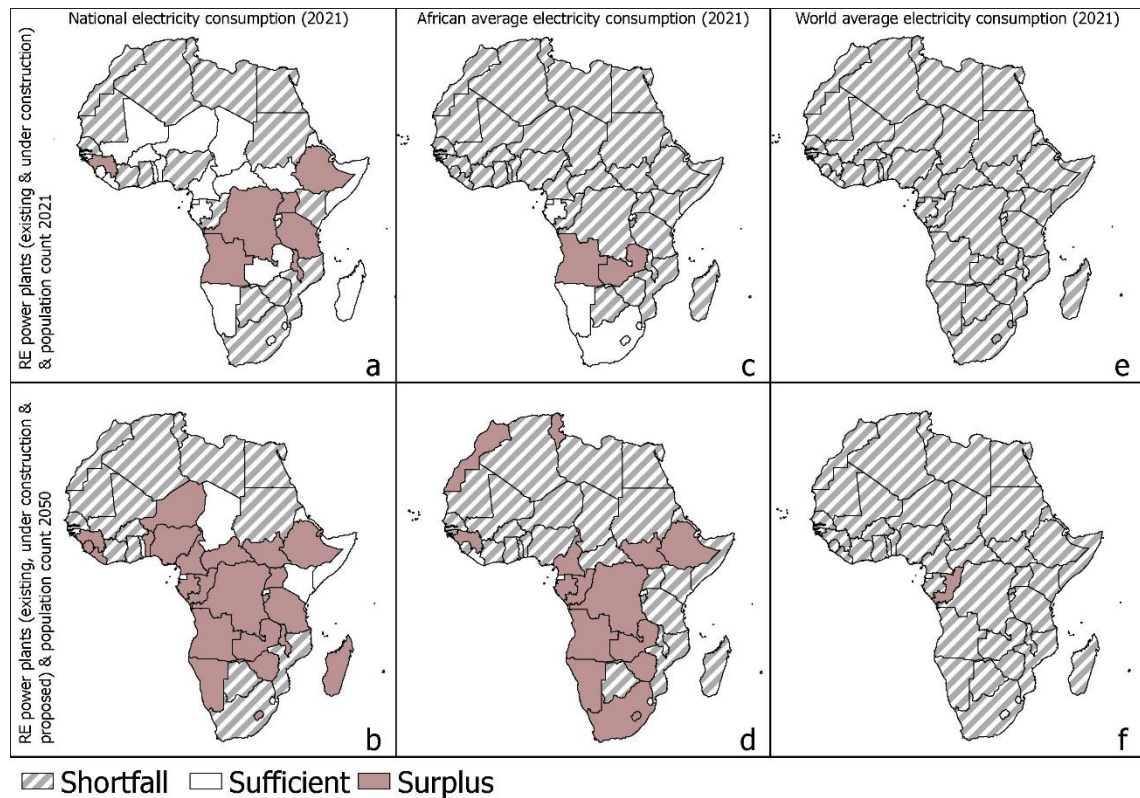


Figure 4.4: Coverage of (projected) electricity demand by renewable energy in 2021 and 2050. Illustrated is the difference between national annual electricity demand and estimated electricity generation by existing/under construction and proposed renewable power plants. Annual national electricity demand for 2021 (a, c, e) and for 2050 (b, d, f) was estimated considering national (a, b), African average (c, d), and world average annual per capita electricity consumption (d, f) and national population counts (2021, and projected for 2050). Electricity generation by hydro-, wind and solar power plants was estimated based on available capacity data from RePP Africa for existing/under construction plants (scenarios 2021; a, c, e) and existing/under construction and proposed plants (scenarios 2050; b, d, f). For details on the calculations please refer to B.2. Supplementary methods. Shortfall: >1000 kWh (uncovered demand); Sufficient: ± 1000 kWh; Surplus: <-1000 kWh. Underlying data: UN (UN, 2022), Our World in Data (Ritchie et al., 2020), RePP Africa (Peters et al., 2023).

Assuming the current national annual per capita electricity consumption [kWh per capita and year] (Ritchie et al., 2020), 29 African countries have already sufficient renewable capacity installed (2021) to meet the national electricity demand (± 1000 kWh), seven countries produce more than needed while 18 countries cannot meet the electricity demand with the national installed capacity from renewables (Figure 4.4a; Tables B.1, B.2). Most of the latter are highly dependent on fossil fuels (Libya, Botswana, Algeria, South Africa, Egypt, Morocco, Senegal, Mauritius, Republic of Congo, Nigeria, Mauritania, Ghana; Figure 4.2) and/or have high annual electricity consumption rates (above African average: Mozambique, Ghana, Republic of Congo, Botswana, Morocco, Tunisia, Algeria, Egypt, Mauritius, South Africa, Libya; Figure B.1).

Of all countries which fell short in 2021, Nigeria, Zimbabwe, and the Republic of Congo have enough RE capacity proposed to not only meet their own electricity demand by RE (considering the projected population number for 2050 (UN, 2022)), but also produce a surplus (Figure 4.4b; Tables B.1, B.2). Kenya can produce sufficient RE to meet domestic demand, while all other countries that are not capable to meet electricity demand with RE in 2021 will not have enough capacity proposed to change their status quo by 2050. Of the 29 countries that have enough RE capacity installed to theoretically meet demand in 2021, only Burkina Faso and Mali fall short by 2050. 13 of these 29 countries can even produce a surplus if all proposed projects go online. All countries with surplus in 2021 have enough RE capacity proposed to also generate a surplus for their respective population projected for 2050.

The estimate of a country's potential to supply its population with 100% electricity from renewable resources is sensitive to or contingent upon the actual implementation of proposed projects and thus not a proxy for the country's potential for transitioning to 100% RE (Figures 4.3, 4.4). The underlying database provides the most consistent and curated dataset on the three renewable electricity sources in African countries so far. Hence, the country-specific data (instead of continental estimates) allow for more realistic RE development scenarios based on actual projects. In addition, these calculations assume a constant electricity consumption in 2021 and 2050, which rather underestimates electricity consumption of most African countries, as they most likely experience substantial socioeconomic development.

Considering an African average annual per capita electricity consumption of 602 kWh (Figures 4.4c, 4.4d; Tables B.1, B.2) or a world average of 3,513 kWh (Figures 4.4e, 4.4f; Tables B.1, B.2), the RE transformation potential is greatly reduced largely, which manifests the need for additional RE potential exploitation and innovation. Considering an electricity consumption based on the African average, most countries have sufficient renewable plants announced to meet the future demand (Figure 4.4d; Tables B.1, B.2). This is partly because of the large projected capacity to be installed (e.g. the Republic of Congo has several very large hydropower plants announced, which would – if implemented and fully operational – exploit large amounts of the national hydropower potential of 3,942 MW (ANDRITZ, 2023)), and partly because of a national electricity consumption that is already above the African average. In contrast, only few countries will be able to cope with a world average electricity demand by projected renewables. Fossil-fuel-dependent countries in northern and southern Africa need to upscale proposed RE capacity if they want to be capable to satisfy national electricity consumption with RE.

In any case, electricity consumption and demand determine the national transformation potential, i.e. when aiming for renewable “energy for all” (SDG 7 (UN, 2015)), it is essential to consider that more than half of all African countries have a domestic electricity consumption that is less than 10% of the global average (2021) (Ritchie et al., 2020). Thus, proposed RE capacity in Africa is huge, but at state level, not all countries are able to perform a transition to entirely RE based electricity systems without innovation and further exploitation of available potential for solar and wind and optimizing an RE mix (Figures 4.3, 4.4; Tables B.1, B.2).

A major challenge in the transition to exclusively RE supply systems originates in the main characteristic of hydro-, solar, and wind power: they rely on natural systems that undergo natural variations, i.e. power generation is not as controllable as from fossil fuel power plants. While hydropower plants operating with a reservoir have the capacity to cope with changing streamflow if adequately managed, solar and wind power plants rely completely on their variable resources driven by meteorological variations that cause sub-hourly to inter-annual changes (Sterl, 2021a; Sterl et al., 2020).

4.7. Optimizing renewable energy systems

To assure a just RE transition with smart and sustainable power plant planning for entire Africa, RE systems need to be optimized by minimizing RE plant failures and losses (e.g. from transmission), improving energy efficiency, minimizing negative ecological, socioeconomic, and political impacts of RE facilities, and exploiting potential under the consideration of climate change impacts.

4.7.1. Minimization of renewable energy failures and losses

Failures and losses can negatively impact electricity generation from RE resources from a local individual power plant to an international power pool level. At the plant level, project delay, lack of maintenance and damage caused by war, protests, or other conflicts have reduced worldwide electricity generation in the past (Bulut & Özcan, 2021; Dorji & Ghomashchi, 2014; Kumar & Saini, 2022; Plummer Braeckman & Guthrie, 2015). Sustainable renewable electricity relies on power plant operators that assure the availability of trained and qualified staff as well as guarantee financing materials and manpower for regular maintenance and technical upgrades. If renewable power plants are implemented and/or operated by foreign organizations, local and regional benefits and ownership should be the ultimate goal via strategies such as capacity building and local profit sharing (Brautigam & Hwang, 2019; Soumonni & Soumonni, 2011). Within power pools, electricity transmission losses are one of the major causes of the electricity access deficit, e. g. 26% are lost on average from distribution companies within the West African Power Pool, equalling several tens of millions of dollars (INTEC, 2021). A major cause is fraud, because centralized energy pools are more vulnerable to corruption than decentralized systems, which negatively impacts long-term power-pool development (INTEC, 2021). Another reported reason for diminished electricity generation is the destruction of power plants by war. War has caused the destruction of transmission lines and substations in Libya (Khalil & Asheibe, 2015), and the destruction of hydropower plants and other energy related infrastructure in Liberia (Tiepoh, 1992). As an example, the Liberian Mount Coffee hydropower plant with 88 MW nominal capacity was destroyed during the first Liberian civil war in 1990, and was not fully recommissioned until the end of 2017 (Szabo & Lang, 2018). Further potential losses occur from a lack of or insufficient transboundary river-basin management, as it implies a high risk of national and international conflicts (de Bruin et al., 2023) and violence (del Bene et al., 2018), causing project delays (Plummer Braeckman & Guthrie, 2015) and missed opportunities (Elsayed et al., 2022). If national politics, diplomacy, and policy frameworks succeed to prevent conflicts by implementing peacebuilding and anti-corruption measures, and succeed to reduce the losses from these international African sharing systems, RE sharing has the potential to reduce national energy costs, shedding, infrastructure, and need for land, and would create co-benefits for all participating countries (Jacobson, 2021). Consequently, energy policy needs to acknowledge, analyse and learn from past failures in order to avoid multi-level generation losses and create an enabling environment (Sokołowski & Heffron, 2022; Yang et al., 2022).

4.7.2. Improving energy efficiency

As the African continent is facing an upsurge in energy consumption, improved energy efficiency is a key supplement to fuel a continental transition towards renewable electricity systems and keep modern energy affordable (Jacobson et al., 2019). According to Gerrard, “improved energy efficiency” means that less energy is consumed to produce the maximum economic output possible (Gerrard, 2011). While northern African countries have average efficiency levels up to 94%, west African countries lag behind with average levels of only 49% or less (Ohene-Asare et al., 2020). Reliable electric grids have historically needed a minimum baseload, which is usually met by power plants that operate continuously to meet a minimum level of power demand (Matek & Gawell, 2015). Suitable resources are fossil fuels (coal, nuclear) or renewables (hydropower, geothermal heat, biomass, biogas) (Duan et al., 2020). Solar and wind power are variable resources and can only store produced energy if storage capacity is provided; a challenge that needs to be addressed when aiming for a transition to exclusively renewable electricity systems. Hybrid systems are economically feasible solutions (Anoune et al., 2018; X. Li et al., 2015; Sawle et al., 2018) and will be entirely renewable if hydropower is used as a storage system (Gebretsadik

et al., 2016; Solomon et al., 2020; Sterl, 2021a). As such, linking wind and solar power to the operation of the Grand Ethiopian Renaissance Dam (GERD) in eastern Africa could be an incentive to retain the rivers seasonal flow regime and protect downstream riparian countries from GERD impacts, e.g. on water supply for households and irrigation and on freshwater ecosystems, while maintaining grid stability (Sterl, Fadly, et al., 2021). One option to tackle the mismatch between varying renewable electricity supply and actual demand are hydropower plants that operate with pumped storage (Hunt et al., 2020). Further potential for improving RE plant efficiency are given by floating photovoltaics: even a low coverage of reservoirs by floating photovoltaics could generate all the solar energy needed to decarbonize the continents electricity sector (Almeida, Schmitt, Grodsky, et al., 2022).

On a continental level, energy and material improvement will continue to reduce the continental electricity demand by 30% from the electricity demand today (IEA, 2022a). In addition, smart grid technologies will be able to match supply and demand in a more concerted and flexible way, making baseload power plants less relevant in the long term (IRENA, 2015). Transnational sharing and increased interconnection could further help mitigate negative climate impact on hydropower capacity production (Cáceres et al., 2022).

4.7.3. Minimizing negative impact of renewable energy facilities

Power plant facilities can cause multiple ecological, social, economic, and political ramifications. Integrated assessments are crucial to facilitate a sustainable long-term development of the renewable electricity sector (Kati et al., 2021; Peters et al., 2021; Turney & Fthenakis, 2011). Impacts of hydropower plants have been and are intensively studied, largely on a plant scale but also on a river catchment scale: Dam construction and reservoir formation alter freshwater ecosystems and reduce water and sediment connectivity (Zarfl & Lucía, 2018), truncate biogeochemical processes (Deemer et al., 2016), and threaten biodiversity due to habitat fragmentation, over-exploitation, pollution, species invasion, and inhibited animal migration (Carrizo et al., 2017; He et al., 2018; Wu et al., 2019). Dam induced resettlement can cause conflicts with resettled people not sufficiently informed and compensated for the loss of their livelihoods (Bilson Obour et al., 2016; Llamosas & Sovacool, 2021; Schulz & Skinner, 2022; Tilt et al., 2009). Dam construction affects public health (Dotse-Gborgbortsi et al., 2022; Polimeni et al., 2014), and reservoir inundation may trigger earthquakes (Tuan et al., 2017).

Wrong site selection and inadequate planning have repeatedly caused project cost overruns, which negatively impact national economy and political trust (Opperman et al., 2017; Plummer Braeckman & Guthrie, 2015). If hydropower is not part of an integrative planning that balances land demands within the water-energy-food nexus, hydropower plant development can be inefficient and not sustainable (C. X. Li et al., 2021; X. Zhang et al., 2018). Because 60% of large rivers cross country borders, geopolitical conflicts between countries may emerge (de Bruin et al., 2023; Gonzalez et al., 2021); one prominent African example is the hydropolitical conflicts surrounding GERD, which started with the upstream nation Ethiopia surprising the downstream countries Egypt and Sudan by publicly announcing the construction of GERD in 2011 without prior consultation (Aljefri et al., 2019).

International conflicts are easier to avoid for wind and solar power plants, because of the resource characteristics of wind and sun light: the area suitable for installing wind or solar power plant facilities is not restricted to rivers and in contrast to other electricity resources, simultaneous electricity generation and agricultural activities are possible; e. g. farming or grazing animals under standalone solar systems or between wind turbines within one wind park (Barron-Gafford et al., 2019; Pascaris et al., 2021; Rediske et al., 2021). Even though many hydropower plants

have irrigation as a co-purpose and support agricultural activities in the surrounding landscape, the area inundated for reservoir creation remains lost for terrestrial ecosystems, human livelihoods and other purposes (Dorber et al., 2020; Tefera & Sterk, 2008; Zeng et al., 2017). The latter is an important argument when promoting wind and solar power, because even though the land use per unit of electricity source has decreased intensively for wind and solar during the last two decades (IEA, 2021a), it is still larger than for hydropower, gas, and nuclear power (Onshore wind: 99 m² (project)/0.4 m² (turbine) per MWh; CSP: 22 m² per MWh; PV (on-ground, silicon): 19 m² per MWh; Hydropower: 33 m² (small) to 14 m² per MWh (large); Coal: 15 m² per MWh; Gas: 1 m² per MWh; Nuclear: 0.3 m² per MWh) (Ritchie, 2022).

Reported impacts of onshore wind power plants mainly include increased habitat loss and animal mortality in particular for bird and bat species (Hamed & Alshare, 2022; Loss et al., 2019; Millon et al., 2018; Popescu et al., 2020); noise pollution (van Kamp & van den Berg, 2018); and perception of visual impact (McKenna et al., 2021; Peri & Tal, 2021). Impacts of solar power plants strongly depend on the operational type and vary with size between rooftop and standalone PV, CPV, CSP, and floating PV (Cousse, 2021). It is reported that large solar facilities alter a landscape and impact visual perception, biodiversity, and microclimate (Hamed & Alshare, 2022; Torres-Sibille et al., 2009). Impacts of floating PV on a reservoir increase with the area covered and can cause algal blooms, reduce oxygen production (through shading), but remain poorly studied (Almeida, Schmitt, Grodsky, et al., 2022). Failure to adequately address mentioned impacts can hinder the short- and long-term sustainable development of RE projects. Large solar power plants proposed on arable land can cause conflicts due to intensified competition for land (van de Ven et al., 2021); in Lesotho proposed wind farms threaten the declining populations of the regionally endangered bearded vulture and globally vulnerable cape vulture (Rushworth & Krüger, 2014); and a lack of transboundary cooperation between Egypt, Sudan, and Ethiopia when managing new and existing hydropower plants risks water supply and energy generation for the riparian population (Wheeler et al., 2018). In contrast, integrative planning can create water-energy-food nexus benefits: Falchetta et al. showed that over one third of unmet crop water requirements in sub-Saharan Africa could be supplied with stand-alone solar PV irrigation systems (Falchetta et al., 2023).

4.7.4. Climate change impact on renewable energy potential

Energy from renewable resources depends on natural systems, which are driven by climate. Freshwater, sun, and wind availability vary on a daily to annual time-scale. Plants producing power from these resources are dependent on this variability. While hydropower plants operating with impoundment are able to cope with changing freshwater availability, wind and solar power output is not perfectly controllable by a transmission system operator, making them variable energy resources (Box 1). As such, renewable power plants create complex interactions and dependencies between nature and anthropogenic infrastructure: plant facilities impact natural systems in their surroundings, but also climate change impacts plant performance (Donk et al., 2023; Sawadogo et al., 2021). While there is scientific consent that climate change impacts long-term plant performance and electricity generation of renewable power plants, a regional high resolution quantification of wind and solar power plant potential under climate change is still at an early stage (Craig et al., 2019; Fant et al., 2016; Ndiaye et al., 2022).

Africa holds one of the largest remaining hydropower potentials globally (Cáceres et al., 2022; Gernaat et al., 2017), which will increase in central Africa under a climate-change-induced increase in streamflow caused by enhanced precipitation (van Vliet et al., 2016). However, countries outside of this region will suffer from diminished existing and potential hydropower

capacity, because these countries will be increasingly affected by drought (Cáceres et al., 2022; Meng et al., 2020; Wan et al., 2021). Consequently, relying on developing hydropower greatly increases the risk of climate-related electricity for eastern and southern countries (Conway et al., 2017). Potential for wind and solar power is large for much of the continent, with an estimated total deployment potential of 4.9 TW for solar PV (average capacity factor of 21.4%) and 3.4 TW for onshore wind (average capacity factor of 54.9%) (ESMAP, 2020; Mentis et al., 2015; Sterl et al., 2022), and will on average remain stable under climate change (Bichet et al., 2019; Fant et al., 2016; Jung & Schindler, 2022). A technical potential of >99% for each wind and solar PV, and 51% for hydropower will remain if all proposed plants and plants under construction are implemented (Figure 4.3) (Hydropower and DAMS, 2021; Peters et al., 2023; Sterl et al., 2022). Thus, an increase of wind and solar in the renewable mix could compensate for hydropower capacity losses and simultaneously pave the path towards 100% RE based electricity systems and stabilize the sustainable exploitation of renewable resources in the long-term.

Finally, a major challenge that African countries need to address when planning sustainable RE systems in times of climate change is that the climate change induced demand for cooling will put increasing pressure on the overall energy demand (Yalew et al., 2020). The cooling demand is supposed to quadruple by end of 2030, and energy efficiency will be key to tackle this challenge (IEA, 2022a).

4.8. Summary and future perspectives

Achieving universal electricity access implies that RE is cost competitive and can be offered at affordable prices. Ongoing technological progress has led to continuous increase in plant efficiency and capacity factors, increasing cost competitiveness in particular for solar PV and onshore wind (IRENA, 2020a). On a global scale, new solar and wind projects are continuously undercutting the cheapest and least sustainable existing coal-fired power plants, making it economically attractive to exit traditional coal dependence. Cost reductions open a window of opportunity even and especially for countries with high coal deposits transit to 100% RE based electricity systems, which also enables fulfilment of their NDCs (IRENA, 2020a).

If all announced hydro-, solar, and wind power plants are implemented, fully operating, and used for electricity, up to 76% of Africa's electricity needs projected for 2040 could be met only by RE (Figure 4.3) (IEA, 2019; Peters et al., 2023). The total capacity of all currently projected projects adds up to only 45% of the 300 GW additional renewable capacity targeted by the African Renewable Energy Initiative Action Plan for 2020 to 2030 (African Renewable Energy Initiative, 2016). Even if African countries implemented all of the currently announced renewable power plants, further renewable resource exploitation and technological innovation within the next decade would be necessary to reach the ambitious goals of Agenda 2063 and SDG 7 and create “environmentally sustainable and climate resilient economies and communities” (African Union, 2015) with “access to affordable, reliable, sustainable and modern energy for all” (UN, 2015).

Research can support the search for adequate pathways by modelling future scenarios. For example, a multi-scenario analysis of the African energy landscape including the Shared Socioeconomic Pathways, the Representative Concentration Pathways, and median and very dry water availability scenarios suggests that hardly any new hydropower will be economically feasible after 2030 due to the projected increase in the frequency and extent of droughts and the economic competitiveness of wind and solar power (Carlino et al., 2023). To implement adequate scenario modelling, georeferenced and plant-specific data must be openly accessible, so that researchers are enabled to provide science-based evidence for discussion and decision support.

Building on up-to-date data, research must stop treating Africa as one entity and acknowledge different national starting points in terms of environmental, socioeconomic, and political conditions (de Bruin et al., 2023; Mulugetta et al., 2022). National development status and electricity access, fossil-fuel dependence, installed renewable capacity, future potential for renewable capacity, and the current political environment are further factors that determine each country's capacity to implement a transition towards RE systems. Diverse and multidisciplinary research teams that integrate local knowledge and global learnings will shape outputs that are needed to have broad impact and be locally accepted (Figure 4.5).

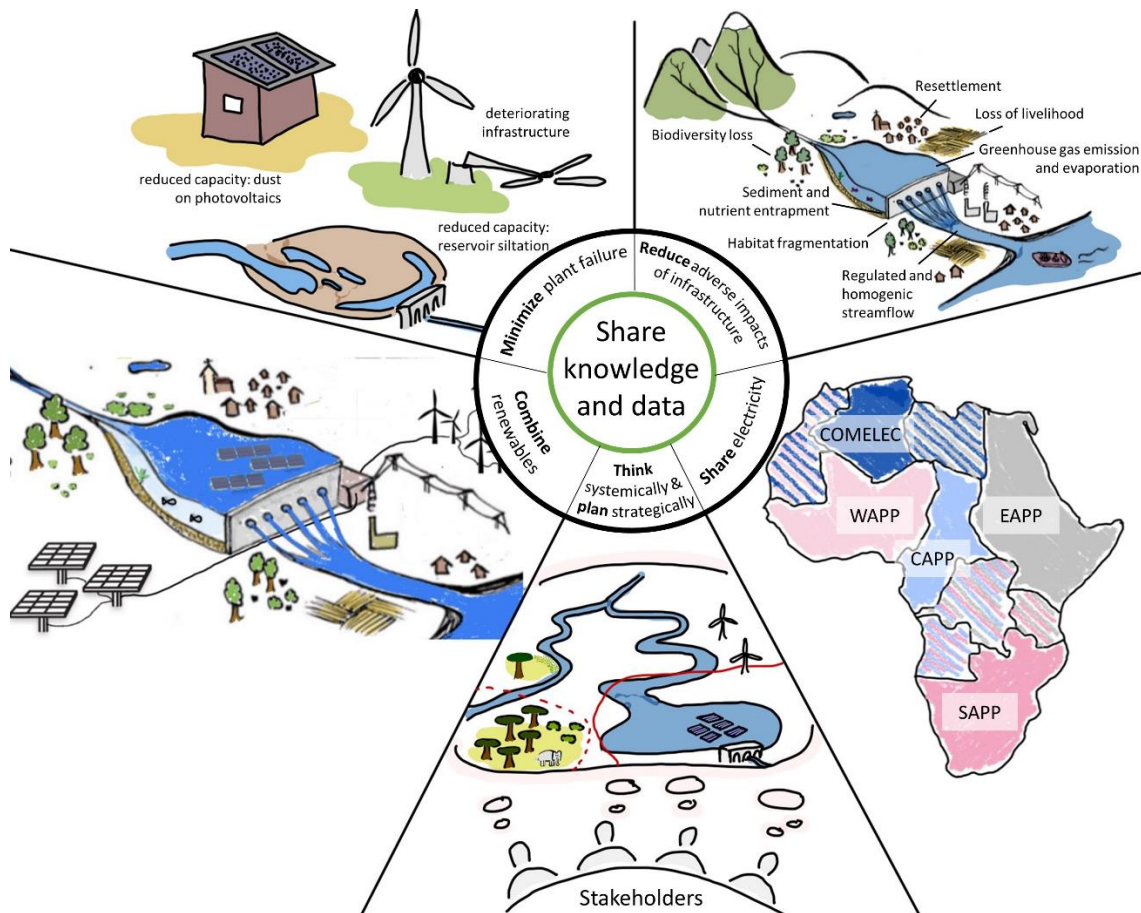


Figure 4.5: Optimization of renewable energy systems in long-term system scale planning. Shared scientific knowledge and open data are key for strategic discussions that support the optimization and decision processes among stakeholders. Clear, context-shaped and sustainable future pathways need to integrate (1) minimization of plant failure for example by improving maintenance of the existing infrastructure; (2) exploitation of the potential to combine different renewable technologies such as the operation of floating photovoltaics on a hydropower reservoir; (3) transparent and scientifically supported planning and discussion processes that bring all stakeholders together; (4) electricity and knowledge sharing across jurisdictional borders (e.g. within international power pools: Maghreb Electricity Committee or Northern African Power Pool (COMELC), Western African Power Pool (WAPP), Central African Power Pool (CAPP), Eastern African Power Pool (EAPP), Southern African Power Pool (SAPP)); and (5) the reduction of adverse impacts of renewable power plant infrastructure. Own visualization.

To produce relevant and impactful research that can support the political discussion process, researchers have to integrate the following multilevel optimization processes to guide a science-based sustainable RE transition (Figure 4.5). Analysis of current power plant failure and transmission losses can help countries to identify where chronic plant failure currently reduces electricity output and how these losses can be eliminated. Power plants need to operate efficiently, even under consideration of future climate developments; renewable hybrid options have the potential to support efficiency, but local and plant specific data is lacking. Research can support and realize integrated impact assessments for proposed power plants on larger scale to minimize negative ecological, socioeconomic, and political impacts and include catchment-wide

ramifications of hydropower plants. Wind and solar potential are far less exploited than hydropower.

Future research needs to further explore how a shift towards solar and wind power exploitation could reduce the dam-building pressure on African rivers. To that point, models need to integrate local changes of climatic conditions as they impact renewable resource availability and power plant performance (Donk et al., 2023). Also a strategic planning of hydropower expansion can provide decision support when comparing the benefits of building dams against their socioenvironmental impacts (Almeida, Schmitt, Castelletti, et al., 2022). Site-specific analyses of wind-solar complementarities in combination with existing hydropower as energy storage are crucial to reduce storage needs and land use. Hybrid plants and optimized resource exploitation will help to tackle the nexus problem of different parties claiming land for energy, water, agriculture or ecosystem protection (Figure 4.5). Knowledge from existing research on how ecosystem integrity can be sustained while the potential for hydropower dams is increased could be applied to African rivers (Garrett et al., 2023). Investigations of diversified renewable energy systems and how a balanced renewable electricity mix can optimize performance started off in Ghana and points towards a path which future RE system research should explore in more detail (Gonzalez et al., 2023).

To tackle the challenge of universal access, grid capacity and international connections need to be enhanced for urban areas while decentralized demand driven off-grid and mini-grid solutions prove to be practical and cheaper for rural areas (Dagnachew et al., 2017; Soumonni & Soumonni, 2011). Centralized and decentralized energy system modelling for Africa has gained increasing attention, but is always limited by the quality of available data, underlining the need for open-accessible datasets and critical model result interpretation. This includes data on existing and proposed renewable power plants that indicate the near-future implementation potential for each country, and data on renewable resource potential to determine each country's opportunities for long-term renewable power plant planning. Furthermore, openly-accessible and high-resolution data on electricity grids is crucial to compare centralized and decentralized connectivity options and forward the electricity access for all.

The transition to universal electricity access from sustainable RE resources promises potential gains in gross domestic product, employment, NDC achievements, and human welfare (IRENA, 2022d). Yet, to achieve “affordable, reliable, sustainable and modern energy for all” (SDG 7 (UN, 2015)), investments must more than double by the end of the century and multilateral development banks must make financial flows to Africa an absolute priority (IEA, 2022a). African countries have a lot of renewable power plants in the pipeline which form a solid foundation for an RE transition. It opens up opportunities for country-specific and explicit research on optimal pathways to plan an efficient mix of renewable power plants. Local research will be key to inform and guide the implementation of enabling national and continental policy frameworks, which will then fuel investment and ensure national benefits. This is crucial to guide a continental transition to 100% RE based efficient and equitable renewable electricity systems for all that considers future climate impacts and protects ecosystem functioning.

4.9. Acknowledgments

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5.

Towards a renewable electricity mix that avoids the increasing fragmentation of African rivers

5.1. Abstract

In Africa, mitigation of climate change in parallel to a growing population and developing economies requires a bold shift to renewable energy (RE) resources. Declining costs for solar photovoltaics (by 90% between 2009 and 2023) and wind turbines (by 57% between 2010 and 2023) fuelled their construction, and hybrid forms such as floating photovoltaics (FPV) on existing hydropower reservoirs are increasingly being explored. Nevertheless, 65% of the proposed RE capacity in Africa remains hydropower, despite confirmed ecological, socioeconomic, and political ramifications on different spatiotemporal scales. The 673 proposed hydropower plants (HPPs) would increasingly disturb river systems and threaten biodiversity hotspots. While literature suggests that an RE transition in Africa is, in general, technically feasible, it lacks spatially explicit studies on how this transition could be implemented. To address this gap, the aim of the present study is to explore options for an RE mix that avoids additional hydropower construction and, therefore, further river fragmentation. Attribute data of the open-accessible Renewable Power Plant Database (RePP Africa) was analysed to assess the amount of lost capacity due to operation stops. Geospatial analyses of solar irradiation data and existing reservoirs was used to derive the potential for FPV. The degree of possible replacement of future hydropower was assessed under consideration of economically feasible wind and solar photovoltaic (PV) potential. To enhance electricity generation from existing HPP, efficient and sustainable renewable power plant planning must integrate the risk of failure, as it has diminished the available capacity in the past up to 24%. Our findings further reveal that covering 40% of each of the existing hydropower reservoirs with FPV would provide 22,596 terawatt hours (TWh) in electricity generation which equals 41 times the electricity from proposed HPPs and three times the current continental electricity demand. All 36 African countries could replace proposed hydroelectricity generation by fully exploiting feasible onshore wind and solar PV potential with a mean surplus of 371 TWh per year. In summary, our findings provide scientific evidence to support policy discussions on the potential electricity gains from (1) minimizing plant failure, (2) installing FPV as a co-use option, and (3) exploiting wind and solar resources. This study provides quantitative, data-based, and spatially explicit scenarios on the implementation of an RE mix that could relieve the dam building pressure on African rivers.

5.2. Introduction

While population growth and growing economies outpace projections and drive a continuous expansion of power capacities in African countries (average real domestic product (GDP) of +4% in 2023 and 2024) (AfDB, 2023), climate change mitigation urges a bold shift to renewable energy (RE) resources. The need for this transition is accompanied by the goal to “ensure access to affordable, reliable, sustainable, and modern energy for all” (Sustainable Development Goal

(SDG) 7 (UN, 2015)) for almost half of the African population that currently lacks access. At state level, hydropower accounts for 83% of the total electricity production from renewables in African countries (150,428 of 187,260 GWh, 2020) (IEA, 2021b). It is broadly studied that hydropower plants (HPPs) operating with reservoir storage and dam can cause ecological, socioeconomic, and political ramifications on different spatiotemporal scales (Chapter 3) (Botelho et al., 2017). However, decisions on future dam locations are commonly driven by political constraints and engineering assessments (Y. Wang et al., 2021).

Environmental Impact Assessments (EIA) are a policy instrument to ensure that the environmental implications of a project are anticipated and minimized (Botelho et al., 2017). In many countries, EIAs are legally binding; but Erlewein found evidence for India highlighting that the implementation of EIAs can barely keep pace with the development of new hydropower projects (Erlewein, 2013). In addition, a major shortcoming of EIAs is the spatial level they cover: EIAs assess the HPP on a project level and often do not consider impacts on a regional, national or international scale. This is in particular problematic for HPPs operating with dam and reservoir because they gain energy by altering the entire flow dynamic of the river they depend on causing large scale and basin-wide impacts.

In Africa, proposed HPPs and other dam-related infrastructure increasingly disturb river systems and threaten biodiversity hotspots (Opperman et al., 2022). According to the Renewable Power Plant Database Africa (RePP Africa), 243 HPPs are proposed to operate with reservoir storage and dams and for a further 281 HPPs information on the type is not available; if all these hydropower dams were implemented, the total number would more than double (Peters et al., 2023). The fragmentation analysis in Chapter 3 reveals that 75% of the African river volume would be moderately to severely impacted if all these proposed HPPs were implemented. To that point, it is often overlooked that hydropower dams are not the only dam infrastructure. Dams and reservoirs are also built and used for irrigation, water supply, flood control, fisheries, and other purposes (Lehner, Liermann, et al., 2011). According to the Global Reservoir and Dam Database (GRanD), a total of 758 dams fragment African rivers, with 400 mainly intended for irrigation, 135 for water supply, 65 for hydroelectricity, four for flood control and one for recreational purposes (Lehner, Liermann, et al., 2011). For 147 dams and reservoirs the purpose is not specified (other or not indicated) (Lehner, Liermann, et al., 2011).

While additional hydropower dams would add to the existing river fragmentation and leave river basins such as the Nile (RFI 90%), Zambezi (RFI 87%), and Niger (RFI 90%) highly fragmented (Chapter 3), the most affected riparian countries are not always the countries benefitting from the additionally generated hydroelectricity (Figure 5.1). If the negative impacts outweigh the hydroelectricity benefits or if a country does not benefit at all, conflict is likely to arise between riparian countries. De Bruin et al. stated that under a business-as-usual scenario, 920 million people worldwide are projected to live in very high to high conflict-risk basins by 2050, with exacerbating risks in river basins of the Sahel, the Horn of Africa and parts of southern Africa (de Bruin et al., 2023). It underlines the need for long-term cooperation between riparian countries, but also the necessity for optimization of existing HPPs and careful large-scale assessments before building additional hydropower dams (Opperman et al., 2023).

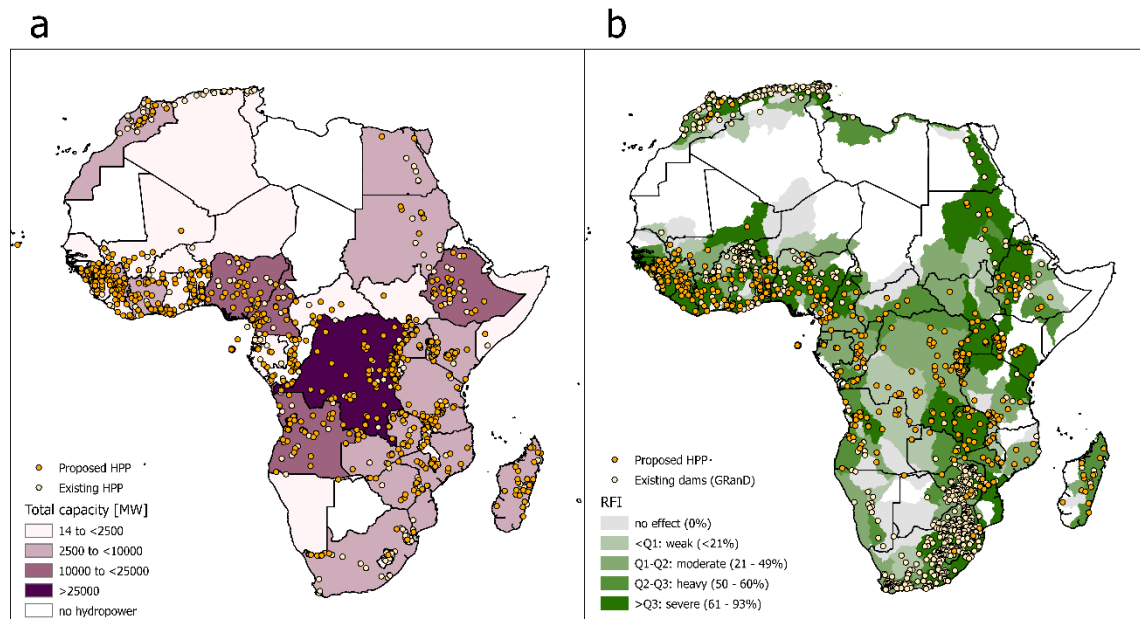


Figure 5.1: (a) Existing and proposed hydropower capacity [MW] in comparison (b) to river fragmentation per sub-basin from existing and proposed dams [%]. Data: (a): RePP Africa (Peters et al., 2023); (b): GRanD (Lehner, Liermann, et al., 2011), River discharge (Meng et al., 2020)

Acknowledging the need for renewable electricity but also the high degree of projected river fragmentation, investigation of possible alternatives and optimization of existing HPPs are possible pathways to relieve the overall pressure on rivers and reach a more sustainable renewable energy transition.

An optimized exploitation of installed hydroelectricity needs to assure that existing HPPs operate on their full potential. Few studies investigate how much electricity is generated by existing HPPs and which factors cause differences between effectively generated and nominal capacity. Wan et al. studied on a global level to which degree hydrological variability and number of operating plants have reduced generated capacity in the past; but results for the African continent were found to be unsatisfactory (Wan et al., 2021). To better assess the risk of plant failure in HPP operation and planning, research needs to provide evidence on how HPPs have performed in the past considering times of reduced capacity production and failure.

Addressing the search for alternatives, a first step is to exploit the complementary spatiotemporal properties of RE resources via hybrid plants. The combination of variable power from solar (SPP) and wind power plants (WPP) with storage capacity from existing HPP is increasingly explored to minimize the need for new energy storage and grid infrastructure (Shivarama Krishna & Sathish Kumar, 2015). One example is the co-use of a hydropower reservoir via floating photovoltaics (FPV) (Almeida, Schmitt, Grodsky, et al., 2022; Gonzalez Sanchez et al., 2021) which also prevents water loss from evaporation (Ates et al., 2020). This combined set-up works on average 11% more efficiently than ground installed solar panels due to the cooling effect of the underlying water and does not require additional land (Sahu et al., 2016). The latter is of particular interest when promoting solar photovoltaic (PV) development because it has been a strong counterargument that a solar PV plant installed on-ground occupies 19 m² per megawatt hour (MWh) while hydropower needs 14 m² per MWh and a nuclear plant only 0.3 m² per MWh (Ritchie, 2022).

Beyond the optimization and co-use of existing HPPs lies the opportunity to rethink proposed HPP infrastructure. During the past decade, the declining costs for solar PV (90% decline since 2009 (IRENA, 2022e)) and wind turbines (55-60% decline since 2010 (IRENA, 2022e)) have led

to increasing growth rates for SPP and WPP. Remaining renewable potential of >99% for both solar and wind power supports the assumption that several African countries could skip a phase of high fossil fuel dependency and transit directly to renewable based electricity systems.

To match the growing electricity demand with RE and build sustainable electricity systems, I hypothesize that aligning existing renewable power plants with the exploitation of non-hydro alternatives can optimize the RE system and reduce the pressure on (functioning) river systems. However, there is a lack of spatially explicit and integrated studies on how this transition could be implemented. Thus, the aims of this study were to estimate the potential of (1) minimizing plant failure and thus increasing the renewable electricity generation by maintaining and improving existing infrastructure, (2) co-using existing (hydropower) reservoirs by complementing them with FPV, and (3) replacing proposed HPPs with potential solar PV and onshore wind power sites. This study provides quantitative, data-based and spatially explicit insights on the status and projections for the implementation of a renewable energy mix that could relieve the dam building pressure on rivers in Africa.

5.3. Material and methods

The analytical procedure includes three analyses that answer the posed research questions (Figure 5.2). The database for each analysis forms HPP data from RePP Africa; Analyses 2 and 3 further use data from the Global Solar Atlas (WB, 2023) and the modelled supply regions for solar photovoltaic and onshore wind respectively (Sterl et al., 2022). While analysis 1 implements an in-depth analysis of RePP Africa attributes on historical operating times, analyses 2 and 3 use geospatial methods to analyse the different datasets.

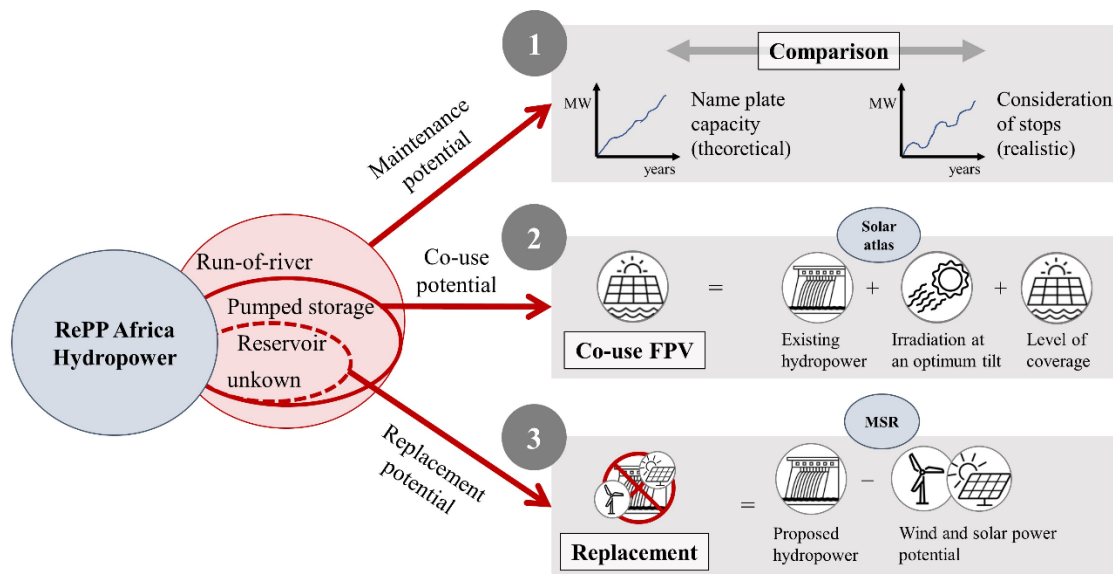


Figure 5.2: Methodological approach. The Renewable Power Plant Database (RePP Africa) forms the data basis for the three analyses. Red circles indicate which hydropower plant operating types are included in a certain analysis. 1. The maintenance potential compares the cumulated capacity of hydropower plants without (theoretical) and with (realistic) operation stops. 2. The co-use potential assesses how much capacity could be generated by installing floating photovoltaics (FPV) on existing reservoirs. The analysis includes data of the Global Solar Atlas (Solar atlas). 3. The replacement potential assesses how much proposed hydropower capacity could be replaced if onshore wind and solar photovoltaic are fully exploited. This analysis includes the modelled energy supply regions (MSR) which are technically and economically feasible areas for onshore wind or solar photovoltaic exploitation.

5.3.1. Data

For this study, data on existing and proposed HPPs was combined with areas that have been selected as potentially best candidates for solar and wind electricity generation. Both datasets

cover all 54 African countries including island states. HPP data was used from RePP Africa, a georeferenced database on existing and proposed hydro-, wind, and solar power plants (Figure 5.2) (Peters et al., 2023). It includes information on capacity [MW] and operational type. For the latter, it distinguishes between reservoir, pumped storage, run-of-river, and unknown. It further lists the year of first operation start, full operation start and operation stop. I used data on modelled energy supply regions from Sterl et al. to assess the economically feasible wind and solar power potential for the entire continent (Sterl et al., 2022). The regions include all areas where solar irradiation or wind speed, respectively, are high enough for commercial exploitation, but exclude areas of high population, high elevation, steep slope, certain categories of land use (e. g. forest areas, floodplains), protected areas, and areas with large distance from an existing road network. The selected sites were ranked according to their respective levelized cost of electricity and only the highest ranked included. The total area sum was calculated and compared to the individual country's surface area. If the total area sum exceeded 5% of the individual country's surface area, lower ranked areas were excluded. Among all African countries, 39 countries have data on 355 existing HPPs, 23 countries on 46 HPPs under construction, and 40 countries on 673 proposed HPPs. 43 countries were assessed to have feasible wind potential, and 49 to have feasible solar PV potential. In this study, the Sahrawi Arab Democratic Republic (Western Sahara) is geographically aggregated with Morocco due to technical reasons. No statements on the political situation are intended. If available and suitable, reservoir data of the Global Reservoir and Dam Database (GRanD) were used for FPV area estimates instead of digitalizing the reservoir manually (Lehner, Liermann, et al., 2011). In order to assess the FPV potential annual average data on the global tilted irradiation of the Global Solar Atlas was used (WB, 2023). The global radiation at an optimum tilt refers to total radiation received on a surface with defined tilt and azimuth and is provided with a spatial resolution of 9 arcsec (nominally 250m). The long-term yearly average of daily totals is calculated from time-series data of global horizontal irradiation, direct normal irradiation, and terrain horizon. The Global Solar Atlas was developed by Solargis under the funding of The World Bank Group (ESMAP, 2020).

5.3.2. Potential for electricity generation by reducing hydropower plant failure (maintenance potential)

I used RePP Africa attribute data on historic plant failure to analyse the amount of historic capacity reduction from hydropower operating stops (Peters et al., 2023). Times of reduced operation or complete stop were used as an indicator of having reduced the exploitation of the installed capacity in the past. HPPs of all types were included in this analysis to assure the largest possible sample size (Figure 5.2). Time and respective "loss" in generated electricity due to technical plant failure was calculated from 1903 to 2020. This includes information on the year of operational start, the year of operational start on full capacity, the year of operational stop, and information on current operational status (operational/not operational, census: 2022). Of the included 355 existing HPPs 29 are not operating. For 350 HPPs the year of operation start, for 53 the year of operating start on full capacity, and for 25 the year of operation stop is indicated. For the years before operation at full capacity, the full installed capacity was reduced to 50% because, according to RePP Africa, many HPPs start operating with half of their turbines active (Peters et al., 2023). Actual electricity generation was then compared to a potential electricity generation assuming that HPPs were operating at full capacity.

5.3.3. Potential for electricity generation by complementing existing hydropower reservoirs with floating photovoltaics (co-use potential)

To calculate the electricity that could possibly be produced by adding FPV to existing hydropower reservoirs, I compiled a dataset with the area information (geometry and size) of reservoirs that corresponds to the dam data points of RePP Africa (Peters et al., 2023). Therefore, all reservoir polygons from the GRanD database were selected that matched satellite images of Google Earth Pro version 7.3.6.9345 (Google Earth, 2023). All other reservoirs (not matching satellite images or not available in GRanD) were manually digitalized in Google Earth Pro. Of the 355 HPPs listed in RePP Africa, 129 HPPs classified as run-of-river plants were excluded. The 226 remaining HPPs operate either with a reservoir (type reservoir and pumped storage) or the type is unknown (Figure 5.2). Of these 226 HPP, 190 reservoirs spread over 35 countries were included in the analysis and further processed in ArcGIS Pro (ESRI, 2022). Data exclusion had the following, different motivations: Cases with conflicting information were excluded for further analysis, i.e. 13 HPPs had a different operating type than indicated in RePP Africa (run-of-river instead of reservoir or unknown). For 20 HPPs, reservoir digitalization was impossible, because no reservoir was found on Google Earth satellite images. From RePP Africa, seven data entries were excluded since they represent capacity updates to an existing reservoir. One power plant was excluded as it appeared twice in RePP Africa. For five HPPs of type pumped storage, two reservoirs were digitalized. I calculated the potential annual electricity production for existing reservoirs as follows:

$$EP_{FPV} = A_{Res} * r_A * GTI \quad (3)$$

Where EP_{FPV} is the annual electricity production [MWh], A_{Res} the total reservoir area [m^2], r_A the ratio of reservoir area covered by FPV (A_{FPV}/A_{Res} in [%] with A_{FPV} being the total reservoir area covered by FPV [m^2], and GTI the annual total of global tilted irradiation for the respective reservoir [kWh/m^2]. The global tilted irradiation is the maximum amount of solar radiation that can be received at the ground at the optimum angle (WB, 2023). Projected polygons of reservoir areas were converted taking the polygon centre of the reservoir as a point. In a next step, the corresponding value of the global tilted irradiation (GTI) was extracted at this location (resolution: 9 arcsec (nominally 250m)). A medium coverage of $r_A = 40\%$ was chosen to assess the area that could potentially be covered with FPV. I selected a 40% coverage, because literature suggests that up to a coverage of 40% effects on algal bloom and organisms remain neglectable or small (Pouran et al., 2022; T. Wang et al., 2022). I calculated the potential for replacing proposed hydropower capacity by exploiting FPV on existing HPP reservoirs as

$$Replacement\ potential\ [GWh] = FPV\ [GWh] - Proposed\ hydropower\ [GWh] \quad (4)$$

Where *Replacement* < 0 means that the exploitation of FPV could not cover the proposed hydroelectricity, and *Replacement* > 0 that the full FPV potential would exceed the generated electricity from proposed HPPs.

Sensitivity was tested by running two additional scenarios with a capacity of 20% and 60%. Results were compared to the scenario with a 40% coverage. In addition, results were compared to a scenario where 40% of non-hydropower plants on the African continent are covered with FPV. The analysis was run for 640 reservoirs from the GRanD database, which have hydropower neither as major nor as secondary purpose (Lehner, Reidy Liermann, et al., 2011).

5.3.4. Potential for electricity generation by solar and wind power replacing proposed hydropower plants (replacement potential)

The potential wind and solar electricity in gigawatt hours (GWh) given for the modelled electricity supply regions by Sterl et al. were cumulated for each country (Sterl et al., 2022). The modelled electricity supply regions are areas that are technically and economically feasible for onshore wind or solar photovoltaic exploitation. The identification of these regions includes the assessment of feasible areas based on a set of different indicators (solar irradiation or wind speed, population, elevation, slope, forest, protected areas, distance to existing road network). All areas are ranked according to their respective levelized cost of electricity and only the highest ranked included. In that regard, the total surface area of the included areas does not exceed 5% of the individual country's surface area.

In order to estimate the overall electricity generation of proposed hydropower plants the capacity values [MW] of 524 proposed HPPs with the operating type “reservoir” or “not known” were summed up by country (Figure 5.2). HPPs of these types are proposed in 37 African countries. Sao Tome and Principe was excluded, because the dataset on modelled supply regions does not cover the island state (Sterl et al., 2022). An average capacity factor of 55% was applied to estimate the total electricity [GWh] generated by country (IRENA, 2022c).

$$\text{Generation [GWh]} = \text{Power plant peak capacity [MW]} * \text{Capacity factor} * 8760 \text{ h} * 0.001 [\text{GW/MW}] \quad (1)$$

The replacement potential [GWh] was calculated as:

$$\text{Replacement potential [GWh]} = (\text{Solar potential [GWh]} + \text{Wind potential [GWh]}) - \text{Proposed hydropower [GWh]} \quad (2)$$

Where *Replacement* < 0 means that the exploitation of solar and wind potential could not cover the proposed hydroelectricity, and *Replacement* > 0 that the full exploitation of solar and wind potential would exceed the generated electricity from proposed HPPs.

5.4. Results

5.4.1. Potential for electricity generation by reducing hydropower plant failure (maintenance potential)

HPPs in Africa have experienced a reduction of their installed capacity due to varying reasons. From 1903, when the first HPP listed in RePP Africa started into operation, to 2020, 137.5 GW of the theoretically installed capacity was not operational due to dysfunctional or not installed turbines (Figure 5.3). The total losses varied from 1950 (total capacity of 0.6 GW) to 2020 (total capacity of 38 GW) between 1% (2020) and 24% (1968). The highest loss in terms of installed capacity was in 2011 and reached 4,178 MW. In 2022, a total of 29 HPPs is existing but not operating, accounting for overall losses of 489.8 MW. The reasons for a capacity reduction are described in the RePP Africa attributes and include project delay, cost-overruns, natural disasters that cause HPP damage, lack of maintenance, war damage, and other (Peters et al., 2023).

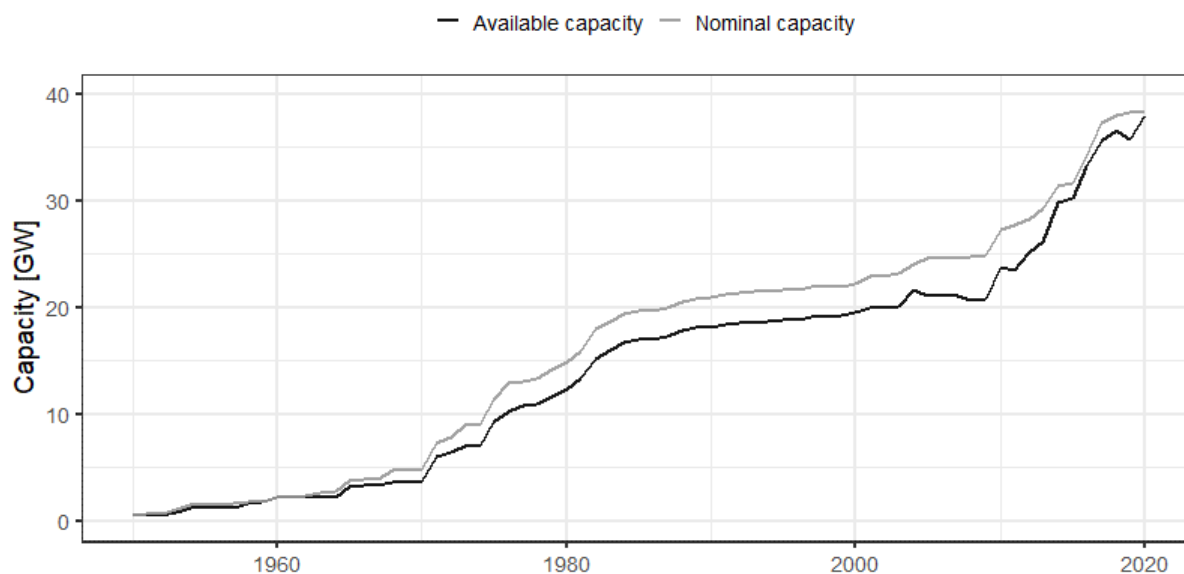


Figure 5. 3: Comparison of the total installed hydropower peak capacity (in GW; grey line) and the effectively available hydropower capacity (black line) in Africa from 1950 to 2020. Data: RePP Africa (Peters et al., 2023).

5.4.2. Potential for electricity generation by complementing existing hydropower reservoirs with floating photovoltaics (co-use potential)

Existing hydropower reservoirs cover 26 billion square meters in 34 African countries (Table C.1). Covering 40% of each reservoir with FPV would result in 10.5 billion m² of FPV area. This translates into a potential electricity generation of 22,596 terawatt hours (TWh) per year (Figure 5.4a) which equals 41 times the electricity generated from proposed HPPs and three times the annual electricity consumption of the entire continent (IEA, 2019).

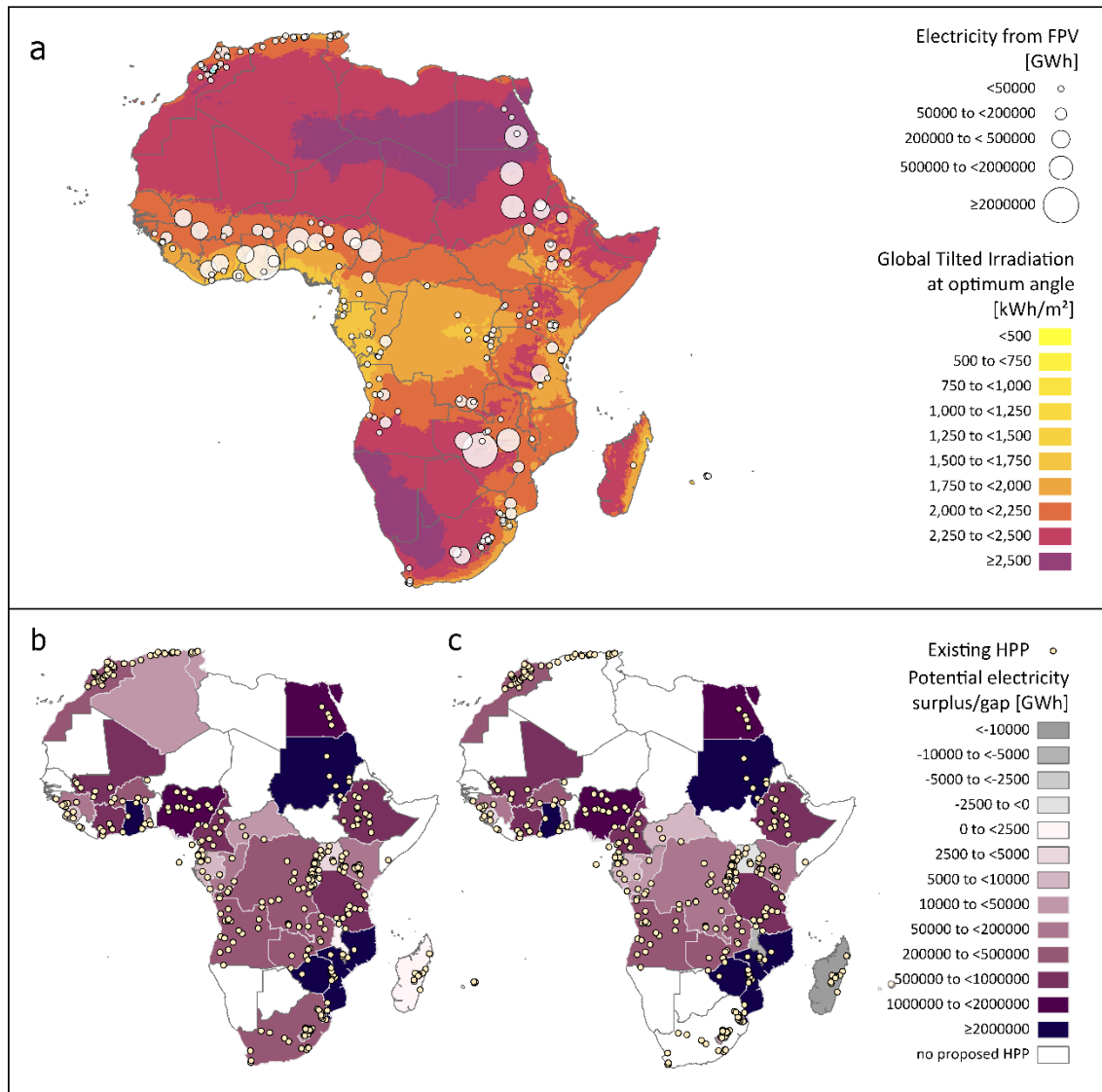


Figure 5.4: (a) Potential electricity produced from covering 40% of existing reservoirs with floating photovoltaics (FPV). Circles indicate existing hydropower reservoirs and increase with potential electricity generation [GWh] by complementing the reservoir with floating photovoltaics (FPV). The background map is coloured according to the annual global tilted irradiation at an optimum angle [kWh/m²]. **(b) Potential electricity from FPV per country.** Countries are coloured according to the total electricity [GWh] that could be produced per country if 40% of all hydropower reservoirs were fully covered with FPV. Colour intensity increases with potential electricity [GWh]; colour coding categories are similar to Figure 5.5. **(c) Potential electricity surplus or gap from comparing FPV with proposed hydropower capacity by country.** Pink colours indicate a surplus; grey colours indicate a shortage, both increasing with increasing colour intensity. Data: (a): RePP Africa (Peters et al., 2023), Global Solar Atlas (WB, 2023); (b), (c): RePP Africa (Peters et al., 2023), All-Africa dataset on energy model “supply regions” for solar PV and wind power (Sterl et al., 2022).

The total annual electricity gains per country vary between 20.45 GWh projected for Madagascar (12 existing HPPs with a total capacity of 21 MW) to 4,880,010 GWh predicted for Zimbabwe (13 existing HPPs with a total capacity of 142 MW; Figure 5.4b). The mean projected electricity gains are $664,556 \pm 1,184,455$ GWh. Thirty countries with existing FPV potential have a hydropower capacity expansion proposed (Table C.1). Except Madagascar, Malawi, Uganda, and Burundi, all the other 26 countries are capable to replace proposed hydropower capacity by exploiting electricity from FPV on existing reservoirs (Figure 5.4c).

I tested sensitivity by running scenarios for an FPV coverage of 20% and 60% respectively. Results showed a decrease of 50% in electricity gains if a coverage of 20% is applied (11,298 TWh in total), and an increase of 50% if a coverage of 60% is applied (33,895 TWh in total). The

mean total electricity outcome for a 20% coverage is 332,278±592,227 GWh, and for a 60% coverage 996,834±1,776,683 GWh. If a 20% coverage is applied, besides the above-mentioned countries also Rwanda and the Democratic Republic of Congo would not be capable to replace proposed hydropower capacity with FPV. If a 60% coverage is applied, the same countries as in the 40% analysis are capable to replace their proposed hydropower capacity, suggesting that this scenario would increase the overall continental electricity generation but not the share of countries with potential to entirely replace their hydropower capacity in pipeline.

The total reservoir area of the 640 non-hydropower reservoirs reaches with 5.6 billion m² only one fifth of the total area from hydropower reservoirs. Consequently, a 40% FPV coverage results in additional 4,850 TWh, which is equal to 21% of the FPV electricity potentially generated from hydropower reservoirs.

5.4.3. Potential for electricity generation by solar and wind power replacing proposed hydropower plants (replacement potential)

All 36 countries with proposed hydropower capacity can replace the electricity gains by exploiting solar and wind alternatives (Table 5.1, Figure 5.5). In Burundi, Gabon, Liberia, Rwanda, and Sierra Leone, where no potential for onshore wind is available, the exploitation of solar PV potential is more than sufficient to replace proposed hydropower capacity (Table C.2). Among all countries, the mean surplus of generated electricity after replacing proposed hydropower is 371 TWh per year (Table C.2).

Table 5.1: Statistical summaries for hydropower (projected reservoir areas), solar, and wind power (energy model supply regions for solar PV/onshore wind power). I assumed an average capacity factor for hydropower. For solar and wind power the mean capacity factor for the African continent was used. Annual values are indicated for electricity generation [TWh per year, MWh per year]. For national summaries please refer to Table C.2. Data: RePP Africa (Peters et al., 2023); All-Africa dataset on energy model “supply regions” for solar PV and wind power (Sterl et al., 2022).

	Projected hydropower	Solar power potential		Wind power potential	
		Total	HPP Countries	Total	HPP Countries
Area [1000 km ²]	46	1,488	1,040	1,151	703
Nominal capacity [GW]	115	4,911	3,431	3,384	2,068
Capacity factor [%]	55	19	19	44	40
Annual electricity generation [TWh]	552	8,476	5,882	13,504	8,046
Land use [m ² /MWh]	83	175	177	85	87
Land use [MWh/m ²]	0.012	0.006	0.006	0.012	0.011

The total surplus is 21 thousand TWh. The smallest surplus would be generated by Burundi (3.2 TWh, Table C.2), the largest by Sudan (1,835 TWh). Projected reservoirs of proposed HPPs would inundate a total area of 46,389 square kilometres (km²) (Chapter 3.4.1). Exploiting the total area feasible for solar PV and onshore wind power in countries with proposed hydropower would require 1743 thousand km², which is 38 times the area required for the projected reservoir areas; yet, projected areas for onshore wind and solar PV include unsealed areas under solar panels and between wind turbines, which is in contrast to hydropower reservoirs. Reservoir inundation alters the entire project area. Exploiting area feasible for wind and solar power instead would produce 25 times the electricity generated from proposed HPPs (14,294 TWh). Using an equal area (summed up total) of the projected reservoir area for solar PV would provide for around 50% of the electricity generated from hydropower (276 TWh); while covering an area of the same size with wind power could even replace the entire proposed hydroelectricity (552 TWh). It should be

noted that these summaries are based on continental averages and do not reflect the national differences in available solar PV and onshore wind potential (Figure 5.5c, 5.5d). While solar PV potential is nationwide available at comparable levels (capacity factor 19.07 ± 1.36), onshore wind potential differs strongly between countries (capacity factor 44.28 ± 7.52).

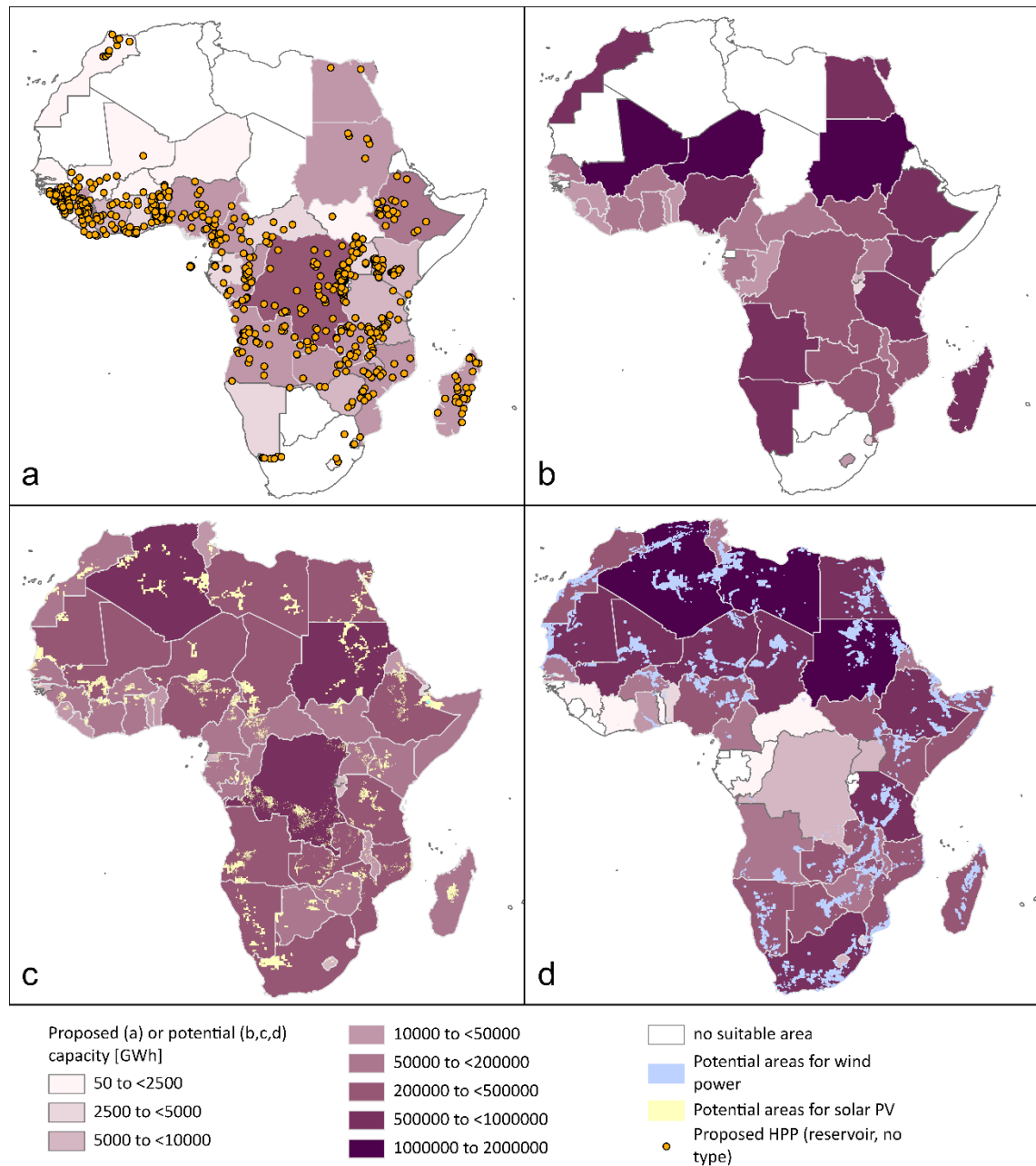


Figure 5.5: (a) Electricity produced by proposed hydropower plants operating with reservoir storage assuming an average capacity factor for Africa (0.55). Countries are coloured according to the total electricity per country that proposed hydropower plants would generate. Colour intensity increases with capacity [GWh] and categories are the same for a, b, c, and d. **(b) Surplus of potential electricity generation [GWh] by the estimated solar PV and wind potential considering that all proposed hydropower plants operating with dam and reservoir were replaced by solar PV and wind power.** **(c) Potential electricity [GWh] from solar PV and (d) wind power.** Countries are coloured according to the total electricity [GWh] that would be produced per country if all potential “supply regions” were fully exploited. Data: (a): RePP Africa (Peters et al., 2023); (c), (d): All-Africa dataset on energy model “supply regions” for solar PV and wind power (Sterl et al., 2022).

5.5. Discussion

The analysis of the RePP Africa database regarding hydropower capacity reduction reveals that HPPs have experienced pronounced losses with up to 4 GW in 2011 (Peters et al., 2023). That is more than each of the 39 countries with existing hydropower capacity has currently installed, except Angola. Causes diminishing the available hydropower capacity are natural (e. g. reservoir sedimentation due to increased soil erosion from land use and climate change in semi-arid east Africa (Amasi et al., 2021)), technical (turbine failure caused by cavitation, erosion, fatigue, or material failure (Dorji & Ghomashchi, 2014)), political (political conflict (de Bruin et al., 2023; del Bene et al., 2018), or destruction from war (Tiepoh, 1992)). A management aiming for efficient hydropower operation must identify and anticipate these risk factors and include them in long-term strategies to maximize the available hydropower capacity (Shaktawat & Vadhera, 2021). In addition, plant-level management must inform large-scale river basin management to fully account for risks caused by the operation of multiple hydropower dams in a connected river network (Opperman et al., 2023). To that point, risk assessment and failure avoidance should not only be aimed for future hydropower development but also for existing hydropower: policy regulations must assure that existing infrastructure is repaired and fully functioning before new hydropower dams are commissioned. Therefore, costs of proposed hydropower should not only include material costs but also weighed against the long-term environmental costs of increasingly fragmented river systems (Moran et al., 2018).

Moran et al. summarized that hydropower could only be part of a sustainable future if it moved from dam only to in-stream turbine and run-of-river technologies; in addition, the integration of volatile wind and solar power into dispatchable hydropower systems would play an increasingly important role in the 21st century (Moran et al., 2018). Building on that outlook, the findings prove that covering 40% of each existing hydropower reservoir with FPV would provide 41 times the electricity from proposed hydropower capacity. In addition, FPV exploitation could cover three times the current electricity demand of the entire continent, supporting findings from Almeida et al. who state that covering 10% of the world's hydropower reservoirs with floating PV would install as much capacity as currently available from fossil fuel power plants (Almeida, Schmitt, Grodsky, et al., 2022). Thirty-one of 35 countries could fully replace proposed hydropower by exploiting electricity from their reservoirs. Despite the FPV analysis being only a proxy as it does not include losses due to spacing, system performance, and solar clipping, it confirms the huge potential for FPV in Africa which has been proven by other studies (Almeida, Schmitt, Grodsky, et al., 2022; Gonzalez Sanchez et al., 2021). FPV are still more cost-intensive than stand-alone systems and licensing requires time and efforts (Essak & Ghosh, 2022). However, a major advantage of installing FPV on hydropower reservoirs is that electricity generation can be granted without further river damming and grid infrastructure.

Singh et al. reported in their recent study on the 63.5 MW Maithon HPP in India that FPV is more effective than land-based solar photovoltaic while saving water (0.0635 million m³) and at lower costs than current electricity supply (US\$ 0.024 per Watt less) (Singh et al., 2023). Jin et al. further highlighted that 106±1 cubic kilometres of annual water loss from evaporation could be avoided when covering 30% of reservoirs with FPV (Jin et al., 2023). Considering that most African countries are increasingly affected by drought (van Vliet et al., 2016) and in particular central Africa increasingly vulnerable to cope with drought impact (Ahmadalipour & Moradkhani, 2018), FPV installation would not only improve electricity generation but also save water loss from reservoirs. In that regard it has been reported that even a coverage of 1% could save about 743 million cubic metres of water annually (Gonzalez Sanchez et al., 2021).

While Jin et al. considered reservoirs of all kinds, the present study focusses on hydropower reservoirs because these locations have the advantage of an available electricity grid that reduces costs and impacts of grid infrastructure implementation (Jin et al., 2023). I tested the additional outcome by calculating the total electricity production from a 40% coverage on non-hydropower reservoirs. Therefore, I selected 641 reservoirs from the GRanD database without hydropower as major or co-purpose (Lehner, Reidy Liermann, et al., 2011). The total area of these reservoirs was, despite the huge number of projects only 20% of the total hydropower reservoir area. Compared to the FPV electricity generated on hydropower reservoirs, non-hydropower reservoirs provide a rather small electricity gain due to their smaller reservoir sizes. In addition, changing water levels that are for example part of water supply management can be a technical barrier for FPV installation and operation.

While hydropower reservoirs appear as an adequate choice for FPV expansion, there is a need for in-depth analyses on the optimum degree of coverage. It yet lacks scientific concern on how much reservoir area should be covered: It has been reported that shading decreases water temperature and incoming sunlight, which reduces photosynthesis and oxygen production and thus impacts food webs and seasonal water circulation (Haas et al., 2020; Sahu et al., 2016). Our results indicate that even a low coverage below the investigated 40% will remarkably increase electricity production while avoiding large infrastructure.

Optimization of existing HPP and exploitation of floating solar PV are not for all African countries an option to replace announced hydropower capacity. In addition, a lack of knowledge on the effects of FPV on reservoir dynamics discourages the covering of all hydropower reservoirs with 40% FPV without further environmental and economic assessments. The exploitation of feasible onshore wind and solar PV potentials would avoid proposed river fragmentation while preserving protected areas and assuring a certain vicinity to the existing road network. Wind and solar power also alter the natural dynamics of the physical resource they generate electricity from, but not the entire available wind or incoming sunlight. Solar PV converts around 20% of solar radiation and reflects the rest in form of thermal radiation or heat. This affects the radiation budget, but more research is required to fully understand, assess, and confirm large-scale effects (Stern et al., 2020). Confirmed are the small and medium scale effects of solar PV and CSP on land use and protected areas (Hernandez et al., 2015) (Figure 6.6b). Wind power plants generate electricity by removing kinetic energy from the atmosphere, which is why large wind parks can cause wind speed reductions, limiting the exploitable energy (Miller & Kleidon, 2016). However, this effect mainly applies to surface wind and can be reduced with adequate planning. Other effects of wind power are restricted to the small scale (habitat loss (Hamed & Alshare, 2022; Loss et al., 2019; Millon et al., 2018; Popescu et al., 2020), noise pollution (van Kamp & van den Berg, 2018), perception of visual impact (McKenna et al., 2021; Peri & Tal, 2021)) up to the medium scale (bird migratory routes (Marques et al., 2020), Figure 5.6c).

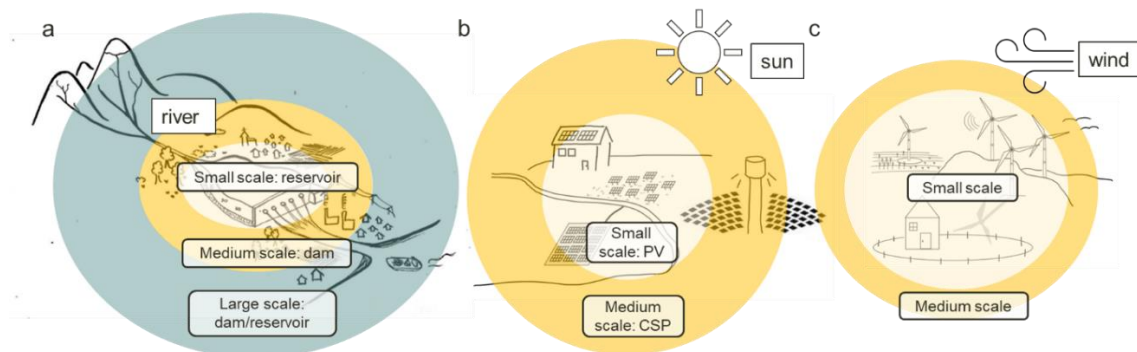


Figure 5.6: Renewable power plants impact the physical dynamics of the resource they depend on. Hydropower plants operating with a dam and reservoir cause effects on small, medium, and large scale (5.6a). Solar (5.6b) and wind power plants (5.6c) do not alter the entire dynamic of the resource they depend on and mainly cause small and medium scale effects.

Consequently, and according to current knowledge, solar and wind power infrastructure does not cause large-scale effects that are comparable to the downstream alterations caused by an HPP that operates with a dam and reservoir. As an example, a river's sediment supply is trapped behind dams which potentially leads to a degradation of heavily populated deltas, such as the Mekong (Almeida, Schmitt, Castelletti, et al., 2022). Still, onshore wind and solar PV require more land per megawatt generated than hydropower, but in particular in African countries both renewable types will be less impacted by climate change and could be integrated with other land use forms to create co-benefits, e. g. in the agricultural sector (Choi et al., 2021). Including climate change and socioeconomic pathway scenarios, Carlino et al. concluded that HPP construction will not be economically attractive beyond 2030 in sub-Saharan Africa (Carlino et al., 2023). That paves the path for onshore wind and in particular solar power plant implementation, not only PV but also in form of concentrated solar power, and can also stimulate further innovation in both fields. Finally, the fact that hydropower plant construction is likely to be economically unattractive for many African countries in the future underlines the need for transnational renewable energy management as potential areas of high onshore wind and solar potential often do not overlap with areas where high shares of hydropower capacity are proposed (Carlino et al., 2023; Sterl et al., 2022).

Driven by the need for climate-change mitigation and renewable energy supply, hydropower continues to be the RE technology of choice not only in African countries (IEA, 2021b). The negative impacts related to hydropower dam and reservoir development have been scientifically reported and discussed in depth (Botelho et al., 2017; Schulz & Adams, 2019). Attempts to engage a more sustainable hydropower plant development manifest in the hydropower sustainability assessment protocol (HSAP) from 2010 or in the newly adopted hydropower sustainability standard from 2021, a global certification scheme and the first of its kind for RE projects (IHA, 2010, 2021b). However, HSAP as voluntary and non-binding auditing tool was strongly criticized by the non-governmental organization International Rivers as attempt to greenwash hydropower dams (International Rivers, 2013). As the debate continues and legally binding environmental impact assessments still fail to fully account for large-scale effects of numerous hydropower dams on river dynamics, the results of this study contribute to the potential optimization of existing infrastructure and alternatives.

5.6. Conclusion

The implementation of all 524 proposed HPPs operating with a dam and reservoir would more than double the number of existing ones, causing a moderate to severe fragmentation of 75% of

the entire African river volume. As costs for solar and wind power decline continuously while climate change threatens hydroelectricity generation, Carlino et al. project that hardly any new hydropower will be built in sub-Saharan Africa after 2030 (Carlino et al., 2023). Still, due to its dispatchable nature, existing hydropower will remain important to integrate variable wind and solar resources and simultaneously provide a stable renewable electricity grid (Moran et al., 2018). Science-based discussions are required to guide the path towards a renewable electricity mix that releases the dam-building pressure on African rivers. Based on the evidence provided by this study, I suggest the following recommendations:

- The capacity of existing HPP infrastructure needs to be optimized as times of reduced operation and failure have diminished the available capacity in the past. If feasible, complementary use via hybrid renewable technology should be implemented to maximize renewable electricity generation without further land-use changes.
- Policy makers should acknowledge the negative impacts of hydropower and assure a fully sustainable renewable energy transition by avoiding river fragmentation wherever possible. Therefore, the development of large-scale and basin-wide power plant assessment protocols could allow a weighing of hydropower impacts against wind and solar power impacts, including positive impacts of a potential agricultural co-use within solar and wind farms. When ranking RE power plants based on integrated impact assessments it is necessary to acknowledge that a ranking might change depending on included impact indicators.
- Replacing proposed hydropower capacity with onshore wind and solar PV is technically feasible on the African continent. Based on our findings and other scientific evidence national and international policy frameworks must set the course for reconsidering hydropower as a renewable energy solution that is not per-se sustainable, and should point out alternatives.

In this regard many African countries have the potential to lead the implementation of sustainable renewable electricity systems and skip a phase of high fossil fuel dependency while protecting rivers.

6.

Discussion and conclusion

The data-based scientific evidence compiled and discussed in this thesis can support discussions on achieving a sustainable renewable energy transition in Africa. The potential for avoiding a phase of fossil-fuel dependency is more pronounced in African countries than elsewhere. However, the lack of available data and scenario analyses hinders a sustainable development that can equally consider the ecological, economic, and social dimension. The thesis concludes that renewable-energy generation and the conservation of ecosystems need to be integrated at a large scale and in long-term planning strategies to promote sustainable development at a systems scale. The following discussion connects the findings of the four previous chapters and puts them into a broader context. I discuss the use of georeferenced power plant data in scenario modelling as a transferable methodological concept and outline the advantages of large-scale spatial analyses to assess both the impact of and the potential for renewable electricity development (Chapter 6.1). I next outline the socioeconomic opportunities for and challenges of a renewable energy transition in Africa (Chapter 6.2). I then discuss existing approaches for integrating renewable electricity generation and river conservation to forward a comprehensive sustainable development (Chapter 6.3). Finally, I identify and summarize implications for future research needs and science-informed policy making (Chapter 6.4).

The key research findings of the present thesis answer the posed research questions (Chapter 1.5):

- (1) The Renewable Power Plant Database (RePP) Africa database compiles a total number of 1074 hydro-, 1128 solar, and 276 wind power plant records (Chapter 2). As of November 2022, 355 hydro-, 361 solar, and 119 wind power plants exist, a further 46 hydro, 50 solar, and 8 wind power plants are under construction, and another 673 hydro-, 717 solar, and 149 wind power plants are proposed. The number of RePP Africa records exceeds the respective values in other open-access databases and matches the available cumulative capacity data reported by international energy organizations best with deviations <13% for hydro-, <23% for wind, and <32% for solar power plants (Chapter 2, Table 2.4).
- (2) By integrating the impact indicators for river regulation, fragmentation, potential evaporation, resettlement, protected area loss, land-use change, sediment entrapment, and affected megafauna, a total of 104 HPPs were assessed to cause severe impact (Chapter 3). If all 507 proposed hydropower plants included in the assessment were to fully operate with dam and reservoir storage, 46,389 km² of terrestrial surface could potentially be flooded. A resulting river regulation of up to 1,226% and a river fragmentation of up to 92% were assessed. Projected reservoirs would flood 13,039 km² of cropland. Some 4.9 million people currently living in potentially flooded areas would need to be resettled. A sum of 168 projected reservoirs would affect a total of 297 protected areas. The projected inundated reservoir area would potentially cause an additional evaporation of 6 km³ of water per year; an increase of 12% over the present evaporation from existing reservoirs and lakes. Up to 11 freshwater megafauna species would potentially be affected by proposed dam construction. Without management activities such as sediment flushing, a total of 2 billion tons of sediment would be trapped behind dam walls annually, which would reduce the lifetimes of the HPPs to up to one year.

- (3) Based on a quantitative analysis of georeferenced data for all 54 African countries on existing and proposed renewable power plants, 76% of Africa's electricity needs projected for 2040 could be met by RE, with a remaining technical potential of >99% each for wind and solar PV, and 51% for hydropower (Chapter 4). Assuming the current national annual per capita electricity consumption and projected population growth, 28 countries have already sufficient capacity in the pipeline to meet the future demand from renewable sources. Efficiently combining the advantages of hydropower with the exploitation of wind and solar potential will be a more sustainable alternative to hydropower-plant construction alone.
- (4) Building on the latter, Chapter 5 reveals that the maintenance of existing hydropower infrastructure, the combination of existing hydropower with floating photovoltaics (FPV), and the replacement of proposed hydropower with solar and wind power, are effective strategies to reduce the need for hydropower expansion. Maintenance failures have diminished the available capacity in the past by up to 24%. The findings further revealed that a 40% FPV coverage of each existing hydropower plant's reservoir surface would provide 22,596 TWh in electricity generation, which equals 41 times the electricity from the proposed HPPs. All 36 African countries covered could replace proposed hydroelectricity generation by fully exploiting feasible onshore wind and solar PV potential with a mean surplus of 371 TWh per year. However, solar PV and onshore wind require more space per megawatt generated (Chapter 5, Table 5.1).

The gained knowledge is primarily relevant for African countries where scientific information at a high resolution remains scarce or restricted to specific regions (Mulugetta et al., 2022; Oyewo et al., 2023). However, other countries in the Global South and North might also benefit from insights on how integrating renewable energy planning and river conservation are crucial to sustainably up-scale renewable electricity generation.

6.1. Methodological approach

6.1.1. Georeferenced power plant data as an indicator for future development scenarios

RePP Africa was compiled as a comprehensive database that provides open-accessible and harmonized data on the three main renewable electricity technologies, hydro-, solar, and wind power (Peters et al., 2023). Hydropower data was used to assess the future impact of proposed dams and reservoirs (Chapter 3). Data on all three technology types was used to analyse each country's state of the art in face of a renewable energy transition. Data on proposed plants including the projection of future reservoirs (Chapter 3) is subject to uncertainty which is true for projections of any kind. Even if a feasibility study has been carried out, power plant development plans can be cancelled due to economic, political, or other unforeseen reasons. In addition, the year in which operations commenced is – even if indicated – highly uncertain. This concern was addressed during the compilation process of RePP Africa by applying strict revision criteria. We reduced uncertainty in the underlying data by neglecting the highly uncertain share of small power plants (<1MW), by referring to at least two references for each database entry, and by crosschecking the database multiple times before final submission.

Despite the intrinsic uncertainty, working with georeferenced data is key to considering specific environmental alterations at all spatial scales. While most national regulations impose companies to realize environmental impact assessments, the synergistic or additive impacts of hydropower dams on natural river systems are not addressed. In that regard georeferenced data at high spatial resolution can advance the scientific understanding of how proposed infrastructure will alter the

environment locally and on a larger scale, that is, in case of a connected river system, information on how local dam construction causes system-scale alterations through natural interdependencies. The number and location of proposed HPPs give a more realistic insight on the degree of future alteration than estimates of theoretical or practical potential, which are often nationally aggregated. Using georeferenced data on existing and proposed power plants is a frequently applied approach in scenario modelling and has been used to analyse potential dam filling, future electricity supply, transboundary river conflict risk, and local economy development (Alova et al., 2021; de Bruin et al., 2023; Fan et al., 2022; Zaniolo et al., 2021).

6.1.2. Integrated large-scale spatial analysis to assess renewable power plant impact and potential

The spatial analyses implemented in the present thesis are based on actual power plant data for the entire African continent. The thesis provides improved (i.e. more specific) insights on renewable power-plant trajectories, and contributes to an improved understanding of their effects on ecosystems and society. The advantage of considering a continental approach is that both, the impacts of and the potentials for renewable power plant development can be missed in assessments restricted to countries or catchments (Opperman et al., 2023). Current renewable energy development is mostly planned within national contexts, owing to the restricted legal competence of international organizations. Efforts to advance a more integrative planning exist for hydropower: river basin organization are a policy instrument to assure management of water uses at the system scale and forward planning at watershed level. Yet, historic development has shown that national interests tend to promote the expansion of hydropower rather than finding more ecologically and socially acceptable alternatives (Dombrowsky & Hensengerth, 2018; Jager et al., 2015).

Taking a continental perspective, this thesis assesses the variety of ecological, socioeconomic, and political effects of proposed hydropower development (Chapter 3). By aggregating and ranking hydropower plants at the continental but also at the river basin-scale, the chapter provides insights on the projected consequences of currently proposed hydropower plants. It is important to note that the sensitivity analysis revealed the interdependence of ranking and included indicators. Indicator selection in real-life scenarios is likely to be influenced by local power dynamics, which makes the implemented scientific analysis at large-scale an important supplement to discussions on the expansion of hydropower (Dombrowsky & Hensengerth, 2018; Jager et al., 2015).

Implementing large-scale analyses while assuring data of high resolution is not always possible. The usage of actual power-plant data aims to provide more realistic scenarios and enhance resolution. However, the future electricity production assessed in Chapter 4 takes average capacity factors for all three renewable types which is a transparent and reproducible approach but lacks accuracy. In-depth power modelling including seasonality and efficiency losses could provide more precise results, but was beyond the scope of this thesis.

In summary, taking a continental perspective on sustainable renewable electricity planning has a major advantage: if a country's renewable power capacity is not sufficient to meet future demand, other countries can step in (Chapters 4 and 5). In addition, countries without sufficient wind, solar, and floating PV potential can benefit from renewable power surpluses generated in neighbouring countries. With respect to the methodological approach, ongoing research efforts must improve the resolution when working at these scales. Scientific evidence from large-scale spatial analyses will continue to support discussions on alternative pathways and address the opportunities of international cooperation.

6.2. Challenges to and opportunities for a renewable energy transition in Africa

The majority of African countries have the potential to avoid a phase of fossil-fuel dependency and build electricity systems that are both renewable and ecologically, socially, and economically sustainable. To achieve the African Union's vision of "modern, efficient, reliable, cost-effective, renewable and environmentally friendly energy to all African households, businesses, industries and institutions", clear context-specific pathways are required (African Union, 2015). Sub-Saharan Africa is at the forefront of renewable energy uptake but also faces the challenge to tackle the lack of electricity access (World Economic Forum, 2023). Poor institutional frameworks and infrastructure, high initial capital costs, weak dissemination strategies, a lack of skilled manpower, poor baseline information and weak maintenance services slow down the development of renewable electricity plants (Ouedraogo, 2019).

The present thesis outlines which countries under current access rates have enough renewable capacity in the pipeline to respond to their future electricity demand (Chapter 4). Chapter 5 analyses the available options to avoid the further development of hydropower and forward a more comprehensive sustainable renewable energy transition. A remaining challenge that is beyond the scope of this work is the economic dimension. Renewables are disadvantaged by today's financial practices in Africa (Sweerts et al., 2019). Despite a high renewable resource potential, renewable power plants need a high initial investment. In contrast to fossil fuels where the capital costs are spread over a longer period of time, renewable power plants require large investments in the beginning. In addition, electricity from variable resources such as wind and solar power is associated with a higher uncertainty in production which increases the overall investment risk (Tietjen et al., 2016).

To safeguard a cost-efficient renewable energy transition, countries have to adapt their financial practices. These vary widely within the continent. The costs of capital must be de-risked and reduced, financial flows must be mobilized, and electricity grids must be capable to take up high variable resource penetration to prevent hidden costs along the way (Sterl et al., 2023). A comparison of the weighted average costs of capital for gas and solar PV demonstrates the national differences. While in Namibia, the average capital costs for renewable solar PV technology undercut the capital costs for gas, the situation is the other way around for Ethiopia, Ghana, and Algeria (Sterl et al., 2023).

Another economic challenge jeopardizing an RE transition in Africa is that the global vision of clean and renewable electricity systems will decrease the worldwide demand for African oil and gas. This may negatively affect local investment in renewable technologies (Evans, 2023). In that regard, it has been proposed that in some African regions natural gas is a candidate fuel to support the gradual decarbonization of the energy system, because an immediate abandonment of natural gas is likely to inhibit investment flows and widen poverty gaps (Bugaje et al., 2022). Another study outlined that the high potential for solar PV in Egypt and the high potential for wind power in South Africa could pave the path for decarbonizing the electricity system of these highly electrified countries (Doorga et al., 2022). Solutions need to be adapted to local circumstances and investigate how the worldwide decreasing demand in African fossil fuels can be handled to build stable and growth-promoting local economies.

Adding on the need for a contextualized renewable energy transition that promotes growth, different sectors require solutions that fit their requirements. In Africa, household cooking and transportation rely mainly on burning biomass and diesel fuel. If these sectors are continuously

electrified, the demand for renewable energy will grow. The World Resource Institute analyses that fossil fuels will play a near-to-medium-term role in cooking, transportation and industry (Sterl et al., 2023). Yet, the need to electrify these sectors and the resulting electricity demands need to be considered in long-term strategic planning. In that regard, hydrogen gas has received increasing attention to decarbonize the heavy transport and industrial sectors without having to fully electrify them (Barasa et al., 2018; Sterl, 2021b).

The need for connecting people to an electricity grid is more pronounced in most African countries than elsewhere. The expansion of electricity grids in particular to rural areas is cost intensive (Bos et al., 2018). Electricity grids that do not exist or that have low inertia can cause unexpected costs in renewable electricity development. The planning of renewable power plants must integrate investment in grid connections to ensure access to and the distribution of renewable electricity (Sanoh et al., 2014). Package deals that oblige the implementers of renewable power plants to also extend the grid are an option for integrative and cost-efficient planning.

The potential for renewable electricity is large with many hydro-, solar, and wind power projects in the pipeline (Chapter 2). Despite the economic challenges that accompany a renewable energy transition, the diversity of the African continent offers opportunities to promote the renewable energy transition. Transnational cooperation in renewable energy planning can avoid conflict, decrease the development risks of renewable power plants, and favour investment flows (Muoneke et al., 2023). It further offers opportunities to share electricity across borders and exploit renewable potential where it is feasible (Chapters 4, 5). The five regional power pools are collaborative initiatives that have been established to manage and develop cross-border electricity networks, infrastructure, and power-generation resources. Yet, they are also subject to electricity losses and vulnerable to fraud, which has been reported for the West African Power Pool (INTEC, 2021).

Consequently, building electricity development on the transnational power-pool development alone should not be the pathway to follow for establishing an equitable electricity supply. As stated above, the development of electricity grids is as important as power plant development and has to be developed complementarily, in particular in urban settings where population density and access deficit are high. However, providing connections via grid expansion to people that live in rural areas is often economically not feasible. In that context, off-grid or mini-grid solutions might serve as the better option (Ortega-Arriaga et al., 2021).

Transnational cooperation is key to exploit available resource potential, expand electricity grids, and share capacity across borders. International visions and frame-works can point out future directions; however, the legal course is set at a national level. A review that analysed renewable energy policies and transition in 34 African countries could identify only a few examples where national policies promote a just renewable energy transition (Müller et al., 2020). For example, Morocco and Algeria were identified as strongly reliant on a market focus with a negligible justice dimension, due to an unshaken trust in trickle-down effects. In contrast, Burkina Faso, Gambia, Mali, and Malawi have implemented promising policies that consider recognitional or distributional justice and could be mainstreamed and fostered by comprehensive policy frameworks (Müller et al., 2020).

6.3. Integrating renewable electricity generation and river conservation

Africa is highly dependent on hydropower, which is the major power source in 18 African countries (Good, 2023). Except for Kenya, where geothermal energy is the dominant power source, hydropower is the leading renewable energy technology across the continent (Good, 2023). While a large number of hydropower plants are proposed throughout the continent, environmental concerns advise against unconstrained dam construction and reservoir inundation (Chapter 3). Wind and solar are exploitable supplements or alternatives that could replace the proposed hydropower capacity (Chapter 5). Yet, a wide range of ecological, socioeconomic, and political interests have to be addressed when proposing realistic pathways to sustainable renewable energy development.

One approach to address environmental concerns while forwarding hydropower development is the implementation of impact assessments. Environmental impact assessments are a policy instrument to assess the implications of dam construction and reservoir inundation on ecosystems and society (Morgan, 2012). Yet, commissioning such assessments is most of the times the responsibility to project developers, which results in a lack in transparency and restricts the assessment to an individual project. Global attempts to implement guiding systems are manifested by the Hydropower Sustainability Standard, a certification scheme that has the aim to ensure net benefits to local communities and ecosystems (IHA, 2021b).

Science and environmental organizations have criticized current systems guiding impact assessment because they fall short on the integration of long-term and large-scale impacts (International Rivers, 2013; Moran et al., 2018; Opperman et al., 2023). Because rivers are connected systems, individual impact assessment will always fail to comprehensively assess an HPP's large-scale and long-term consequences (Chapter 3). To better integrate systems-scale HPP impacts, it has been proposed to use network approaches to evaluate multiple post-dam environmental stressors and track energy flows for a more comprehensive science-based discussion (Chen et al., 2015). It has been further suggested to move from individual assessments of hydropower projects to integrative energy system planning, with case studies from Chile and Uganda proving the economic feasibility (Opperman et al., 2023).

While hydropower development expands globally regardless of attempts to draw attention to its negative effects, the consequences of historic river damming are measurable at a global scale. Only 23% of rivers longer than 1,000 kilometres remain free-flowing, and these are restricted to remote regions such as large parts of the Congo basin (Grill et al., 2019). The loss of connectivity contributes to the global biodiversity crisis and jeopardizes important ecosystem services (He et al., 2017; Jones & Bull, 2020). To protect the last free-flowing rivers worldwide requires not only a minimization of HPP trade-offs but also corridors of strict environmental protection, where ecosystems are comprehensively protected against anthropogenic development pressures. Standardized impact assessments can support the mitigation of negative consequences caused by proposed infrastructure, but it is beyond their scope to safeguard corridors of strict conservation.

In Europe, the Natura 2000 network of nature conservation areas is subject to strict legal protection and hinders countries to pursue the unconstrained development of power plants to reach their energy and emission reduction targets (Jackson, 2011). Still, conservation areas such as Natura 2000 are bounded by terrestrial borders and do normally not include entire river systems. Fully protecting (free-flowing) rivers requires a range of additional mechanisms that are not limited to protected-area boundaries, and that consider a river's connectivity, water quality, and

biota (Higgins et al., 2021; Opperman et al., 2021). The reclamation of the Vjosa river as the first Wild River National Park in Europe was a legal innovation in current environmental protection frameworks (Störbrock, 2023). Further examples to protect rivers as systems are approaches that acknowledge rivers as legal entities. A successful example is the Whanganui river in New Zealand, which gained legal status through the engagement of the Maori people (Sheber, 2020).

Such examples for conservation at river system scale remain scarce because human population growth and economic development drive the development for dams and reservoirs (Zarfl et al., 2015). In Africa, no regional legal framework that is comparable to the complex legal structure of the supranational European Union currently exists. As a result, the protection and management of transnational river systems is subject to national law and bi- or multilateral treaties (Zawahri & Mitchell, 2011). River Basin Organizations are a policy instrument to guide cross-border nexus governance and to support benefit-sharing arrangements, but their success depends strongly on the integration of stakeholders and power dynamics (Dombrowsky & Hensengerth, 2018). In that regard, nexus decisions can be limited by power dynamics, in particular because energy investments are rarely decided at basin scale (Dombrowsky & Hensengerth, 2018; Weitz et al., 2017).

While policies in place struggle to promote the comprehensive sustainable development of renewable energy, scientific studies have provided guidance for sustainable hydropower development that puts the ecological dimension in focus. Thieme et al. suggest to navigating the trade-offs between dams and river conservation by following a mitigation hierarchy that includes (1) avoidance through river protection or exploration of alternatives; (2) minimization of impacts through strategic or system-scale planning or re-regulation of downstream flows; (3) restoration of rivers through dam removal; and (4) mitigation of dam impacts through biodiversity offsets that include restoration and protection (Thieme et al., 2021). The World Wildlife Fund advises keeping rivers connected and flowing by moving rapidly towards electricity systems that are (1) low carbon, (2) low cost, (3) and low impact (Opperman et al., 2019). Xu et al. advise exploiting unused profitable hydropower potential under a framework of strict environmental constraints (Xu et al., 2023). Another study from Jones et al. concludes that the principle of “No Net Loss” (i.e. biodiversity impacts of hydropower projects are quantified and fully mitigated) needs to be applied in dam development (Jones & Bull, 2020). Although these scientifically based recommendations are publicly available, they appear to have had little influence on policy making to date, highlighting the gap of knowledge exchange between science and policy makers (Head, 2016).

The present thesis has outlined the consequences of proposed hydropower development at different scales (Chapter 3). It further highlights that impact assessment protocols in place lack the precise estimation of long-term and large-scale consequences of hydropower dams and reservoir inundation (Chapter 3). While alternatives exist (Chapter 5), African river management is governed by national legal regulations. River management is further not strategically integrated with renewable energy planning. A sustainable development of water resource requires cooperation at all levels. Therefore, the science-policy dialogue has to improve to mainstream a basin-wide river management and establish an enabling legal framework.

6.4. Future perspective and outlook

While the social and ecological consequences of dam construction and reservoir inundation put into doubt the status of hydropower as an entirely sustainable renewable electricity resource (according to the definition presented in Chapter 1.2), hydropower is favoured in renewable

electricity mixes due to its storage capacity. Historically, reliable renewable electricity systems operate with a certain baseload capacity so they can respond flexibly to demand. Because the sun does not always shine and the wind does not always blow, both technologies are – in contrast to hydropower – considered as variable renewable electricity sources (Engeland et al., 2017; Sterl, 2021b). Due to declining costs of both solar and wind technologies, it has been increasingly investigated to what degree these variable renewable resources can be better integrated while assuring grid stability. The costs of low variable renewable energy penetration are low or even negative, but data on high penetration remains scarce (Heptonstall & Gross, 2021). **Future research has to expand knowledge on how high penetration of variable resources will affect grid stability and what that means for variable resource exploitation.**

In contrast to most of the Global North, Africa's need for renewable capacity expansion offers a window of opportunity to build electricity systems with high variable renewable energy penetration (Sterl, 2021a). A high penetration of variable renewable electricity will need increased grid flexibility to simultaneously safeguard supply and balance demand (Sterl, 2021a). Sterl et al. differentiate between generation-driven flexibility (dispatchable power plants and trade), storage-driven flexibility (pumped storage hydropower, batteries, power-to-gas technology), and demand-driven flexibility (demand-response, sectoral coupling) (NREL, 2015; Sterl, 2021a). A better integration of wind and solar power will rely on the successful increase of demand-driven flexibility. In West Africa, the investigation of an improved use of hydro-solar-wind synergies with wind and solar contributing 50% to the region's power-pool generation showed that electricity from these sources could be at least 10% cheaper than electricity from natural gas (Sterl et al., 2020). In addition, the introduction of demand-driven management can better align the implementation of renewable power plants to regional needs and may eventually result in the postponement of renewable power-plant construction in favour of maintenance investments (Pina et al., 2012). This would enable the exploitation of renewable power plant potential to be economically optimized and adapted to the existing needs of the local population. **Here, the knowledge gained on the smart exploitation of renewable synergies as well as insights on demand-driven electricity generation should be applied and adapted to other regions in Africa and elsewhere.**

This thesis argues that one option to avoid the increasing alteration of intact river systems is the replacement of proposed hydropower capacity with solar and wind farms (Chapter 5). In that regard, two factors have to be considered: (1) Solar PV and onshore wind power have lower capacity factors than hydropower, that is, the power actually produced by a plant relative to its peak capacity (Bolson et al., 2022). In addition, (2) an on-ground installed solar PV plant or an onshore wind plant takes up more land than a HPP of the same capacity (Ritchie, 2022). If the concept of land-use footprint is extended to a technology's life-cycle, it is necessary to consider the additional land needed for (a) mining construction materials; (b) mining fuels to produce materials; (c) connections to or extension of the electricity grid; and (d) managing waste (Ritchie, 2022).

The weighted mean capacity factors for Africa for 2000 to 2017 are 0.55 for hydropower, 0.17 for solar power, and 0.27 for wind power (Bolson et al., 2022). The capacity factor for hydropower is highest among these renewable technologies, yet it is smaller than the weighted average capacity factors for fossil fuels (0.57) and nuclear power (0.80) (Bolson et al., 2022). The land use of a proposed HPP operating with reservoir storage can be assessed by calculating the area inundated by the impoundment (Chapter 3). In contrast, a comprehensive definition of the land covered by a solar or wind power plant is subject to solar panel or wind turbine spacing. Between or under the solar panels or wind turbines, unsealed areas remain and could be co-used. Integrating

a technologies life-cycle, rooftop solar PV as the smallest land use (1.2 m² (cadmium) to 3 m² (silicon) per megawatt hour (MWh)), followed by on-ground solar PV (12.6 m² (cadmium) to 19 m² (silicon) per MWh), large hydropower (>660 MW; 14 m² per MWh), concentrating solar power (22 m² per MWh), and small to medium hydropower (<360 MW; 33 m² per MWh). The land use for the project area of an onshore wind park is 99 m² per MWh, but only 0.4 m² per MWh if only the direct impact area of the turbines is considered. In comparison, a gas plant requires 1 m² per MWh and a nuclear plant only 0.3 m² per MWh (Ritchie, 2022). The considerably lower land use of gas and nuclear is an often-claimed counter-argument for renewable development (Walker, 1995). **An improved understanding and a clear definition of renewable infrastructure land use, including a life cycle assessment, will enable more precise assessments of land use impacts to be expected from proposed renewable power plants.**

Solar PV and onshore wind require more land than other technologies, but offer the opportunity for co-use. On-ground solar PV systems can be co-located with sheep grazing, pollinator friendly fields, or crops. At the state level, dual-use systems have higher capital costs than conventional ground-mounted PV installed over bare ground due to the higher costs in site investigation and additional planning requirements (Horowitz et al., 2020). Yet, the technology is at an early stage and further research is needed to weigh the costs against the benefits. Farms use a significant amount of energy, and a co-use could generate income, lower electricity costs, and protect sheep from rain, hail and heat, increasing their grazing time (Kampherbeek et al., 2023). Grazing enhances the vegetational biodiversity under the solar panels in the long term and prevents erosion, with improved carbon storage of plants and soil (B. Zhang et al., 2024). **Transdisciplinary research on dual-system use, such as the combination of on-ground solar PV and sheep grazing, will provide important evidence to tackle the cross-sectoral competition for space.**

The benefits and opportunities for co-use have been studied and reported mainly for countries in the Global North. However, in India, Kenya, Morocco, and Norway large renewable power plants have also been set up in sparsely populated areas without consultation with the local land users making former common grazing land unavailable for pastoralists (Waters-Bayers & Wario, 2022). The 310 MW Lake Turkana Wind Farm in Kenya is with 365 turbines the largest wind farm on the African continent and was set up on 60,704 ha of land previously used by pastoralists (Lomax et al., 2023; Waters-Bayers & Wario, 2022). The wind farm was justified as contributing to the renewable energy needs in the region, but the approach was donor-led, and increased conflict in the region (Lomax et al., 2023). In 2021, the court declared the process of land acquisition to be illegal (Waters-Bayers & Wario, 2022). **While research can inform on renewable power-plant potential and ecological and socioeconomic effects of renewable infrastructure, power-plant planning and land acquisition must be discussed in participatory processes engaging civil society to avoid conflict and enable the fair sharing of benefits.**

A sustainable development of solar PV and onshore wind power is further dependent on the technologies' ecological, socioeconomic, and political impacts, which have been extensively discussed for hydropower (Chapter 3). Onshore wind power plants increase habitat loss and impact bird and bat species, for which an increased mortality has been reported (Hamed & Alshare, 2022; Loss et al., 2019; Millon et al., 2018; Popescu et al., 2020). Increased noise pollution (van Kamp & van den Berg, 2018) and changes in visual impact (McKenna et al., 2021; Peri & Tal, 2021) have been studied in relation to wind power development. Impacts of solar power plants depend on the implemented technology (PV, CPV, CSP) and whether they are stand-alone, rooftop, or floating (Cousse, 2021). Large solar facilities were reported to cause landscape

alterations and affect visual perception, biodiversity, and microclimate (Hamed & Alshare, 2022; Torres-Sibille et al., 2009). Floating PVs can cause algal blooms and reduce oxygen production through shading (Almeida, Schmitt, Grodsky, et al., 2022). **Building on clear RE space requirement definitions, research on the effects of solar and wind facilities needs to be expanded to provide a systematic assessment of the consequences of power plants to inform sustainable renewable power-plant planning.**

The development of renewable power plants requires space. Space undoubtedly exists: for example, the highest-potential areas worldwide of PV power are located in uninhabited desert areas (WB, 2023). However, a cost-optimal transition includes grid connections and accessibility, which makes remote areas less attractive and results in an increasing competition for land (Sterl, 2021b). The exploitation of co-use options will be key to tackle the nexus problem, where different parties claim space for energy, water, agriculture or ecosystem protection. Therefore, **transdisciplinary research teams that investigate the multidimensional need for space at system scale can provide meaningful cross-sectoral evidence for ministries and other governmental organizations.**

Further potential to improve the generation of renewable energy without using more land lies in the optimization of existing renewable infrastructure. Quaranta et al. assess the potential in Europe for small run-of-river or diversion hydropower (<100 kW) in water wheels of old mills (1.6 TWh/y), and waste water networks (3.1 TWh/y) at an average investment cost of 5,000 €/kW (Quaranta et al., 2022). In Italy, Butera et al. have developed a methodology to assess the potential for hydroelectricity production in existing irrigation networks (Butera & Balestra, 2015). Falchetta et al. showed that over one third of unmet crop water requirements in sub-Saharan Africa could be supplied by adding stand-alone solar PV to existing irrigation systems (Falchetta et al., 2023). Another study by Gonzalez Sanchez et al. concluded that a 1% coverage of existing hydropower reservoirs with floating PV would increase the electricity output by 58% (Gonzalez Sanchez et al., 2021). In Kenya, the first 200 kW hybrid hydro- and solar power plant entered operation in October 2023, connecting 150 households, eight schools, two medical facilities, and 10 businesses to power (Skujins, 2023). Exploiting the potential for floating PV offers notable upgrades in electricity generation without additional land sealing. However, **research has yet to fully assess the effects of shading on the dynamics of reservoir biology and chemistry in different climatic regions.**

Renewable power from solar and wind resources enables a renewable energy transition that diminishes the need for further hydropower damming. Thus, solar and wind power pave the path towards a more sustainable renewable energy development that integrates river-system protection. However, the findings of this thesis outline that with respect to hydropower, the ecological dimension of a sustainable renewable energy development tends to fall short (Chapters 3, 5). As such, future research efforts should reveal and systemically assess the effects of wind and solar power-plant infrastructure at all spatial and temporal scales. From a sustainability perspective, there is a global need to protect ecological valuable corridors from anthropogenic pressures. **Co-use options have to be further explored as important options to diminish the need for new infrastructure and space.**

In Africa, the need to expand the installed renewable capacity is more pronounced than elsewhere, outlining the need for in-depth research on the potential and effects of renewable electricity expansion including grid infrastructure. At the same time, Africa is home to the Congo river basin, one of the last mainly free-flowing river systems of high ecological relevance anywhere in the world. The need for renewable electricity and the high hydropower potential in the tropics will put the Congo river basin increasingly under anthropogenic pressure. A sustainable renewable

energy development in Africa needs to integrate and balance ecological and socioeconomic interests to ensure the envisioned “modern, efficient, reliable, cost-effective, renewable and environmentally friendly energy to all African households, businesses, industries and institutions” (African Union, 2015). **Interdisciplinary research projects integrating social science, natural science, and engineering will be key to informing evidence-based cross-sectoral discussions. Participatory approaches will safeguard a renewable development that avoids conflict and assures energy democracy** (Szulecki & Overland, 2020).

In the context of climate change, a reliance on hydropower can jeopardize a country’s reliability in electricity supply because several African river basins will experience increased drought (Falchetta et al., 2019). An increased integration of solar and wind resources would not only protect rivers from increasing fragmentation, but also safeguard the renewable electricity supply by diversifying the electricity mix. Carlino et al. predict that declining costs of renewables and climate change will enable wind and solar to outcompete hydropower by 2030 (Carlino et al., 2023). However, they underline that **additional research and methodology development are needed to connect local, regional, and continental scales, and to provide high-resolution analyses for robust planning of water and energy systems.**

This thesis has focused on the African continent due to the following reasons: (1) the electricity access gap is large despite the continents pronounced renewable potential; (2) open-access geospatial data on renewable resource potential, power plants, grids, and ecological effects is scarce and restricted to specific countries; (3) despite the various challenges discussed above, the continent has the opportunity to avoid a phase of fossil fuel dependence. **Yet, the approaches and gained knowledge merit extension to other regions.**

6.5. Final conclusion

The climate change crisis has resulted in an extensive expansion of renewable electricity capacity worldwide. In Africa, the decarbonization of existing electricity grids is accompanied by the need to connect 566 million people that currently lack access to power (World Bank, 2021b). Hydropower has been the RE source of choice to connect people to renewable electricity, but hydropower damming is also recognized as one of the drivers of global biodiversity loss (Zarfl et al., 2019). Particularly in countries of the Global South, the impact of building (or not building) a dam can imply a decision between electricity access for people or conservation of ecosystems and biodiversity. Yet, the Agenda 2030 envisions a sustainable development that integrates both, “affordable and clean energy” (SDG 7) and “climate action” (SDG 13), as well as restoration of water-related ecosystems (SDG 6.6) and conservation and restoration of freshwater ecosystems (SDG 15.1) (UN, 2015).

Based on the findings of the present thesis, the author proposes the following recommendations to support evidence-based discussions on sustainable development pathways in Africa:

1. Political agendas should acknowledge that a comprehensive sustainable development has to consider the environmental dimension. In the case of connected river systems, there is a need for ecological corridors that are protected against anthropogenic pressures (Chapter 3).
2. Opportunities to increase renewable electricity generation without increasing the anthropogenic pressure on free-flowing rivers include (1) the minimization of plant failure (maintenance potential); (2) the combination of renewables (co-use potential); (3) the exploitation of alternatives (replacement potential); (4) the sharing of electricity

(international cooperation); and (5) the avoidance of harmful infrastructure (impact assessment) (Chapters 4 and 5).

3. Openly accessible spatial data at high resolution can induce more contextualized and interdisciplinary research that supports discussions and informs policy making (Chapter 2). Therefore, the science-policy dialog has to improve.
4. To safeguard a successful long-term sustainable development, renewable energy planning has to be participatory to avoid conflict and assure fair benefit-sharing and energy democracy (Chapters 2 and 3).

Africa has the potential to avoid a phase of comprehensive fossil fuel dependency and transit to renewable electricity generation, and also to take a leading role in integrating river conservation and renewable infrastructure trade-offs in renewable electricity planning. In doing so, African countries would not only be perceived as pioneers of a renewable energy transition, but also as frontrunners in promoting sustainable development.

A.

Supporting information – Chapter 3

Table A.1: Proposed hydropower plants. Overview on sums of included and excluded data points per indicator.

Data (Status <i>proposed</i>)	R	RU	Included	Excluded	Notes
Hydropower Type <i>Reservoir (R)</i>	x		236	7	Reason for exclusion: Failed reservoir delineation (e. g. due to extension of existing hydropower plant)
Hydropower Type <i>Reservoir and unknown (RU)</i>		x	507	17	Reason for exclusion: Failed reservoir delineation
River Regulation Index (Level 3)	x		242	1	
River Regulation Index (Level 3)		x	515	9	
River Regulation Index (Level 4)	x		242	1	
River Regulation Index (Level 4)		x	515	9	
River Fragmentation Index (Level 3)	x		242	1	
River Fragmentation Index (Level 3)		x	514	10	
River Fragmentation Index (Level 4)	x		230	13	
River Fragmentation Index (Level 4)		x	510	14	
Protected Area	x		84 152*	7	*no overlap with protected areas
Protected Area		x	168 339*	17	*no overlap with protected areas
Resettlement	x		236	7	
Resettlement		x	506	18	
Land Use Change (Cropland)	x		236	7	
Land Use Change (Cropland)		x	507	17	
Megafauna	x		236	7	
Megafauna		x			
Sediment Entrapment	x		218	25	Hydropower with projected lifespan of <1 year and >10 MW were excluded.
Sediment Entrapment		x	453	71	Hydropower with projected lifespan of <1 year and >10 MW were excluded.
Potential Evaporation	x		236	7	
Potential Evaporation		x	507	17	
Impact assessment	x		211	32	All hydropower plants with failed assessment of one or more indicators were excluded
Impact assessment		x			All hydropower plants with failed assessment of one or more indicators were excluded

Table A.2: Proposed hydropower plants of Type *Reservoir*. Each hydropower plant (HPP) can be identified with the respective HPPD_ID from the Renewable Power Plant Database (RePP) Africa (Peters et al., 2023). Calculation of impact per indicator and resulting quartile (Q) for River Regulation (RRI, HydroBASIN level 04), River Fragmentation (RFI, HydroBASIN level 04), Resettlement (Res), Protected Area (PA), Megafauna (MF), Potential Evaporation (PE), Sediment Entrapment (SE) and resulting Lifespan, and Land Use Change for Cropland (LU_C). Quartile values are indicated with 1 (low impact, $\leq 1^{\text{st}}$ quartile), 2 (moderate impact, $> 1^{\text{st}}$ to $\leq 2^{\text{nd}}$ quartile), 3 (heavy impact, $< 2^{\text{nd}}$ to $\leq 3^{\text{rd}}$ quartile), and 4 (severe impact, $> 3^{\text{rd}}$ quartile).

	10033	10028	10027	10025	10022	10021	10020	10019	10018	10016	10015	10007	10006		HPPD_ID
1200		485	72	67	33	5	940	640	1800	250	1000	470	1000	[MW]	Cap
1577		3604	1993	2513	36	57	30	0	1327	1217	112	72	x	[million m³]	r_vol
85		68	53	245	5	21	9	0	67	64	34	5	x	[million m²]	r_area
39		46	46	46	2	39	39	39	39	39	39	39	39	[%]	RRI_04
2		2	2	2	1	2	2	2	2	2	2	2	2		RRI_04_Q
78		49	49	49	23	78	78	78	78	78	78	78	78	[%]	RRI_04
3		2	2	2	1	3	3	3	3	3	3	3	3		RRI_04_Q
10456		5368	23662	1899	291	114	92	1	1820	416	37258	165	x	count	Res
4		3	4	2	1	1	1	1	2	2	4	1	x		Res_Q
		1									1		x	count	PA_No
0		6870267	0	0	0	0	0	0	0	0	17171062	0	x	[m²]	PA
1		4	1	1	1	1	1	1	1	1	4	1	x		PA_Q
8		9	10	9	6	7	9	9	9	9	9	8	x	count	MF
4		4	4	4	3	3	4	4	4	4	4	4	x		MF_Q
9431898		7820842	5824247	29551980	654628	2349331	1006429	1852	7272455	6777019	3589321	542766	x	[m3/year]	PE
3		3	3	4	2	2	2	1	3	3	3	1	x		PE_Q
7186173		6020412	3708997	1152088	4635378	5542075	19010349	50141	6498931	30	1127706	21871669	x	[t/year]	SE
581		1586	1424	5781	21	27	4	5	541	106277653	264	9	x	[year]	Lifespan
3		2	3	2	4	4	4	4	3	1	3	4	x		SE_Q
0		411023	4526014	99076	0	19504	107594	7349	3964642	4745438	630680	0	x	[m²]	LU_C
1		2	3	2	1	2	2	1	3	3	2	1	x		LU_C_Q
21		22	22	19	14	18	19	17	21	19	25	17	x		SUM_Q

10107	10106	10105	10104	10103	10095	10093	10049	10047	10043	10038	10037	10036	10035	10034		HPPD_ID
4800	6706	6684	6970	7180	600	150	1000	1000	300	180	40	1	600	400	[MW]	Cap
704	704	704	704	704	834	12089	16535	12646	131	492	90	99	3251	1579	[million m³]	r_vol
22	22	22	22	22	152	371	996	833	62	65	25	15	111	108	[million m²]	r_area
6	6	6	6	6	10	7	45	45	0	10	0	1	10	39	[%]	RRl_04
1	1	1	1	1	1	1	2	2	1	1	1	1	1	2		RRl_04_Q
x	x	x	x	x	64	31	45	45	5	64	5	9	64	78	[%]	RFI_04
x	x	x	x	x	3	1	1	1	1	3	1	1	3	3		RFI_04_Q
2890	2890	2890	2890	2890	1031	3616	11907	8437	1081	2375	204	18764	1517	7181	count	Res
3	3	3	3	3	2	3	4	4	2	3	1	4	2	3		Res_Q
					5		3	2					1		count	PA_No
0	0	0	0	0	103346520	0	234331146	246482932	0	0	0	0	45325338	0	[m²]	PA
1	1	1	1	1	4	1	4	4	1	1	1	1	4	1		PA_Q
11	11	11	11	11	8	7	7	6	10	7	5	5	6	9	count	MF
4	4	4	4	4	4	3	3	3	4	3	2	2	3	4		MF_Q
2102755	2102755	2102755	2102755	2102755	15076837	37830034	98590496	82514112	6978078	6746656	2890490	1483545	10663587	12341525	[m3/year]	PE
2	2	2	2	2	4	4	4	4	3	3	3	2	4	4		PE_Q
x	x	x	x	90	x	330	2204964	10126398	76234591	7318510	10683518	10507	3347491	20	[t/year]	SE
x	x	x	x	20765561	x	96956047	19873	3309	5	178	22	24861	2574	211904235	[year]	Lifespan
x	x	x	x	1	x	1	1	2	4	3	4	1	2	1		SE_Q
15769513	15769513	15769513	15769513	15769513	560918	52814291	98895767	79625983	295532	1084786	0	12832623	0	2233150	[m²]	LU_C
4	4	4	4	4	2	4	4	4	2	2	1	3	1	3		LU_C_Q
x	x	x	x	x	x	18	23	24	18	19	14	15	20	21		SUM_Q

10233	10232	10215	10214	10213	10212	10211	10204	10185	10176	10175	10174	10167	10145	10127	HPPD_ID
1600	371	301	88	150	2000	1700	10	8	180	73	35	410	28	6747	Cap
284	188	1262	116	2150	1536	571	126	1041	27	163	20	45	8	704	[million m³]r_vol
13	4	21	18	49	64	39	6	17	6	10	2	10	1	22	[million m²]r_area
338	212	338	9	292	338	338	27	27	0	1	1	0	585	6	RRL_04
4	4	4	1	4	4	4	2	2	1	1	1	1	4	1	RRL_04_Q
81	75	81	6	69	81	81	61	61	47	9	9	47	63	x	RFI_04
4	3	4	1	3	4	4	2	2	1	1	1	1	2	x	RFI_04_Q
7762	1306	8693	1505	17217	10107	1041	9924	24519	111	27	28	3055	20	2890	Res
4	2	4	2	4	4	2	4	4	1	1	1	3	1	3	Res_Q
			1			1			1		1	1	3		PA_No
0	0	0	5124061	0	0	7992235	0	0	7248011	0	1961687	4934732	4321021	0	PA
1	1	1	4	1	1	4	1	1	4	1	3	4	3	1	PA_Q
3	3	3	1	2	4	4	6	6	7	9	7	9	8	11	MF
1	1	1	1	1	2	2	3	3	3	4	3	4	4	4	MF_Q
1611848	568337	2479388	2818423	6082534	7850060	5289469	720399	1728134	586230	1019579	156324	960644	144461	2102755	PE
2	1	2	3	3	3	3	2	2	2	2	1	2	1	2	PE_Q
240519548	106608	1213030	74423524	42809044	15588270	49915129	31	189988	419	662424	1825	28	20241914	x	SE
3	4683	2756	4	133	261	30	10784008	14518	173187	650	29030	4295234	1	x	Lifespan
4	2	2	4	3	3	4	1	1	1	3	1	1	4	x	SE_Q
97033	2318291	14204787	0	0	15632900	374262	5212775	17113734	181691	0	0	956400	0	15769513	LU_C
2	3	3	1	1	3	2	3	4	2	1	1	2	1	4	LU_C_Q
22	17	21	17	20	24	25	18	19	15	14	12	18	20	x	SUM_Q

10280	10250	10249	10248	10247	10246	10245	10243	10242	10241	10239	10238	10236	10235	10234		HPPD_ID
34	256	100	560	1700	166	507	467	304	424	423	150	189	265	278	[MW]	Cap
545	878	173	353	192	64	317	26	76735	22889	16322	15	692	132	26	[million m³]	r_vol
30	36	5	25	5	1	10	3	2310	1400	466	2	7	3	2	[million m²]	r_area
38	52	52	292	8	8	8	8	338	338	292	292	338	338	338	[%]	RR1_04
2	3	3	4	1	1	1	1	4	4	4	4	4	4	4		RR1_04_Q
52	57	57	69	23	23	23	23	81	81	69	69	81	81	81	[%]	RF1_04
2	2	2	3	1	1	1	1	4	4	3	3	4	4	4		RF1_04_Q
16531	1694	286	1310	165	514	2881	641	228107	139302	86802	2729	3349	2063	558	count	Res
4	2	1	2	1	2	3	2	4	4	4	3	3	2	2		Res_Q
1			2	2				1	1	1					count	PA_No
7325705	0	0	15861142	5531660	0	0	0	844941410	618928156	95257	0	0	0	0	[m²]	PA
4	1	1	4	4	1	1	1	4	4	3	1	1	1	1		PA_Q
2	2	2	5	6	6	6	4	4	4	2	2	3	3	3	count	MF
1	1	1	2	3	3	3	2	2	2	1	1	1	1	1		MF_Q
4537510	5630728	807965	3658979	585186	160893	1347034	368146	299009007	181219462	54336092	189238	782156	291188	184313	[m3/year]	PE
3	3	2	3	1	1	2	1	4	4	4	1	2	1	1		PE_Q
216667	701194	1698063	11603308	86554	2662555	12171336	4028602	x	615	3539782	3354485	x	1895299	29031	[t/year]	SE
6671	3317	270	81	5865	64	69	17	x	98559989	12219	12	x	184	2354	[year]	Lifespan
2	2	3	4	2	4	4	4	x	1	2	4	x	3	2		SE_Q
26007559	403110	0	0	0	0	0	0	987081649	590652171	262473641	478515	987289	646193	0	[m²]	LU_C
4	2	1	1	1	1	1	1	4	4	4	2	2	2	1		LU_C_Q
22	16	14	23	14	14	16	13	x	27	25	19	x	18	16		SUM_Q

10342	10323	10322	10314	10311	10309	10301	10300	10299	10293	10292	10290	10283	10282	10281		HPPD_ID
580	240	86	693	90	19	20	45	80	50	2	120	25	56	99	[MW]	Cap
5	13	36	1169	419	1	109	0	450	291	0	572	3129	0	300	[million m³]	r_vol
1	1	3	76	28	0	2	0	8	14	0	19	157	0	29	[million m²]	r_area
4	0	4	87	87	87	292	292	292	585	585	585	585	585	585	[%]	RRL_04
1	1	1	3	3	3	4	4	4	4	4	4	4	4	4		RRL_04_Q
51	x	51	57	57	57	69	69	69	63	63	63	63	63	63	[%]	RFI_04
2	x	2	2	2	2	3	3	3	2	2	2	2	2	2		RFI_04_Q
111	320	307	2968	2174	1863	3587	183	5370	2700	236	33638	985	1	97	count	Res
1	1	1	3	2	2	3	1	3	3	1	4	2	1	1		Res_Q
1			2				1	1	1			2	1	1	count	PA_No
865896	0	0	14143859	0	0	0	29928	9752066	10101411	0	0	158439864	41342	30651978	[m²]	PA
3	1	1	4	1	1	1	3	4	4	1	1	4	3	4		PA_Q
1	1	1	3	4	4	4	3	3	5	5	6	5	5	5	count	MF
1	1	1	1	2	2	2	1	1	2	2	3	2	2	2		MF_Q
113916	88102	337608	13157733	4365786	26607	304471	2086	1045401	1961355	24309	2547445	21040993	3472	3995771	[m3/year]	PE
1	1	1	4	3	1	1	1	2	2	1	2	4	1	3		PE_Q
4966	6851537	2848	2617580	2618836	116676	230746	82257	104972	679036	2982842	3144740	1480	118	2064545	[t/year]	SE
2701	5	33546	1184	424	24	1251	6	11352	1137	0	482	5602198	1710	385	[year]	Lifespan
2	4	1	3	3	4	3	4	2	3	4	3	1	2	3		SE_Q
0	0	0	27614105	27047178	225147	1409279	17096	6535877	4797928	193890	21662990	148376783	21054	19961627	[m²]	LU_C
1	1	1	4	4	2	3	1	3	3	2	4	4	2	4		LU_C_Q
12	x	9	24	20	17	20	18	22	23	17	23	23	17	23		SUM_Q

10429	10421	10414	10413	10412	10410	10402	10398	10395	10360	10358	10357	10356	10348	10343		HPPD_ID
47	648	205	420	312	360	14	4	44	41	155	43	105	300	600	[MW]	Cap
x	243	187	8	47	89	102	6	5256	2033	107	73	102	93	505	[million m³]	r_vol
x	66	100	14	18	25	45	1	154	260	34	24	33	1	39	[million m²]	r_area
56	252	253	252	252	252	0	585	585	107	0	0	0	0	4	[%]	RRL_04
3	4	4	4	4	4	1	4	4	3	1	1	1	1	1		RRL_04_Q
47	80	50	80	80	80	21	63	63	6	46	46	46	46	51	[%]	RFL_04
1	4	2	4	4	4	1	2	2	1	1	1	1	1	2		RFL_04_Q
x	3860	54823	65	2415	1178	7930	2209	197701	81986	4607	2517	4376	320	2994	count	Res
x	3	4	1	3	2	4	2	4	4	3	3	3	1	3		Res_Q
x															count	PA_No
x	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[m²]	PA
x	1	1	1	1	1	1	1	1	1	1	1	1	1	1		PA_Q
x	6	8	7	7	6	4	4	4	3	1	1	1	1	1	count	MF
x	3	4	3	3	3	2	2	2	1	1	1	1	1	1		MF_Q
x	13847909	18716582	3170109	4466772	5389381	6460362	55714	15654905	33034776	3703440	2630029	3619914	119332	4227982	[m3/year]	PE
x	4	4	3	3	3	3	1	4	4	3	3	3	1	3		PE_Q
x	4910	198401663	x	6855	1396051	5	51645	930	x	83	468	12874384	2123653	445	[t/year]	SE
x	131109	2	x	18355	170	53448255	285	14978620	x	3389135	410208	21	116	3004579	[year]	Lifespan
x	1	4	x	1	3	1	3	1	x	1	1	4	4	1		SE_Q
x	9963034	52326529	113239	1799236	4483629	4474941	614332	167698206	158432029	23055227	14843060	22409875	0	2218247	[m²]	LU_C
x	3	4	2	3	3	3	2	4	4	4	3	4	1	3		LU_C_Q
x	23	27	x	22	23	16	17	22	x	15	14	18	11	15		SUM_Q

10572	10571	10570	10569	10550	10535	10526	10515	10479	10474	10469	10462	10459	10452	10431		HPPD_ID
453	330	260	381	26	38	45	360	7	520	300	358	60	160	118	[MW]	Cap
65	3	54	2274	141	1	9	0	12	361	58	x	8	363	3095	[million m³]	r_vol
7	1	5	166	18	0	0	0	1	6	1	x	5	19	52	[million m²]	r_area
94	94	94	94	0	585	585	585	585	107	107	56	56	56	107	[%]	RRI_04
3	3	3	3	1	4	4	4	4	3	3	3	3	3	3		RRI_04_Q
67	67	67	67	x	63	63	63	63	6	6	47	47	47	6	[%]	RFI_04
3	3	3	3	x	2	2	2	2	1	1	1	1	1	1		RFI_04_Q
235	55	143	5108	125	494	182	0	2856	1031	136	x	295	453	1528	count	Res
1	1	1	3	1	2	1	1	3	2	1	x	1	2	2		Res_Q
						1	1				x	2	2		count	PA_No
0	0	0	0	0	0	241058	18121	0	0	0	x	8679651	29121714	0	[m²]	PA
1	1	1	1	1	1	3	3	1	1	1	x	4	4	1		PA_Q
4	4	3	2	4	4	5	9	8	3	4	x	3	4	3	count	MF
2	2	1	1	2	2	2	4	4	1	2	x	1	2	1		MF_Q
800569	109468	573004	18470886	2166521	21926	21905	1130	88405	782921	163458	x	729218	2640784	6828844	[m3/year]	PE
2	1	1	4	2	1	1	1	1	2	1	x	2	3	3		PE_Q
155409	663993	41981	2103602	124	96	7647	x	1213807	316379	12794	x	20	192	1165033	[t/year]	SE
1107	11	3439	2865	3027324	14003	3082	x	26	3022	12012	x	1035049	5007800	7040	[year]	Lifespan
3	4	2	2	1	1	2	x	4	2	2	x	1	1	2		SE_Q
0	0	341926	5010206	490797	2377	0	0	873491	187521	0	x	779519	58000	705704	[m²]	LU_C
1	1	2	3	2	1	1	1	2	2	1	x	2	2	2		LU_C_Q
16	16	14	20	x	14	16	x	21	14	12	x	15	18	15		SUM_Q

10604	10602	10596	10594	10585	10584	10583	10581	10579	10578	10577	10576	10575	10574	10573		HPPD_ID
74	230	190	41	57	86	157	403	283	217	121	203	120	114	460	[MW]	Cap
6785	520	16	198	3	41	138	4617	59	34	1151	47	35557	51	267	[million m³]	r_vol
295	37	1	8	0	5	10	440	2	5	64	1	3202	3	14	[million m²]	r_area
140	125	2	2	94	94	94	49	49	49	36	36	94	94	94	[%]	RRl_04
4	3	1	1	3	3	3	3	3	3	2	2	3	3	3		RRl_04_Q
x	50	13	13	67	67	67	7	7	7	0	0	67	67	67	[%]	RFI_04
x	2	1	1	3	3	3	1	1	1	1	1	3	3	3		RFI_04_Q
5107	2604	150	1932	51	231	1902	32827	491	364	2280	116	16103	220	660	count	Res
3	3	1	2	1	1	2	4	2	2	2	1	4	1	2		Res_Q
												2			count	pA_No
0	0	0	0	0	0	0	0	0	0	0	0	965594865	0	0	[m²]	pA
1	1	1	1	1	1	1	1	1	1	1	1	4	1	1		pA_Q
3	2	5	5	3	3	3	3	3	3	4	3	4	4	4	count	MF
1	1	2	2	1	1	1	1	1	1	2	1	2	2	2		MF_Q
38161111	4556683	82785	880910	47089	576208	1111220	46555523	247541	556315	6843337	145197	366089020	384928	1607411	[m³/year]	PE
4	3	1	2	1	1	2	4	1	1	3	1	4	1	2		PE_Q
6003028	14	10625369	549199	2069821	356	110153	9278378	968470	273432	1810115	142937	222	24860	328424	[t/year]	SE
2995	96293997	4	956	3	307679	3331	1319	162	332	1685	868	424049347	5437	2157	[year]	Lifespan
2	1	4	3	4	1	2	3	3	3	2	3	1	2	2		SE_Q
25608759	0	8737	0	0	0	0	127897811	0	727849	12537037	0	17345704	20005	6696	[m²]	LU_C
4	1	1	1	1	1	1	4	1	2	3	1	4	2	1		LU_C_Q
x	15	12	13	15	12	15	21	13	14	16	11	25	15	16		SUM_Q

10744	10743	10741	10722	10680	10672	10670	10669	10653	10650	10649	10647	10642	10638	10637		HPPD_ID
14	100	10	320	612	1245	200	650	350	55	50	50	150	30	60	[MW]	Cap
9	1232	8	83372	700	247309	5	65	1336	239	19	10	789	29	7	[million m³]	r_vol
4	106	2	2626	17	4728	2	25	64	10	2	5	14	2	0	[million m²]	r_area
15	92	26	509	125	1066	1066	1066	107	107	107	107	107	107	107	[%]	RRL_04
1	3	2	4	3	4	4	4	3	3	3	3	3	3	3		RRL_04_Q
19	52	52	36	50	60	60	60	6	6	6	6	6	6	6	[%]	RFI_04
1	2	2	1	2	2	2	2	1	1	1	1	1	1	1		RFI_04_Q
126	2085	170	51394	105	38424	72	332	3629	0	0	1317	2368	312	39	count	Res
1	2	1	4	1	4	1	1	3	1	1	2	3	1	1		Res_Q
	1	1	8	2	2				1	1				1	count	PA_No
0	851044	1034517	438220577	16608402	460823007	0	0	0	10534017	2046802	0	0	0	135334	[m²]	PA
1	3	3	4	4	4	1	1	1	4	3	1	1	1	3		PA_Q
4	3	4	5	5	5	5	5	4	4	4	4	4	5	5	count	MF
2	1	2	2	2	2	2	2	2	2	2	2	2	2	2		MF_Q
487488	13613185	313033	364860007	1871109	654496164	336698	3616344	8832391	1261066	224603	710469	1697339	244592	51781	[m³/year]	PE
1	4	1	4	2	4	1	3	3	2	1	2	2	1	1		PE_Q
6069356	521005	17918026	25195161	10	30150183	10560533	14	41701904	966877	113	1145611	2555225	584863	75968	[t/year]	SE
4	6264	1	8769	194015391	21737	1	12452332	85	654	450798	23	818	130	256	[year]	Lifespan
4	2	4	2	1	1	4	1	4	3	1	4	3	4	3		SE_Q
456622	7055842	541796	121171848	0	330168092	0	381097	53886044	0	0	4934560	1275210	768093	335364	[m²]	LU_C
2	3	2	4	1	4	1	2	4	1	1	3	2	2	2		LU_C_Q
13	20	17	25	16	25	16	16	21	17	13	18	17	15	16		SUM_Q

10822	10820	10794	10793	10787	10786	10783	10772	10770	10762	10761	10760	10754	10748	10745		HPPD_ID
60	11	108	160	5	15	620	320	200	108	86	132	330	40	1	[MW]	Cap
759	1959	177	1506	0	7	935	83372	196	1386	599	1417	257	2953	0	[million m³]	r_vol
201	294	19	109	0	1	70	2626	18	46	21	87	14	122	0	[million m²]	r_area
162	103	10	10	44	44	138	509	44	27	27	27	92	15	15	[%]	RR1_04
4	3	1	1	2	2	4	4	2	2	2	2	3	1	1		RR1_04_Q
56	6	81	81	65	65	50	36	65	61	61	61	52	19	19	[%]	RF1_04
2	1	4	4	3	3	2	1	3	2	2	2	2	1	1		RF1_04_Q
12625	7986	2110	8348	26	338	593	51394	3457	185	290	939	200	2264	9	count	Res
4	4	2	4	1	2	2	4	3	1	1	2	1	2	1		Res_Q
1	4	2	2	1		3	8		1	2	1		4		count	PA_No
32764363	96461901	4947310	29048485	17042	0	55703698	438220577	0	21574061	22684516	89476967	0	67845340	0	[m²]	PA
4	4	4	4	3	1	4	4	1	4	4	4	1	4	1		PA_Q
4	6	11	9	3	3	5	5	4	6	6	6	3	4	3	count	MF
2	3	4	4	1	1	2	2	2	3	3	3	1	2	1		MF_Q
26967145	39935919	2396095	13768004	964	130347	9813790	364860007	2176764	5916935	2712523	11213106	1778971	13882976	10206	[m³/year]	PE
4	4	2	4	1	1	3	4	2	3	3	4	2	4	1		PE_Q
26971417	4265403	6332758	185842	313323	1121	29923472	x	2317786	268765	275298	1748637	297873	16	155908	[t/year]	SE
75	1217	74	21469	1	15458	83	x	224	13665	5767	2147	2282	494676069	4	[year]	Lifespan
4	3	4	1	4	1	4	x	3	2	2	2	2	1	4		SE_Q
1706711	71417679	3151148	18536099	0	28195	222954	121171848	7947420	383657	487	844096	0	0	87473	[m²]	LU_C
3	4	3	4	1	2	2	4	3	2	1	2	1	1	2		LU_C_Q
27	26	24	26	16	13	23	x	19	19	18	21	13	16	12		SUM_Q

10899	10895	10892	10878	10877	10876	10871	10860	10853	10852	10847	10833	10832	10827	10825		HPPD_ID
2	100	13	36	43	87	50	225	150	156	280	90	90	14	5	[MW]	Cap
3	189	x	1479	413	229	403	32	311	108	2403	1486	68	x	259	[million m ³ /r_vol	
1	18	x	188	146	95	100	11	61	12	208	261	5	x	108	[million m ² /r_area	
22	22	22	94	94	39	8	22	49	49	49	103	103	94	20	[%]	RRL_04
1	1	1	3	3	2	1	1	3	3	3	3	3	3	1		RRL_04_Q
80	80	80	70	70	50	65	80	67	67	67	6	6	70	20	[%]	RFI_04
4	4	4	3	3	2	3	4	3	3	3	1	1	3	1		RFI_04_Q
289	2974	x	6699	7710	7894	46629	181	7421	7979	1484	48911	609	x	8109	count	Res
1	3	x	3	4	4	4	1	3	4	2	4	2	x	4		Res_Q
	1	x	1					3		1	4	2	x	2	count	PA_No
0	270785	x	30149747	0	0	0	0	35147975	0	14701895	67185888	2961365	x	38035998	[m ²]	PA
1	3	x	4	1	1	1	1	4	1	4	4	3	x	4		PA_Q
6	6	x	6	8	10	7	8	8	9	9	7	7	x	4	count	MF
3	3	x	3	4	4	3	4	4	4	4	3	3	x	2		MF_Q
105507	2391767	x	25802348	19855855	12525100	10816525	1143762	6821144	1307808	22840478	29323824	513853	x	15512754	[m3/year]	PE
1	2	x	4	4	4	4	2	3	2	4	4	1	x	4		PE_Q
216736	707688	x	23	9610620	88	6138590	3569	530	28972411	541454	16944139	42138	x	19	[t/year]	SE
40	706	x	167759831	114	6906617	174	23893	1555186	10	11761	232	4279	x	36127970	[year]	Lifespan
4	3	x	1	4	1	3	1	1	4	2	3	2	x	1		SE_Q
587461	11238166	x	186745	5785115	11751312	97999365	1880257	39132797	7264134	206011716	241172188	343970	x	4221473	[m ²]	LU_C
2	3	x	2	3	3	4	3	4	3	4	4	2	x	3		LU_C_Q
17	22	x	23	26	21	23	17	25	24	26	26	17	x	20		SUM_Q

10921	10920	10919	10917	10916	10915	10914	10913	10912	10911	10909	10908	10907	10906	10901		HPPD_ID
90	115	120	81	84	19	14	24	21	29	40	15	23	27	67	[MW]	Cap
87	141	512	95	600	18	231	1462	1069	1818	1031	56	381	751	244	[million m³]	r_vol
8	11	40	7	14	1	16	64	91	128	33	13	28	89	16	[million m²]	r_area
22	22	22	22	22	22	22	22	22	22	22	22	22	22	22	[%]	RRL_04
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		RRL_04_Q
80	80	80	80	80	80	80	80	80	80	80	80	80	80	80	[%]	RFI_04
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		RFI_04_Q
1819	2167	5269	2838	2452	227	3014	5897	7762	9442	2276	2352	2049	10707	2145	count	Res
2	2	3	3	3	1	3	3	4	4	2	3	2	4	2		Res_Q
				1											count	PA_No
0	0	0	0	1098518	0	0	0	0	0	0	0	0	0	0	[m²]	PA
1	1	1	1	3	1	1	1	1	1	1	1	1	1	1		PA_Q
6	6	6	5	5	5	5	5	5	5	5	5	5	5	6	count	MF
3	3	3	2	2	2	2	2	2	2	2	2	2	2	3		MF_Q
1028968	1395101	5138845	897100	1671709	116597	2049947	7995614	11716274	16481535	4104656	1635926	3649057	11126965	2133908	[m³/year]	PE
2	2	3	2	2	1	2	3	4	4	3	2	3	4	2		PE_Q
825529	8175	222146	594253	229057	9024	905225	294985	134618	44700	780970	15913	1433315	231	1283849	[t/year]	SE
279	45850	6112	422	6946	5321	675	13130	21040	107781	3497	9358	705	8625250	504	[year]	Lifespan
3	1	2	3	2	2	3	2	1	1	2	2	3	1	3		SE_Q
5171439	6956140	19844808	0	1303403	448030	5311244	6662101	6125639	8783330	1039164	2949511	1172928	15391821	4583932	[m²]	LU_C
3	3	4	1	3	2	3	3	3	3	2	3	2	3	3		LU_C_Q
19	17	21	17	20	14	19	19	20	20	17	18	18	20	19		SUM_Q

10990	10989	10986	10984	10980	10970	10968	10965	10962	10956	10944	10930	10926	10924	10922	HPPD_ID
90	72	161	281	76	40	98	58	21	18	174	128	16	82	36	Cap
1070	806	3670	27089	229	89	349	503	843	122	1798	1990	25	1273	81	[million m ³]r_vol
163	153	220	612	80	18	24	15	78	1	57	128	10	60	12	[million m ²]r_area
30	30	958	958	958	22	22	958	22	22	22	84	22	22	22	RRL_04
2	2	4	4	4	1	1	4	1	1	1	3	1	1	1	RRL_04_Q
26	26	68	68	68	80	80	68	80	80	80	x	80	80	80	RFI_04
1	1	3	3	3	4	4	3	4	4	4	x	4	4	4	RFI_04_Q
6861	2261	5532	31603	9779	2341	5207	1586	2182	155	9298	3614	1080	2820	2456	Res
3	2	3	4	4	3	3	2	2	1	4	3	2	3	3	Res_Q
2	2	2	4										1		PA_No
164964235	73494252	105422144	366265105	0	0	0	0	0	0	0	0	0	9351874	0	PA
4	4	4	4	1	1	1	1	1	1	1	1	1	4	1	PA_Q
7	9	3	5	4	5	6	5	5	6	5	5	5	5	6	MF
3	4	1	2	2	2	3	2	2	3	2	2	2	2	3	MF_Q
22027089	20985979	30374598	80572712	10148277	2395727	3145750	1967740	10071541	160926	7175296	17709249	1324146	7869937	1574333	PE
4	4	4	4	3	2	3	2	3	1	3	4	2	3	2	PE_Q
x	4796843	11097962	833	1567817	475	379591	94848	13053	25041	1722702	8714395	7730440	1708387	1130038	SE
x	445	876	86194849	387	498151	2436	14051	171132	12916	2765	605	9	1975	190	Lifespan
x	3	3	1	3	1	2	1	1	2	2	3	4	2	3	SE_Q
15148843	0	8730413	2421674	186578	983612	1156138	373198	1677	0	4038111	501971	0	2458221	4902767	LU_C
3	1	3	3	2	2	2	2	1	1	3	2	1	3	3	LU_C_Q
x	21	25	25	22	16	19	17	15	14	20	x	17	22	20	SUM_Q

11051	11048	11047	11045	11042	11041	11039	11036	11029	11024	11023	11021	11012	11009	11002		HPPD_ID
1870	26	123	18	70	30	50	4	25	518	150	9	48	48	100	[MW]	Cap
5005	8713	98	307	860	1095	30	377	882	7652	144	0	36	107	1029	[million m³]	r_vol
1120	744	52	81	113	107	11	115	528	480	40	0	10	25	225	[million m²]	r_area
130	62	62	1226	7	958	958	30	62	22	22	22	22	22	30	[%]	RR1_04
4	3	3	4	1	4	4	2	3	1	1	1	1	1	2		RR1_04_Q
x	71	71	9	18	68	68	26	71	80	80	80	80	80	26	[%]	RF1_04
x	3	3	1	1	3	3	1	3	4	4	4	4	4	1		RF1_04_Q
157118	5492	2974	21572	1216	1901	433	14701	23347	32879	2729	93	3925	3324	7304	count	Res
4	3	3	4	2	2	2	4	4	4	3	1	3	3	3		Res_Q
4	7	5	1	1										2	count	PA_No
201191338	272057695	55096399	556508	357805	0	0	0	0	0	0	0	0	0	322811489	[m²]	PA
4	4	4	3	3	1	1	1	1	1	1	1	1	1	4		PA_Q
8	7	7	3	3	2	3	7	3	9	8	8	6	5	7	count	MF
4	3	3	1	1	1	1	3	1	4	4	4	3	2	3		MF_Q
150084219	124541269	9049881	13140229	17672070	15797011	1542745	17551501	106927676	54301816	4421484	10123	1063459	2735909	29503594	[m³/year]	PE
4	4	3	4	4	4	2	4	4	4	3	1	2	3	4		PE_Q
94	1907155	x	20784016	24744260	3327066	4975103	1470	x	859116	2858405	661	321397	3542357	8820319	[t/year]	SE
140485611	12107	x	39	92	872	16	679541	x	23603	134	1580	299	80	309	[year]	Lifespan
1	2	x	4	4	3	4	1	x	1	3	3	3	4	3		SE_Q
131328366	137668072	22172888	48423240	35844817	12146474	0	63012907	20145429	223325879	31973698	71661	7477506	11472678	841813	[m²]	LU_C
4	4	4	4	4	3	1	4	4	4	4	2	3	3	2		LU_C_Q
x	26	x	25	20	21	18	20	x	23	23	17	20	21	22		SUM_Q

11118	11113	11110	11106	11104	11103	11081	11079	11076	11074	11073	11072	11069	11068	11066		HPPD_ID
2100	13	6	8	9	24	2192	9	2	1062	1	20	360	1	4	[MW]	Cap
x	13	19	52	44	230	4942	694	0	2614	1	33	1035	167	616	[million m³]	r_vol
x	3	5	14	14	49	439	76	0	499	6	0	63	15	82	[million m²]	r_area
x	39	39	10	10	10	14	10	105	46	46	46	105	105	44	[%]	RRI_04
x	2	2	1	1	1	1	1	3	2	2	2	3	3	2		RRI_04_Q
x	50	50	81	81	81	x	81	64	49	49	49	64	64	19	[%]	RFI_04
x	2	2	4	4	4	x	4	3	2	2	2	3	3	1		RFI_04_Q
x	649	436	1550	1738	4859	70870	13183	12	238484	70	91	10699	45573	32604	count	Res
x	2	2	2	2	3	4	4	1	4	1	1	4	4	4		Res_Q
x	1	1			1	3			2		1	2		3	count	PA_No
x	187340	273410	0	0	13789792	112057721	0	0	12962097	0	257984	24307154	0	13327781	[m²]	PA
x	3	3	1	1	4	4	1	1	4	1	3	4	1	4		PA_Q
x	6	7	8	8	8	10	7	7	8	8	7	8	5	3	count	MF
x	3	3	4	4	4	4	3	3	4	4	3	4	2	1		MF_Q
x	468375	605187	1723633	1767357	6065310	47677854	9145866	1055	69068581	809292	33918	9620054	2603476	15283112	[m³/year]	PE
x	1	2	2	2	3	4	3	1	4	2	1	3	3	4		PE_Q
x	1049533	1283658	997754	109469	5449805	15325810	x	43	x	114802	233399	1476592	41953	214771	[t/year]	SE
x	33	39	138	1053	112	855	x	3130	x	12	371	1858	10575	7600	[year]	Lifespan
x	4	4	3	3	4	3	x	2	x	4	3	2	2	2		SE_Q
x	2142853	0	0	4604150	38368269	17430549	17121900	0	91128126	20966	0	616519	14894933	37149586	[m²]	LU_C
x	3	1	1	3	4	4	4	1	4	2	1	2	3	4		LU_C_Q
x	20	19	18	20	27	x	x	15	x	18	16	25	21	22		SUM_Q

11194	11193	11191	11187	11186	11185	11178	11175	11174	11158	11157	11156	11152	11149	11148		HPPD_ID
287	147	480	150	160	238	12	10	30	63	30	38	18	12	26	[MW]	Cap
313	205	2	2406	6782	24194	1383	67	1467	1003	983	136	1	11	91	[million m³]	r_vol
4	3	0	103	203	959	35	12	36	38	39	7	0	1	3	[million m²]	r_area
27	27	94	107	107	92	109	398	398	533	533	533	533	533	533	[%]	RR1_04
2	2	3	3	3	3	3	4	4	4	4	4	4	4	4		RR1_04_Q
61	61	67	6	6	52	81	65	65	56	56	56	56	56	56	[%]	RF1_04
2	2	3	1	1	2	4	3	3	2	2	2	2	2	2		RF1_04_Q
5367	4425	27	29626	45223	13120	801	3565	21628	120890	1539	2756	35	406	719	count	Res
3	3	1	4	4	4	2	3	4	4	2	3	1	2	2		Res_Q
					5	2			1	1			1	3	count	PA_No
0	0	0	0	0	629373844	30640554	0	0	27761625	3340999	0	0	320575	1692724	[m²]	PA
1	1	1	1	1	4	4	1	1	4	3	1	1	3	3		PA_Q
6	6	2	4	4	5	1	1	1	1	1	1	1	1	1	count	MF
3	3	1	2	2	2	1	1	1	1	1	1	1	1	1		MF_Q
443152	329407	38753	13106717	25897728	132110856	4048068	1259695	3865234	4290385	4449079	777867	14470	83723	383897	[m3/year]	PE
1	1	1	4	4	4	3	2	3	3	3	2	1	1	1		PE_Q
2673	4922776	x	1966688	713965	18136723	1386709	357669	80	79	1124501	1404301	283349	6177298	21643	[t/year]	SE
310179	110	x	3242	25172	3535	2644	495	48500743	33860652	2316	256	12	5	11103	[year]	Lifespan
1	4	x	2	1	2	2	3	1	1	2	3	4	4	2		SE_Q
1570194	917657	0	37997659	108468647	43166557	7545957	3977637	26437227	22073197	5457411	505590	0	312007	550104	[m²]	LU_C
3	2	1	4	4	4	3	3	4	4	3	2	1	2	2		LU_C_Q
16	18	x	21	20	25	22	20	21	23	20	18	15	19	17		SUM_Q

10238	10235	10234	10233	10232	10215	10214	10213	10212	10211	10204	10185	10176	10175	10174	10167	10145	10093	10049	10047	10043	10038	10037	10036	10035	10034	10033	10028	HPPD_ID
2	2	1	3	2	3	2	3	4	4	2	2	1	1	1	2	3	2	4	4	2	2	1	1	3	3	3	3	Ranking_all continent
10300 10300 40260 34260	10300 10300 34260 34260	10300 10300 34260 34260	10300 10300 34260 34260	10300 10300 08100 34260	10300 10300 34260 34260	10300 10300 34260 34260	10300 10300 40260 34260	10300 10300 34260 34260	10300 10300 20040 34260	10300 10300 20040 20050	10300 10300 20040 20050	10300 10300 20050 20050	10300 10300 20050 20050	10300 10300 20050 20050	10300 10300 20050 20050	10300 10300 34260 20040	10300 10300 20040 20050	10300 10300 20050 20050	10300 10300 20050 20050	10300 10300 20040 20050	10300 10300 20040 20050	10300 10300 20040 20050	10300 10300 20050 20050	10300 10300 20040 20050	10300 10300 20050 20050	10300 10300 20050 20050	10300 10300 22420	HYBAS_ID
	Nile	Nile	Nile		Nile	Nile			Congo	Congo						Nile	Congo			Congo	Congo	Congo					Niger	Basin name
	2	1	3		3		4	4	2	3						2	2			2	3	2		4			3	Ranking_all basin
2	2	1	3	2	2	2	4	4	2	2	2	1	1	1	2	2	2	4	4	2	3	1	2	3	3	3	4	Ex_RRI
2	1	1	3		3	3	4	4	2	3	3	1	1	1	3	3	3	4	4	3	2	1	1	3	3	3	4	Ex_RFI
2	2	1	3	2	3	2	4	4	1	2					2	3	2	3	4	2	2	1	1	3	3	3	3	Ex_Res
3	2	2	4	1	3	3	4	4	2	3	3	1	1	1	1	2	2	3	3	2	3	1	1	2	3	3	3	Ex_PA
3	3	2	4	2	4	2	4	4	2	2	2	1	1	1	1	2	2	4	4	1	2	1	1	3	3	3	3	Ex_MF
3	3	2	4	2	3	3	4	4	2	3	3	1	1	1	2	3	1	3	4	2	2	1	1	2	3	3	3	Ex_PE
2	2	1	3	1	3	1	4	4	3	3	3	1	1	1	3	2	3	4	4	1	2	1	1	3	4	3	4	Ex_SE
3	2	2	4	2	3	2	4	4	2	2	2	1	1	1	2	3	1	3	4	2	3	1	1	3	4	4	4	Ex_LU_C
2	1	1	2	2	3	2	3	3	3	4	4	2	1	1	4	1	3	4	4	1	2	1	3	2	2	2	4	Ranking A
2	1	1	2	2	1	2	1	2	1	1	1	1	4	1	2	4	1	1	2	4	3	3	1	2	2	4	3	Ranking B
3	3	3	4	1	4	1	4	4	1	1	1	1	1	1	1	2	1	2	2	1	2	1	1	3	3	3	2	Ranking C

10357	10356	10348	10343	10342	10322	10314	10311	10309	10301	10300	10299	10293	10292	10290	10283	10282	10281	10280	10250	10249	10248	10247	10246	10245	10243	10241	10239	HPPD_ID
1	2	1	1	1	1	4	3	2	3	2	3	4	2	4	4	2	4	3	1	1	4	1	1	1	1	4	4	Ranking_all continent
10300 35180	10300 35180	10300 35180	10300 35180	10300 35180	10300 35180	10300 08110	10300 08110	10300 08110	10300 40260	10300 40260	10300 40260	10300 34260	10300 34260	10300 34260	10300 34260	10300 34260	10300 34260	10300 08110	10300 08100	10300 08100	10300 40260	10300 34260	10300 34260	10300 34260	10300 34260	10300 34260	10300 40260	HYBAS_ID
												Nile	Nile	Nile	Nile	Nile	Nile					Nile	Nile	Nile	Nile	Nile		Basin name
												3	2	3	3	2	3					1	1	1	1	4		Ranking_all basin
1	2	1	2	1	1	4	2	2	2	2	3	3	1	3	3	1	3	4	1	1	3	1	1	2	1	4	4	Ex_RRI
1	3	1	1	1	1	4	3	1	3	1	3	4	1	4	4	1	4	4	1	1	4	1	1	1	1	4	4	Ex_RFI
1	2	1	1	1	1	4	3	2	3	3	3	4	2	3	4	2	4	3	1	1	4	1	1	1	1	4	4	Ex_Res
1	2	1	1	1	1	3	3	2	3	2	3	3	2	4	3	1	3	3	2	1	3	1	1	2	1	4	4	Ex_PA
1	3	1	1	1	1	4	3	2	3	3	4	4	2	4	4	2	4	4	2	1	4	1	1	1	1	4	4	Ex_MF
1	2	1	1	1	1	4	3	2	3	3	4	4	2	4	3	2	4	3	1	1	4	1	1	1	1	4	4	Ex_PE
1	1	1	1	1	1	4	3	1	3	1	4	4	1	4	4	2	4	4	1	1	3	1	1	1	1	4	4	Ex_SE
1	1	1	1	1	1	4	2	2	3	3	3	4	2	3	3	2	3	3	1	1	4	1	1	2	1	4	4	Ex_LU_C
2	3	1	2	1	1	4	2	1	2	1	4	4	1	4	4	2	4	4	1	1	2	2	1	1	1	4	4	Ranking A
1	2	2	1	1	1	1	2	3	2	2	1	2	3	3	1	1	2	1	1	1	3	2	4	4	3	1	1	Ranking B
1	1	1	1	1	1	3	3	1	3	3	3	3	2	3	4	2	3	2	3	2	4	1	1	1	1	4	4	Ranking C

10581	10579	10578	10577	10576	10575	10574	10573	10572	10571	10570	10569	10535	10526	10479	10474	10469	10459	10452	10431	10421	10414	10412	10410	10402	10398	10395	10358	HPPD_ID
3	1	1	1	1	4	1	1	1	1	1	3	1	1	3	1	1	1	2	1	4	4	3	4	1	2	3	1	Ranking_all continent
10300 18110	10300 18110	10300 18110	10300 18110	10300 18110	10300 18110	10300 18110	10300 18110	10300 18110	10300 18110	10300 18110	10300 18110	10300 34260	10300 34260	10300 34260	10300 11660	10300 11660	10300 08110	10300 08110	10300 11660	10300 34260	10300 34260	10300 34260	10300 34260	10300 34260	10300 34260	10300 34260	10300 35180	HYBAS_ID
												Nile	Nile	Nile	Zambezi	Zambezi			Zambezi	Nile	Nile	Nile	Nile	Nile	Nile	Nile		Basin name
												1	1	2	1	1			2	3	4	3	3	1	2	3		Ranking_all basin
3	1	1	2	1	4	1	1	1	1	1	2	1	1	2	1	1	1	2	1	3	4	3	3	2	1	3	2	Ex_RRI
4	1	1	1	1	4	1	1	1	1	1	3	1	1	3	1	1	1	3	1	3	4	3	3	1	1	4	1	Ex_RFI
3	1	1	1	1	4	1	1	2	2	1	3	1	2	3	1	1	1	2	1	4	4	3	4	1	2	3	1	Ex_Res
3	1	1	2	1	4	1	2	2	2	1	3	1	1	3	1	1	1	1	4	4	4	4	2	2	4	1	Ex_PA	
4	1	1	1	1	4	1	1	1	1	1	4	1	1	3	1	1	1	2	1	4	4	4	1	2	4	1	Ex_MF	
3	1	1	1	1	4	1	1	1	2	1	2	1	2	4	1	1	1	2	1	3	4	3	4	1	2	3	1	Ex_PE
3	1	1	1	1	4	1	1	1	1	1	3	1	1	3	1	1	1	3	1	4	4	4	2	1	4	1	Ex_SE	
3	1	1	1	1	4	1	2	2	2	1	3	1	2	3	1	1	1	2	1	4	3	4	1	2	3	1	Ex_LU_C	
4	1	1	2	1	4	1	1	1	1	1	2	1	1	2	1	1	2	3	1	2	2	3	1	4	4	3	Ranking A	
1	1	1	1	1	1	1	1	2	3	1	1	1	1	4	1	1	1	1	1	4	1	3	1	2	1	1	Ranking B	
3	1	1	1	1	4	2	3	3	2	2	4	2	2	2	1	1	1	2	4	4	4	4	1	2	4	1	Ranking C	

10770	10762	10761	10760	10754	10748	10745	10744	10743	10741	10722	10680	10672	10670	10669	10653	10650	10649	10647	10642	10638	10637	10602	10596	10594	10585	10584	10583	HPPD_ID
2	2	2	3	1	1	1	1	3	2	4	1	4	1	1	3	2	1	2	2	1	1	1	1	1	1	1	1	Ranking_all continent
10300 11670 20040	10300 20040	10300 20040	10300 20040	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 18110	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 11660 11660	10300 18110 18110	10300 18110 18110	10300 18110 18110	10300 18110 18110	10300 18110 18110	10300 18110 18110	HYBAS_ID	
	Congo	Congo	Congo	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi		Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi						Basin name	
	3	2	4	1	2	1	1	3	3	4		4	2	2	4	2	1	3	3	2	2						Ranking_all basin	
2	2	2	3	1	2	1	1	2	2	4	1	4	1	1	3	2	1	2	2	1	1	1	1	1	1	1	Ex_RRI	
2	3	2	3	1	1	1	1	3	1	4	1	4	1	1	4	2	1	3	2	1	1	1	1	1	1	1	Ex_RFI	
2	3	3	3	1	1	1	1	3	2	4	2	4	2	2	3	2	1	2	1	1	2	1	1	1	1	1	Ex_Res	
3	2	1	2	1	1	1	1	2	1	4	1	4	2	2	3	1	1	2	2	1	1	1	1	1	1	1	Ex_PA	
3	2	2	3	1	1	1	1	4	2	4	1	4	1	1	4	2	1	2	2	1	1	1	1	1	1	1	Ex_MF	
3	2	2	3	1	1	1	1	2	2	4	1	4	2	1	3	2	1	2	2	1	2	1	1	1	1	1	Ex_PE	
2	3	2	3	1	2	1	1	3	1	4	2	4	1	2	3	1	1	1	1	1	1	1	1	1	1	1	Ex_SE	
2	3	3	3	1	2	1	1	3	2	4	2	4	2	1	3	2	1	2	2	1	1	1	1	1	1	1	Ex_LU_C	
2	2	2	3	1	2	1	1	3	2	4	2	4	1	1	3	2	1	2	2	1	2	1	1	1	1	1	Ranking A	
2	2	2	2	1	1	2	3	1	3	1	1	1	3	1	3	2	1	3	2	3	2	1	2	2	1	1	Ranking B	
2	2	2	3	2	1	1	1	3	1	3	2	4	2	3	2	1	1	1	1	1	3	1	1	2	2	3	Ranking C	

10913	10912	10911	10909	10908	10907	10906	10901	10899	10895	10878	10877	10876	10871	10860	10853	10852	10847	10833	10832	10825	10822	10820	10794	10793	10787	10786	10783	HPPD_ID
2	3	3	2	2	2	3	2	2	3	4	4	3	4	2	4	4	4	4	2	3	4	4	4	4	1	1	4	Ranking_all continent
10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23300	10300 23300	10300 23300	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23300	10300 23300	10300 23310	10300 22430	10300 22430	10300 11670	10300 11670	10300 11660	HYBAS_ID
										Volta	Volta	Volta								Volta	Volta					Zambezi	Basin name	
										3	4	3								2	4					4	Ranking_all basin	
3	3	3	2	2	2	3	3	2	4	4	4	3	4	2	4	4	4	4	2	3	4	4	4	4	2	1	3	Ex_RRI
1	2	2	1	1	1	2	1	1	3	4	4	3	4	1	4	4	4	4	2	3	4	4	4	4	1	1	4	Ex_RFI
2	2	2	2	2	2	2	3	2	3	4	4	3	3	2	4	4	4	4	2	2	4	4	4	4	2	1	4	Ex_Res
3	3	3	2	2	2	3	3	2	3	3	4	3	4	2	4	4	4	4	1	2	4	4	3	4	1	1	3	Ex_PA
3	3	3	2	2	2	3	2	1	4	4	4	3	4	1	4	4	4	4	1	3	4	4	4	4	2	1	4	Ex_MF
2	2	2	1	2	2	2	3	2	4	3	4	3	3	2	4	4	4	4	2	2	4	4	4	4	2	1	4	Ex_PE
3	3	3	2	2	2	3	2	1	3	4	4	4	4	2	4	4	4	4	2	3	4	4	4	4	1	1	3	Ex_SE
2	3	3	2	2	2	3	2	2	3	4	4	3	3	1	4	4	4	4	2	3	4	4	4	4	2	1	4	Ex_LU_C
2	3	3	1	2	1	3	2	1	4	4	3	3	4	1	4	3	4	4	2	4	4	4	4	4	1	1	3	Ranking A
1	1	1	1	1	2	1	3	4	3	1	4	2	3	2	2	4	3	3	2	1	3	3	4	2	1	1	3	Ranking B
3	3	3	3	2	3	3	2	1	2	4	4	3	3	2	3	3	4	3	1	1	4	2	2	3	1	1	3	Ranking C

11039	11036	11024	11023	11021	11012	11009	11002	10989	10986	10984	10980	10970	10968	10965	10962	10956	10944	10926	10924	10922	10921	10920	10919	10917	10916	10915	10914	HPPD_ID
2	3	4	4	2	3	3	3	3	4	4	3	1	2	2	1	1	3	2	3	3	2	2	3	2	3	1	2	Ranking_all continent
10300 27410	10300 22420	10300 23310	10300 23310	10300 23310	10300 23310	10300 22420	10300 22420	10300 27410	10300 27410	10300 27410	10300 27410	10300 23310	10300 23310	10300 27410	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	10300 23310	HYBAS_ID
	Niger					Niger	Niger																					Basin name
	2					3	2																					Ranking_all basin
2	3	4	4	2	3	4	3	4	4	4	3	2	3	1	2	1	3	2	4	3	3	2	4	2	3	1	3	Ex_RRI
1	3	3	3	1	2	4	4	4	4	4	3	1	1	1	1	2	1	1	3	2	1	1	3	1	2	1	1	Ex_RFI
2	2	3	4	2	3	3	3	4	4	4	3	1	2	2	1	2	2	3	3	3	2	3	3	1	3	1	2	Ex_Res
2	3	4	4	2	3	3	3	4	4	4	4	2	3	2	1	3	2	2	3	3	2	2	3	2	2	1	3	Ex_PA
3	3	4	4	1	3	4	4	4	4	4	4	1	2	2	1	3	2	2	4	3	2	1	4	2	3	1	3	Ex_MF
2	2	3	4	2	3	3	3	4	4	4	3	1	2	2	1	3	2	2	3	3	2	2	3	2	3	1	3	Ex_PE
1	3	4	4	1	3	3	3	4	4	4	3	2	3	2	1	3	1	1	4	3	2	2	3	1	3	1	2	Ex_SE
3	2	3	3	2	3	4	4	4	4	4	4	1	3	2	1	3	2	2	3	3	2	1	3	2	3	1	2	Ex_LU_C
1	4	4	3	1	2	4	2	4	4	4	2	2	2	1	1	3	1	1	4	2	2	2	3	1	4	1	2	Ranking A
2	1	2	4	4	3	4	3	4	1	1	2	1	2	1	1	2	1	3	1	3	1	2	2	2	1	1	2	Ranking B
3	2	3	3	1	2		2	4	4	4	4	2	3	3	3	1	3	2	3	2	2	2	3	2	2	1	2	Ranking C

11193	11187	11186	11185	11178	11175	11174	11158	11157	11156	11152	11149	11148	11113	11110	11106	11104	11103	11076	11073	11072	11069	11068	11066	11048	11045	11042	11041	HPPD_ID
2	3	3	4	3	3	3	4	3	2	1	2	2	3	2	2	3	4	1	2	1	4	3	3	4	4	3	3	Ranking_all continent
10300 20040	10300 11660	10300 11660	10300 11660	10300 29810	10300 27430	10300 27430	10300 27430	10300 27430	10300 27430	10300 27430	10300 27430	10300 27430	10300 23300	10300 23300	10300 22430	10300 22430	10300 22430	10300 22420	10300 22420	10300 22420	10300 22420	10300 22420	10300 22420	10300 22420	10300 27410	10300 27410	10300 27410	HYBAS_ID
Congo	Zambe zi	Zambe zi	Zambe zi										Volta	Volta				Niger	Niger	Niger	Niger	Niger	Niger				Basin name	
	2	4	3	4									2	1				1	1	1	4	2	3	4			Ranking_all basin	
	2	3	2	4	3	2	2	3	2	1	2	1	3	2	2	3	4	1	2	2	4	3	4	4	4	3	2	Ex_RRI
	2	4	3	4	3	3	4	3	2	1	3	1	3	3	1	2	4	1	2	1	4	3	4	4	4	3	3	Ex_RFI
2	3	2	4	4	3	3	3	3	2	1	3	2	3	3	2	3	4	1	3	2	4	3	4	4	3	3	Ex_Res	
2	3	3	4	3	3	3	3	2	2	1	2	1	2	2	2	3	4	1	2	1	4	3	3	4	4	2	3	Ex_PA
2	4	3	4	4	4	4	4	4	3	1	3	2	3	2	1	2	4	1	1	1	4	4	4	4	4	4	4	Ex_MF
3	3	2	4	3	3	3	4	3	2	1	3	2	3	3	2	3	4	1	2	2	4	3	3	4	4	2	3	Ex_PE
1	3	3	4	4	3	4	4	3	2	1	2	2	2	2	2	3	4	1	1	1	4	3	4	4	4	2	3	Ex_SE
2	3	2	4	3	3	3	3	3	2	1	3	2	3	3	3	3	4	1	2	2	4	3	3	4	4	2	3	Ex_LU_C
2	4	4	4	4	2	4	4	3	2	1	2	2	3	2	1	2	4	1	1	1	4	3	4	4	4	4	2	Ranking A
4	1	1	1	1	1	1	1	2	1	2	2	1	4	4	4	4	4	2	4	3	1	1	1	2	2	2	1	Ranking B
1	3	3	3	4	3	4	3	3	3	2	2	2	1	1	2	2	3	2	1	1	3	3	2	4	3	1	4	Ranking C

11226	11202	11197	11196	11194	HPPD_ID
3	4	3	2	1	Ranking_all continent
10300	10300	10300	10300	10300	HYBAS_ID
34260	34260	23310	23310	20040	
Nile	Nile			Congo	Basin name
3	4			2	Ranking_all basin
3	4	4	3	2	Ex_RRI
3	4	3	2	1	Ex_RFI
3	4	3	3	1	Ex_Res
4	4	4	2	2	Ex_PA
4	4	4	2	1	Ex_MF
3	4	3	3	2	Ex_PE
3	4	3	2	2	Ex_SE
3	4	3	2	1	Ex_LU_C
2	4	4	2	2	Ranking A
2	3	3	4	1	Ranking B
4	3	2	1	1	Ranking C

Table A.4: Proposed hydropower plants of Type Reservoir and unknown. Each hydropower plant (HPP) can be identified with the respective HPPD_ID from the Renewable Power Plant Database (RePP) Africa (Peters et al., 2023). Calculation of impact per indicator and resulting quartile (Q) for River Regulation (RRI, HydroBASIN level 04), River Fragmentation (RFI, HydroBASIN level 04), Resettlement (Res), Protected Area (PA), Megafauna (MF), Potential Evaporation (PE), Sediment Entrapment (SE) and resulting Lifespan, and Land Use Change for Cropland for Cropland (LU_C). Quartile values are indicated with 1 (low impact, $\leq 1^{st}$ quartile), 2 (moderate impact, $>1^{st}$ to $\leq 2^{nd}$ quartile), 3 (heavy impact, $>2^{nd}$ to $\leq 3^{rd}$ quartile), and 4 (severe impact, $>3^{rd}$ quartile).

	10019	10018	10017	10016	10015	10010	10008	10007	10006	HPPD_ID
640	1800	365	250	1000	6	200	470	1000		Cap
0	1327	135	1217	112	72	71	72	x		[million m ³] r_vol
0	67	18	64	34	18	10	5	x		[million m ²] r_area
39	39	1	39	39	10	14	39	39		RRI_04
2	2	1	2	2	1	1	2	2		RRI_04_Q
78	78	45	78	78	43	49	78	78		RFI_04
3	3	2	3	3	1	2	3	3		RFI_04_Q
1	1820	796	416	37258	1403	2151	165	x		Res
1	3	2	2	4	3	3	1	x		Res_Q
				1				x		PA_No
0	0	0	0	17171062	0	0	0	x		PA
1	1	1	1	4	1	1	1	x		PA_Q
9	9	8	9	9	7	10	8	x		MF
4	4	4	4	4	3	4	4	x		MF_Q
1852	7272455	1814803	6777019	3589321	1960770	1062120	542766	x		pE
1	4	3	4	3	3	2	2	x		pE_Q
50141	6498931	2408528	30	1127706	x	14413530	21871669	x		SE
5	541	148	106277653	264	x	13	9	x		Lifespan
4	3	3	1	3	x	4	4	x		SE_Q
7349	3964642	2269177	4745438	630680	2782449	0	0	x		LU_C
2	3	3	3	2	3	1	1	x		LU_C_Q
18	23	19	20	25	x	18	18	x		SUM_Q

10040	10038	10037	10036	10035	10034	10033	10031	10028	10027	10025	10024	10022	10021	10020		HPPD_ID
20	180	40	1	600	400	1200	5	485	72	67	66	33	5	940	[MW]	Cap
x	492	90	99	3251	1579	1577	1	3604	1993	2513	25	36	57	30	[million m³]	r_vol
x	65	25	15	111	108	85	0	68	53	245	1	5	21	9	[million m²]	r_area
2	10	0	1	10	39	39	0	49	49	49	49	2	39	39	[%]	RRI_04
1	1	1	1	1	2	2	1	3	3	3	3	1	2	2		RRI_04_Q
23	43	52	45	43	78	78	x	72	72	72	72	23	78	78	[%]	RFI_04
1	1	2	2	1	3	3	x	3	3	3	3	1	3	3		RFI_04_Q
x	2375	204	18764	1517	7181	10456	23	5368	23662	1899	122	291	114	92	count	Res
x	3	1	4	3	4	4	1	3	4	3	1	1	1	1		Res_Q
x				1				1							count	PA_No
x	0	0	0	45325338	0	0	0	6870267	0	0	0	0	0	0	[m²]	PA
x	1	1	1	4	1	1	1	4	1	1	1	1	1	1		PA_Q
x	7	5	5	6	9	8	10	9	10	9	9	6	7	9	count	MF
x	3	2	2	2	4	4	4	4	4	4	4	2	3	4		MF_Q
x	6746656	2890490	1483545	10663587	12341525	9431898	19013	7820842	5824247	29551980	164761	654628	2349331	1006429	[m³/year]	PE
x	4	3	2	4	4	4	1	4	3	4	1	2	3	2		PE_Q
x	7318510	10683518	10507	3347491	20	7186173	218392	6020412	3708997	1152088	170848	4635378	5542075	19010349	[t/year]	SE
x	178	22	24861	2574	211904235	581	11	1586	1424	5781	383	21	27	4	[year]	Lifespan
x	3	4	1	2	1	3	4	2	2	2	3	4	4	4		SE_Q
x	1084786	0	12832623	0	2233150	0	182993	411023	4526014	99076	0	0	19504	107594	[m²]	LU_C
x	3	1	4	1	3	1	2	2	3	2	1	1	2	2		LU_C_Q
x	19	15	17	18	22	22	x	25	23	22	17	13	19	19		SUM_Q

10066	10065	10064	10063	10060	10059	10058	10054	10053	10052	10051	10049	10047	10043	10042		HPPD_ID
7	5	9	24	14	9	28	800	950	1968	650	1000	1000	300	2	[MW]	Cap
158	36	338	310	18	9	1659	x	x	11	24	16535	12646	131	156	[million m³]	r_vol
24	11	74	45	12	2	120	x	x	11	9	996	833	62	34	[million m²]	r_area
10	10	11	11	11	11	11	9	9	9	9	45	45	0	1	[%]	RRI_04
1	1	1	1	1	1	1	1	1	1	1	3	3	1	1		RRI_04_Q
43	43	3	3	3	3	3	51	51	51	51	51	51	52	x	[%]	RFI_04
1	1	1	1	1	1	1	2	2	2	2	2	2	2	x		RFI_04_Q
407	182	1007	237	131	61	590	x	x	384	812	11907	8437	1081	453	count	Res
2	1	2	1	1	1	2	x	x	2	2	4	4	2	2		Res_Q
1	1					1	x	x			3	2			count	PA_No
25736067	7900488	0	0	0	0	43196533	x	x	0	0	234331146	246482932	0	0	[m²]	PA
4	4	1	1	1	1	4	x	x	1	1	4	4	1	1		PA_Q
7	7	7	7	10	11	8	x	x	10	11	7	6	10	6	count	MF
3	3	3	3	4	4	4	x	x	4	4	3	2	4	2		MF_Q
2371894	1067138	7683670	4562171	1293239	264707	12439603	x	x	1173768	909205	98590496	82514112	6978078	4134366	[m³/year]	PE
3	2	4	3	2	1	4	x	x	2	2	4	4	4	3		PE_Q
64	49	1385124	354715	32	198068	906186	x	x	345476122	216	2204964	844133	69263736	434320	[t/year]	SE
6486745	1954637	646	2315	1504822	117	4852	x	x	x	297076	19873	39699	5	951	[year]	Lifespan
1	1	3	2	1	3	2	x	x	x	1	1	1	4	3		SE_Q
2786017	2383988	9487781	6677646	1880836	234688	42435446	x	x	0	52745	98895767	79625983	295532	0	[m²]	LU_C
3	3	4	4	3	2	4	x	x	1	2	4	4	2	1		LU_C_Q
18	16	19	16	14	14	22	x	x	x	15	25	24	20	x		SUM_Q

10106	10105	10104	10103	10095	10094	10093	10091	10090	10084	10076	10074	10071	10070	10069		HPPD_ID
6706	6684	6970	7180	600	18	150	60	50	3	3	4	2	8	8	[MW]	Cap
704	704	704	704	834	1	12089	23	38	38	20	254	0	3	72	[million m³]	r_vol
22	22	22	22	152	0	371	8	10	3	4	87	0	1	21	[million m²]	r_area
9	9	9	9	10	11	11	9	45	10	10	10	10	10	10	[%]	RRI_04
1	1	1	1	1	1	1	1	3	1	1	1	1	1	1		RRI_04_Q
51	51	51	51	43	3	3	51	51	43	43	43	43	43	43	[%]	RFI_04
2	2	2	2	1	1	1	2	2	1	1	1	1	1	1		RFI_04_Q
2890	2890	2890	2890	1031	13	3616	933	146	12	58	63	3	4	393	count	Res
3	3	3	3	2	1	3	2	1	1	1	1	1	1	2		Res_Q
				5				2			3	1		1	count	PA_No
0	0	0	0	103346520	0	0	0	2965376	0	0	16518169	94470	0	22768626	[m²]	PA
1	1	1	1	4	1	1	1	4	1	1	4	3	1	4		PA_Q
11	11	11	11	8	7	7	11	6	10	7	10	7	7	7	count	MF
4	4	4	4	4	3	3	4	2	4	3	4	3	3	3		MF_Q
2102755	2102755	2102755	2102755	15076837	9458	37830034	867355	939378	333151	391952	8442774	7697	121703	2091530	[m³/year]	PE
3	3	3	3	4	1	4	2	2	1	2	4	1	1	3		PE_Q
x	x	x	90	x	x	330	223	9282265	39522	104	1758711	301317	333447	424851	[t/year]	SE
x	x	x	20765561	x	x	96956047	268750	11	2567	498758	383	1	26	448	[year]	Lifespan
x	x	x	1	x	x	1	1	4	2	1	3	4	4	3		SE_Q
15769513	15769513	15769513	15769513	560918	1373	52814291	3715	3636445	1118210	1907153	9688063	77423	0	8715202	[m²]	LU_C
4	4	4	4	2	2	4	2	3	3	3	4	2	1	4		LU_C_Q
x	x	x	19	x	x	18	15	21	14	13	22	16	13	21		SUM_Q

10123	10122	10121	10120	10119	10118	10117	10116	10115	10114	10112	10111	10110	10109	10108	10107	HPPD_ID
53	36	8	66	120	204	153	16	30	3	128	2	22	12	22	4800	Cap
28	109	0	1	220	400	3108	13	105	138	35	112	0	1	7	704	Cap
9	14	0	0	11	53	232	4	12	52	6	8	0	0	3	22	Cap
8	8	19	19	19	19	19	2	2	2	2	2	2	2	9	9	Cap
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Cap
46	46	75	75	75	75	75	17	17	17	17	17	17	17	51	51	Cap
2	2	3	3	3	3	3	1	1	1	1	1	1	1	2	2	Cap
425	759	56	21	454	3790	4356	793	2274	3502	188	524	86	70	127	2890	Cap
2	2	1	1	2	3	3	2	3	3	1	2	1	1	1	3	Cap
			2						1							Cap
0	0	0	277357	0	0	0	0	0	21421767	0	0	0	0	0	0	Cap
1	1	1	3	1	1	1	1	1	4	1	1	1	1	1	1	Cap
10	10	6	8	6	7	5	5	5	5	3	4	4	5	10	11	Cap
4	4	2	4	2	3	2	2	2	2	1	1	1	2	4	4	Cap
1062439	1658090	21002	14806	1302461	6779901	29202904	470947	1347610	5845557	630285	881131	1925	10292	343935	2102755	Cap
2	3	1	1	2	4	4	2	2	3	2	2	1	1	1	3	Cap
2830440	89999626	x	x	2125882	2219537	2811450	x	810650	24	6219723	10303	x	536086	x	x	Cap
26	3	x	x	274	478	2930	x	343	15413172	15	28866	x	4	x	x	Cap
4	4	x	x	3	3	2	x	3	1	4	1	x	4	x	x	Cap
0	2309345	0	50575	0	0	3964912	2084023	2502527	101795	58959	0	0	0	1143	15769513	Cap
1	3	1	2	1	1	3	3	3	2	2	1	1	1	2	4	Cap
17	20	x	x	15	19	19	x	16	17	13	10	x	12	x	x	Cap

10140	10139	10138	10137	10136	10135	10134	10133	10132	10131	10130	10129	10128	10127	10126	10124		HPPD_ID
5	42	60	3	50	20	50	460	17	688	38	50	14	6747	13	21	[MW]	Cap
516	335	204	2	64	5	43	60	13	43	5	2	290	704	78	40	[million m³]	r_vol
169	55	31	1	19	3	12	17	8	58	2	1	76	22	45	11	[million m²]	r_area
8	8	8	8	8	8	8	8	8	8	8	8	8	9	8	8	[%]	RRI_04
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		RRI_04_Q
46	46	46	46	46	46	46	46	46	46	46	46	46	51	46	46	[%]	RFI_04
2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2		RFI_04_Q
5745	3916	243	35	339	299	32309	51620	56960	424	180	30	1341	2890	1264	528	count	Res
4	3	1	1	2	2	4	4	4	2	1	1	2	3	2	2		Res_Q
																count	PA_No
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[m²]	PA
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		PA_Q
8	11	6	5	8	8	12	12	8	12	6	10	10	11	10	10	count	MF
4	4	2	2	4	4	4	4	4	4	2	4	4	4	4	4		MF_Q
17754936	5963370	3541083	89107	2069491	304107	1300419	1838245	802942	6204484	175322	92814	8382338	2102755	5121484	1271314	[m³/year]	PE
4	3	3	1	3	1	2	3	2	4	1	1	4	3	3	2		PE_Q
28	1531	103	481584	170	8029794	3130858	1531	2151459	32960266	x	x	1355	x	321	134	[t/year]	SE
49536295	579747	5261341	10	996947	2	36	103727	15	3	x	x	567462	x	640204	785491	[year]	Lifespan
1	1	1	4	1	4	4	1	4	4	x	x	1	x	1	1		SE_Q
449402	4807617	0	0	0	259235	1843756	2197300	6039230	2100588	96878	90819	3645276	15769513	1439141	19666	[m²]	LU_C
2	3	1	1	1	2	3	3	3	3	2	2	3	4	3	2		LU_C_Q
19	18	12	13	15	17	21	19	21	21	x	x	18	x	17	15		SUM_Q

10158	10156	10155	10154	10153	10152	10151	10150	10149	10148	10147	10146	10145	10144	10143	10142		HPPD_ID
5	15	28	10	30	240	36	3	4	5	3	40	28	6	6	3	[MW]	Cap
8	50	22	2	350	143	35	151	0	53	2	5	8	0	1	40	[million m³]	r_vol
3	18	5	0	16	12	2	2	0	4	0	1	1	0	0	14	[million m²]	r_area
2	33	8	8	8	33	33	8	596	8	8	8	596	596	596	2	[%]	RRI_04
1	2	1	1	1	2	2	1	4	1	1	1	4	4	4	1		RRI_04_Q
17	40	46	46	46	40	40	46	81	46	46	46	81	81	81	17	[%]	RFI_04
1	1	2	2	2	1	1	2	4	2	2	2	4	4	4	1		RFI_04_Q
49	5911	264	112	9889	9568	26660	948	226	3551	128	1276	20	7	4	244	count	Res
1	4	1	1	4	4	4	2	1	3	1	2	1	1	1	1		Res_Q
	1											3	3	3		count	PA_No
0	2984619	0	0	0	0	0	0	0	0	0	0	4321021	356789	451242	0	[m²]	PA
1	4	1	1	1	1	1	1	1	1	1	1	4	3	3	1		PA_Q
2	7	6	7	5	6	6	5	7	5	5	5	8	8	7	5	count	MF
1	3	2	3	2	2	2	2	3	2	2	2	4	4	3	2		MF_Q
366783	2367283	611434	36164	1641090	1379228	239525	183287	3708	426529	35955	68566	144461	9687	14531	1473464	[m³/year]	PE
2	3	2	1	3	2	1	1	1	2	1	1	1	1	1	2		PE_Q
2067555	41	7493924	2460773	13	1580682	4515767	31484	704227	484848	314310	1875	27067	x	18571	x	[t/year]	SE
10	3208340	8	2	71984902	240	21	12741	2	289	13	7755	815	x	97	x	[year]	Lifespan
4	1	4	4	1	3	4	2	4	3	4	2	3	x	3	x		SE_Q
181997	554236	2322675	226194	8662018	8137077	425724	1980194	50400	4960466	0	1047480	0	0	0	448155	[m²]	LU_C
2	2	3	2	4	4	2	3	2	3	1	3	1	1	1	2		LU_C_Q
13	20	16	15	18	19	17	14	20	17	13	14	22	x	20	x		SUM_Q

10211	10206	10204	10203	10201	10185	10184	10183	10182	10181	10180	10179	10176	10175	10174	10167		HPPD_ID
1700	13	10	68	38	8	17	2	2	10	4	2	180	73	35	410	[MW]	Cap
571	518	126	666	1	1041	5	96	61	362	70	95	27	163	20	45	[million m³]	r_vol
39	8	6	33	0	17	0	3	2	9	2	2	6	10	2	10	[million m²]	r_area
340	33	33	596	33	33	33	x	x	x	x	x	0	1	1	0	[%]	RRI_04
4	2	2	4	2	2	2	x	x	x	x	x	1	1	1	1		RRI_04_Q
81	40	40	81	40	40	40	x	x	x	x	x	47	45	45	47	[%]	RFI_04
4	1	1	4	1	1	1	x	x	x	x	x	2	2	2	2		RFI_04_Q
1041	12508	9924	72091	1838	24519	1208	1408	1343	542	1121	446	111	27	28	3055	count	Res
2	4	4	4	3	4	2	3	2	2	2	2	1	1	1	3		Res_Q
1									2	1		1		1	1	count	PA_No
7992235	0	0	0	0	0	0	0	0	10600677	1735744	0	7248011	0	1961687	4934732	[m²]	PA
4	1	1	1	1	1	1	1	1	4	4	1	4	1	4	4		PA_Q
4	6	6	3	6	6	11	4	4	4	4	4	7	9	7	9	count	MF
1	2	2	1	2	2	4	1	1	1	1	1	3	4	3	4		MF_Q
5289469	792751	720399	3735231	14817	1728134	53397	277818	192523	833926	134225	147031	586230	1019579	156324	960644	[m³/year]	PE
3	2	2	3	1	3	1	1	1	2	1	1	2	2	1	2		PE_Q
49915129	1202	31	66	94560	189988	9	x	x	x	x	x	419	662424	1825	28	[t/year]	SE
30	1142650	10784008	26659374	31	14518	1341950	x	x	x	x	x	173187	650	29030	4295234	[year]	Lifespan
4	1	1	1	4	2	1	x	x	x	x	x	1	3	1	1		SE_Q
374262	8086749	5212775	27946906	168867	17113734	218822	0	0	1655710	0	0	181691	0	0	956400	[m²]	LU_C
2	4	3	4	2	4	2	1	1	3	1	1	2	1	1	3		LU_C_Q
24	17	16	22	16	19	14	x	x	x	x	x	16	15	14	20		SUM_Q

10243	10242	10241	10240	10239	10238	10236	10235	10234	10233	10232	10215	10214	10213	10212		HPPD_ID
467	304	424	550	423	150	189	265	278	1600	371	301	88	150	2000	[MW]	Cap
26	76735	22889	483	16322	15	692	132	26	284	188	1262	116	2150	1536	[million m³]	r_vol
3	2310	1400	34	466	2	7	3	2	13	4	21	18	49	64	[million m²]	r_area
8	340	340	340	292	292	340	340	340	340	212	340	9	292	340	[%]	RRI_04
1	4	4	4	4	4	4	4	4	4	4	4	1	4	4		RRI_04_Q
23	81	81	81	69	69	81	81	81	81	75	81	6	69	81	[%]	RFI_04
1	4	4	4	3	3	4	4	4	4	3	4	1	3	4		RFI_04_Q
641	228107	139302	9625	86802	2729	3349	2063	558	7762	1306	8693	1505	17217	10107	count	Res
2	4	4	4	4	3	3	3	2	4	2	4	3	4	4		Res_Q
	1	1		1								1			count	PA_No
0	844941410	618928156	0	95257	0	0	0	0	0	0	0	5124061	0	0	[m²]	PA
1	4	4	1	3	1	1	1	1	1	1	1	4	1	1		PA_Q
4	4	4	3	2	2	3	3	3	3	3	3	1	2	4	count	MF
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		MF_Q
368146	299009007	181219462	4148831	54336092	189238	782156	291188	184313	1611848	568337	2479388	2818423	6082534	7850060	[m³/year]	PE
2	4	4	3	4	1	2	1	1	3	2	3	3	4	4		PE_Q
4028602	x	615	15298335	3539782	3354485	x	1895299	29031	240519548	106608	1213030	74423524	42809044	289935	[t/year]	SE
17	x	98559989	84	12219	12	x	184	2354	3	4683	2756	4	133	14036	[year]	Lifespan
4	x	1	3	2	4	x	3	2	4	2	2	4	3	2		SE_Q
0	987081649	590652171	1867618	262473641	478515	987289	646193	0	97033	2318291	14204787	0	0	15632900	[m²]	LU_C
1	4	4	3	4	2	3	2	1	2	3	4	1	1	4		LU_C_Q
13	x	26	23	25	19	x	19	16	23	18	23	18	21	24		SUM_Q

10294	10293	10292	10290	10283	10282	10281	10280	10259	10257	10250	10249	10248	10247	10246	10245		HPPD_ID
3	50	2	120	25	56	99	34	10	3	256	100	560	1700	166	507	[MW]	Cap
0	291	0	572	3129	0	300	545	0	8	878	173	353	192	64	317	[million m³]	r_vol
0	14	0	19	157	0	29	30	0	1	36	5	25	5	1	10	[million m²]	r_area
596	596	596	596	596	596	596	43	596	596	52	52	292	8	8	8	[%]	RRI_04
4	4	4	4	4	4	4	3	4	4	3	3	4	1	1	1		RRI_04_Q
81	81	81	81	81	81	81	63	81	81	57	57	69	23	23	23	[%]	RFI_04
4	4	4	4	4	4	4	2	4	4	2	2	3	1	1	1		RFI_04_Q
986	2700	236	33638	985	1	97	16531	1711	1229	1694	286	1310	165	514	2881	count	Res
2	3	1	4	2	1	1	4	3	2	3	1	2	1	2	3		Res_Q
1	1			2	1	1	1					2	2			count	PA_No
137173	10101411	0	0	158439864	41342	30651978	7325705	0	0	0	0	15861142	5531660	0	0	[m²]	PA
3	4	1	1	4	3	4	4	1	1	1	1	4	4	1	1		PA_Q
6	5	5	6	5	5	5	2	7	5	2	2	5	6	6	6	count	MF
2	2	2	2	2	2	2	1	3	2	1	1	2	2	2	2		MF_Q
15451	1961355	24309	2547445	21040993	3472	3995771	4537510	12075	108634	5630728	807965	3658979	585186	160893	1347034	[m³/year]	PE
1	3	1	3	4	1	3	3	1	1	3	2	3	2	1	2		PE_Q
37715	679036	2504060	3144740	1480	118	2064545	216667	x	478782	701194	1698063	11603308	86554	2662555	12171336	[t/year]	SE
29	1137	0	482	5602198	1710	385	6671	x	46	3317	270	81	5865	64	69	[year]	Lifespan
4	3	4	3	1	2	3	2	x	4	2	3	3	2	4	4		SE_Q
137173	4797928	193890	21662990	148376783	21054	19961627	26007559	59496	872919	403110	0	0	0	0	0	[m²]	LU_C
2	3	2	4	4	2	4	4	2	3	2	1	1	1	1	1		LU_C_Q
22	26	19	25	25	19	25	23	x	21	17	14	22	14	13	15		SUM_Q

10350	10348	10344	10343	10342	10341	10340	10323	10322	10320	10314	10311	10309	10302	10301	10300	10299		HPPD_ID
24	300	56	600	580	19	6	240	86	6	693	90	19	40	20	45	80	[MW]	Cap
4	93	32	505	5	108	0	13	36	x	1169	419	1	214	109	0	450	[million m³]	r_vol
0	1	4	39	1	6	0	1	3	x	76	28	0	9	2	0	8	[million m²]	r_area
0	0	0	4	4	0	0	0	4	0	90	90	90	43	292	292	292	[%]	RRI_04
1	1	1	1	1	1	1	1	1	1	3	3	3	3	4	4	4		RRI_04_Q
23	55	55	51	51	55	55	23	51	55	76	76	76	63	69	69	69	[%]	RFI_04
1	2	2	2	2	2	2	1	2	2	3	3	3	2	3	3	3		RFI_04_Q
255	320	1042	2994	111	276	138	320	307	x	2968	2174	1863	7607	3587	183	5370	count	Res
1	2	2	3	1	1	1	2	2	x	3	3	3	4	3	1	3		Res_Q
		1		1	1	2			x	2					1	1	count	PA_No
0	0	4746859	0	865896	8505596	17608	0	0	x	14143859	0	0	0	0	29928	9752066	[m²]	PA
1	1	4	1	3	4	3	1	1	x	4	1	1	1	1	3	4		PA_Q
1	1	1	1	1	1	1	1	1	x	3	4	4	4	4	3	3	count	MF
1	1	1	1	1	1	1	1	1	x	1	1	1	1	1	1	1		MF_Q
45607	119332	376430	4227982	113916	702344	950	88102	337608	x	13157733	4365786	26607	1239904	304471	2086	1045401	[m³/year]	PE
1	1	2	3	1	2	1	1	1	x	4	3	1	2	1	1	2		PE_Q
187	2123653	3805	445	4966	1107	28841	6851350	2848	x	503707	2618836	116676	399864	230746	82257	104972	[t/year]	SE
50420	116	22058	3004579	2701	258408	5	5	33546	x	6153	424	24	1419	1251	6	11352	[year]	Lifespan
1	3	1	1	2	1	4	4	1	x	2	3	4	2	2	4	2		SE_Q
36090	0	263238	2218247	0	0	0	0	0	x	27614105	27047178	225147	9602007	1409279	17096	6535877	[m²]	LU_C
2	1	2	3	1	1	1	1	1	x	4	4	2	4	3	2	3		LU_C_Q
9	12	15	15	12	13	14	12	10	x	24	21	18	19	18	19	22		SUM_Q

10403	10402	10398	10395	10393	10392	10390	10389	10388	10360	10358	10357	10356	10355	10354		HPPD_ID
120	14	4	44	4	1	2	3	3	41	155	43	105	20	19	[MW]	Cap
9	102	6	5256	0	239	77	301	311	2033	107	73	102	22	79	[million m³]	r_vol
4	45	1	154	0	5	2	15	13	260	34	24	33	15	3	[million m²]	r_area
596	0	596	596	33	33	596	596	596	483	0	0	0	0	0	[%]	RRI_04
4	1	4	4	2	2	4	4	4	4	1	1	1	1	1		RRI_04_Q
81	21	81	81	40	40	81	81	81	7	55	55	55	x	55	[%]	RFI_04
4	1	4	4	1	1	4	4	4	1	2	2	2	x	2		RFI_04_Q
218	7930	2209	197701	1082	2756	4868	36082	30260	81986	4607	2517	4376	369	985	count	Res
1	4	3	4	2	3	3	4	4	4	3	3	3	2	2		Res_Q
													1		count	PA_No
0	0	0	0	0	0	0	0	0	0	0	0	0	12119666	0	[m²]	PA
1	1	1	1	1	1	1	1	1	1	1	1	1	4	1		PA_Q
7	4	4	4	5	6	5	4	4	3	1	1	1	1	1	count	MF
3	1	1	1	2	2	2	1	1	1	1	1	1	1	1		MF_Q
492205	6460362	55714	15654905	758	397760	173678	1458361	1221382	33034776	3703440	2630029	3619914	1903181	344528	[m³/year]	PE
2	4	1	4	1	2	1	2	2	4	3	3	3	3	2		PE_Q
x	5	51645	930	24671	29530	197179	2185	437471	x	83	468	12874384	2	84636	[t/year]	SE
x	53448255	285	14978620	5	21481	1034	365267	1881	x	3389135	410208	21	25721581	2478	[year]	Lifespan
x	1	3	1	4	1	3	1	2	x	1	1	4	1	2		SE_Q
0	4474941	614332	167698206	18125	5485783	1017493	16235176	14811036	158432029	23055227	14843060	22409875	1643619	0	[m²]	LU_C
1	3	2	4	2	3	3	4	4	4	4	4	4	3	1		LU_C_Q
x	16	19	23	15	15	21	21	22	x	16	16	19	x	12		SUM_Q

10469	10467	10462	10459	10454	10452	10434	10433	10431	10429	10421	10414	10413	10412	10411	10410		HPPD_ID
300	2	358	60	3	160	8	4	118	47	648	205	420	312	312	360	[MW]	Cap
58	112	x	8	0	363	1	28	3095	x	243	187	8	47	x	89	[million m³]	r_vol
1	5	x	5	0	19	0	2	52	x	66	100	14	18	x	25	[million m²]	r_area
483	483	56	56	56	56	33	33	483	56	253	254	253	253	253	253	[%]	RRI_04
4	4	3	3	3	3	2	2	4	3	4	4	4	4	4	4		RRI_04_Q
7	7	47	47	47	47	40	40	7	47	81	50	81	81	81	81	[%]	RFI_04
1	1	2	2	2	2	1	1	1	2	3	2	3	3	3	3		RFI_04_Q
136	455	x	295	12	453	75	4650	1528	x	3860	54823	65	2415	x	1178	count	Res
1	2	x	2	1	2	1	3	3	x	3	4	1	3	x	2		Res_Q
		x	2		2				x					x		count	PA_No
0	0	x	8679651	0	29121714	0	0	0	x	0	0	0	0	x	0	[m²]	PA
1	1	x	4	1	4	1	1	1	x	1	1	1	1	x	1		PA_Q
4	4	x	3	3	4	6	5	3	x	6	8	7	7	x	6	count	MF
1	1	x	1	1	1	2	2	1	x	2	4	3	3	x	2		MF_Q
163458	547862	x	729218	2331	2640784	27418	271361	6828844	x	13847909	18716582	3170109	4466772	x	5389381	[m³/year]	PE
1	2	x	2	1	3	1	1	4	x	4	4	3	3	x	3		PE_Q
12794	3256	x	20	865367	192	22890534	33130	1165033	x	4910	163109638	x	6855	x	1395372	[t/year]	SE
12012	91086	x	1035049	0	5007800	0	2241	7040	x	131109	3	x	18355	x	170	[year]	Lifespan
2	1	x	1	4	1	4	2	2	x	1	4	x	1	x	3		SE_Q
0	2442993	x	779519	0	58000	124186	1694898	705704	x	9963034	52326529	113239	1799236	x	4483629	[m²]	LU_C
1	3	x	2	1	2	2	3	2	x	4	4	2	3	x	3		LU_C_Q
12	15	x	17	14	18	14	15	18	x	22	27	x	21	x	21		SUM_Q

10542	10539	10538	10537	10536	10535	10533	10526	10522	10521	10515	10486	10480	10479	10478	10475	10474		HPPD_ID
7	7	7	2	109	38	8	45	5	11	360	1	350	7	1	10	520		Cap
179	23	68	135	10	1	121	9	329	15	0	982	21	12	16	135	361		r_vol
4	5	8	2	5	0	5	0	48	2	0	76	5	1	10	6	6		r_area
596	596	596	596	596	596	596	596	596	596	596	596	596	596	0	483	483		RRI_04
4	4	4	4	4	4	4	4	4	4	4	4	4	4	1	4	4		RRI_04_Q
81	81	81	81	81	81	81	81	81	81	81	81	81	81	x	7	7		RFI_04
4	4	4	4	4	4	4	4	4	4	4	4	4	4	x	1	1		RFI_04_Q
13835	3890	13456	0	4334	494	6640	182	3987	230	0	56103	4999	2856	781	10755	1031		Res
4	3	4	1	3	2	4	1	3	1	1	4	3	3	2	4	2		Res_Q
			2				1			1	1	2		1				PA_No
0	0	0	3969310	0	0	0	241058	0	0	18121	961748	434997	0	11170634	0	0		PA
1	1	1	4	1	1	1	3	1	1	3	3	3	1	4	1	1		PA_Q
7	7	7	8	9	4	8	5	5	5	9	7	9	8	6	3	3		MF
3	3	3	4	4	1	4	2	2	2	4	3	4	4	2	1	1		MF_Q
526368	780351	1174191	222067	643320	21926	485674	21905	6773461	344244	1130	6961673	622608	88405	1314558	824157	782921		PE
2	2	2	1	2	1	2	1	4	2	1	4	2	1	2	2	2		PE_Q
198658	69	518708	32047	x	96	1061695	7647	1161700	1492384	x	425464	x	152113	241	300481	316379		SE
2394	887454	347	11147	x	14003	302	3082	750	26	x	6115	x	205	172269	1187	3022		Lifespan
2	1	3	2	x	2	3	2	3	4	x	2	x	3	1	3	2		SE_Q
3197214	3260828	6610101	1021895	915839	2377	5475686	0	15826	0	0	15233944	905966	873491	10744709	6586135	187521		LU_C
3	3	3	3	3	2	3	1	2	1	1	4	3	3	4	3	2		LU_C_Q
23	21	24	23	x	17	25	18	23	19	x	28	x	23	x	19	15		SUM_Q

10579	10578	10577	10576	10575	10574	10573	10572	10571	10570	10569	10567	10550	10547	10545	10544	10543		HPPD_ID
283	217	121	203	120	114	460	453	330	260	381	3	26	9	3	2	5	[MW]	Cap
59	34	1151	47	35557	51	267	65	3	54	2274	3	141	2	0	73	0	[million m³]	r_vol
2	5	64	1	3202	3	14	7	1	5	166	1	18	0	0	1	0	[million m²]	r_area
49	49	36	36	97	97	97	97	97	97	97	4	2	292	596	596	596	[%]	RRI_04
3	3	2	2	3	3	3	3	3	3	3	1	1	4	4	4	4		RRI_04_Q
7	7	0	0	68	68	68	68	68	68	68	54	17	69	81	81	81	[%]	RFI_04
1	1	1	1	3	3	3	3	3	3	3	2	1	3	4	4	4		RFI_04_Q
491	364	2280	116	16103	220	660	235	55	143	5108	26	125	1775	561	1076	x	count	Res
2	2	3	1	4	1	2	1	1	1	3	1	1	3	2	2	x		Res_Q
				2													count	PA_No
0	0	0	0	965594865	0	0	0	0	0	0	0	0	0	0	0	0	[m²]	PA
1	1	1	1	4	1	1	1	1	1	1	1	1	1	1	1	1		PA_Q
3	3	4	3	4	4	4	4	4	3	2	6	4	4	6	6	6	count	MF
1	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2	2		MF_Q
247541	556315	6843337	145197	366089020	384928	1607411	800569	109468	573004	18470886	86360	2166521	29406	2293	112370	1147	[m³/year]	PE
1	2	4	1	4	2	3	2	1	2	4	1	3	1	1	1	1		PE_Q
968470	273432	1810115	142937	222	24860	328424	155409	663993	41981	2103602	1615088	124	221698	1378	x	108676	[t/year]	SE
162	332	1685	868	424049347	5437	2157	1107	11	3439	2865	5	3027324	27	195	x	1	[year]	Lifespan
3	3	2	3	1	2	2	3	4	2	2	4	1	4	3	x	4		SE_Q
0	727849	12537037	0	17345704	20005	6696	0	0	341926	5010206	0	490797	10792	3768	46286	18130	[m²]	LU_C
1	2	4	1	4	2	2	1	1	2	3	1	2	2	2	2	2		LU_C_Q
13	15	18	11	24	15	17	15	15	15	20	13	11	19	19	x	x		SUM_Q

10608	10606	10605	10604	10603	10602	10601	10599	10597	10596	10595	10594	10585	10584	10583	10581		HPPD_ID
32	48	8	74	4	230	79	160	58	190	29	41	57	86	157	403	[MW]	Cap
10	766	733	6785	157	520	2448	17	2	16	5	198	3	41	138	4617	[million m³]	r_vol
1	81	152	295	18	37	195	1	1	1	1	8	0	5	10	440	[million m²]	r_area
2	97	16	144	144	177	177	2	2	2	2	2	97	97	97	49	[%]	RRI_04
1	3	1	3	3	4	4	1	1	1	1	1	3	3	3	3		RRI_04_Q
17	68	20	33	33	51	51	54	54	54	54	54	68	68	68	7	[%]	RFI_04
1	3	1	1	1	2	2	2	2	2	2	2	3	3	3	1		RFI_04_Q
36	2285	247	5107	1922	2604	20695	235	72	150	752	1932	51	231	1902	32827	count	Res
1	3	1	3	3	3	4	1	1	1	2	3	1	1	3	4		Res_Q
																count	PA_No
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[m²]	PA
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		PA_Q
3	3	4	3	3	2	2	2	5	5	5	5	3	3	3	3	count	MF
1	1	1	1	1	1	1	1	2	2	2	2	1	1	1	1		MF_Q
138138	9240360	18475424	38161111	2154430	4556683	23016499	140981	86342	82785	102170	880910	47089	576208	1111220	46555523	[m³/year]	PE
1	4	4	4	3	3	4	1	1	1	1	2	1	2	2	4		PE_Q
524220	327747	1284922	6003014	14	14	136	5803550	249660	4821819	541839	7360	2069821	356	110153	9278378	[t/year]	SE
50	6195	1512	2995	30301703	96293997	47714073	8	24	9	25	71323	3	307679	3331	1319	[year]	Lifespan
4	2	2	2	1	1	1	4	4	4	4	1	4	1	2	2		SE_Q
0	0	13594	25608759	1539872	0	5925109	0	0	8737	0	0	0	0	0	127897811	[m²]	LU_C
1	1	2	4	3	1	3	1	1	2	1	1	1	1	1	4		LU_C_Q
11	18	13	19	16	16	20	12	13	14	14	13	15	13	16	20		SUM_Q

10651	10650	10649	10647	10645	10644	10642	10638	10637	10636	10618	10615	10611	10610	10609		HPPD_ID
62	55	50	50	3	28	150	30	60	2	12	120	30	33	16	[MW]	Cap
67192	239	19	10	4445	3242	789	29	7	0	6	1653	11	131	11	[million m³]	r_vol
3266	10	2	5	352	276	14	2	0	0	1	38	4	14	3	[million m²]	r_area
483	483	483	483	483	483	483	483	483	483	167	167	2	2	2	[%]	RRI_04
4	4	4	4	4	4	4	4	4	4	4	4	1	1	1		RRI_04_Q
7	7	7	7	7	7	7	7	7	7	60	60	17	17	17	[%]	RFI_04
1	1	1	1	1	1	1	1	1	1	2	2	1	1	1		RFI_04_Q
676933	0	0	1317	44461	38451	2368	312	39	249	469	4131	1775	77	583	count	Res
4	1	1	2	4	4	3	2	1	1	2	3	3	1	2		Res_Q
1	1	1		3	2			1			1				count	PA_No
98652337	10534017	2046802	0	148313437	99031829	0	0	135334	0	0	2304675	0	0	0	[m²]	PA
4	4	4	1	4	4	1	1	3	1	1	4	1	1	1		PA_Q
3	4	4	4	3	3	4	5	5	4	3	3	3	5	3	count	MF
1	1	1	1	1	1	1	2	2	1	1	1	1	2	1		MF_Q
415055755	1261066	224603	710469	43552594	33314303	1697339	244592	51781	18184	70918	4115981	439753	1645288	394971	[m³/year]	PE
4	2	1	2	4	4	3	1	1	1	1	3	2	3	2		PE_Q
659724	307153	113	1145611	83	703864	1851278	584863	75968	930266	854111	1061542	4406889	40	394538	[t/year]	SE
269899	2060	450798	23	142364523	12207	1129	130	256	1	20	4127	7	8769163	72	[year]	Lifespan
1	2	1	4	1	2	3	3	3	4	4	2	4	1	4		SE_Q
2581392673	0	0	4934560	147317369	109973078	1275210	768093	335364	182755	192709	11937294	187600	0	0	[m²]	LU_C
4	1	1	3	4	4	3	2	2	2	2	4	2	1	1		LU_C_Q
23	16	14	18	23	24	19	16	17	15	17	23	15	11	13		SUM_Q

10680	10678	10676	10675	10672	10670	10669	10668	10666	10660	10659	10658	10657	10655	10653		HPPD_ID
612	20	50	37	1245	200	650	50	40	15	80	55	60	37	350	[MW]	Cap
700	5	0	1	247309	5	65	6	109	23	22	16	22	0	1336	[million m³]	r_vol
17	4	0	1	4728	2	25	2	14	10	7	3	8	0	64	[million m²]	r_area
177	141	44	44	1070	1070	1070	0	0	82	44	0	0	483	483	[%]	RRI_04
4	3	3	3	4	4	4	1	1	3	3	1	1	4	4		RRI_04_Q
51	0	72	72	60	60	60	30	30	62	72	27	27	7	7	[%]	RFI_04
2	1	3	3	2	2	2	1	1	2	3	1	1	1	1		RFI_04_Q
105	1119	55	214	38424	72	332	535	2117	182	1591	594	650	194	3629	count	Res
1	2	1	1	4	1	2	2	3	1	3	2	2	1	3		Res_Q
2	2			2						1					count	PA_No
16608402	1901826	0	0	4608230075	0	0	0	0	0	7844308	0	0	0	0	[m²]	PA
4	4	1	1	4	1	1	1	1	1	4	1	1	1	1		PA_Q
5	6	3	3	5	5	5	3	3	4	4	4	3	4	4	count	MF
2	2	1	1	2	2	2	1	1	1	1	1	1	1	1		MF_Q
1871109	461483	8733	78162	654496164	336698	3616344	214441	1867298	1153773	945389	471392	1033304	1956	8832391	[m³/year]	PE
3	2	1	1	4	1	3	1	3	2	2	2	2	1	4		PE_Q
10	5046122	x	21400	29590259	10560533	14	4714254	1490624	x	102	14642447	29	x	40467901	[t/year]	SE
194015391	3	x	127	22148	1	12452332	3	195	x	566816	3	2051832	x	87	[year]	Lifespan
1	4	x	3	1	4	1	4	3	x	1	4	1	x	3		SE_Q
0	0	0	0	330168092	0	381097	0	5189	5241981	5106146	453981	0	6610	53886044	[m²]	LU_C
1	1	1	1	4	1	2	1	2	3	3	2	1	2	4		LU_C_Q
18	19	x	14	25	16	17	12	15	x	20	14	10	x	21		SUM_Q

10759	10758	10757	10756	10755	10754	10751	10749	10748	10745	10744	10743	10742	10741	10722		HPPD_ID
6	6	75	34	300	330	12	4	40	1	14	100	65	10	320	[MW]	Cap
10	117	1405	323	15	257	95	100	2953	0	9	1232	326	8	83372	[million m³]	r_vol
0	10	68	21	3	14	8	40	122	0	4	106	14	2	2626	[million m³]	r_area
33	19	117	117	19	117	117	117	16	16	16	117	117	26	509	[%]	RRI_04
2	1	3	3	1	3	3	3	1	1	1	3	3	2	4		RRI_04_Q
40	75	66	66	75	66	66	66	20	20	20	66	66	52	36	[%]	RFI_04
1	3	2	2	3	2	2	2	1	1	1	2	2	2	1		RFI_04_Q
14	377	1616	499	102	200	149	249	2264	9	126	2085	450	170	51394	count	Res
1	2	3	2	1	1	1	1	3	1	1	3	2	1	4		Res_Q
			1				2	4			1		1	8	count	PA_No
0	0	0	40083	0	0	0	36935996	67845340	0	0	851044	0	1034517	4382205770	[m²]	PA
1	1	1	3	1	1	1	4	4	1	1	3	1	3	4		PA_Q
6	4	4	5	5	3	4	5	4	3	4	3	3	4	5	count	MF
2	1	1	2	2	1	1	2	1	1	1	1	1	1	2		MF_Q
33821	1245484	8552340	2587656	344863	1778971	955663	5665700	13882976	10206	487488	13613185	1725064	313033	364860007	[m³/year]	PE
1	2	4	3	2	3	2	3	4	1	2	4	3	1	4		PE_Q
74	35118	101	19285	15557154	297873	79	13880193	16	155908	4784434	521005	559844	17918026	25195161	[t/year]	SE
339867	8804	36795691	44345	3	2282	3166745	19	494676069	4	5	6264	1541	1	8769	[year]	Lifespan
1	2	1	1	4	2	1	4	1	4	4	2	2	4	2		SE_Q
0	385366	16949	5864874	0	0	416131	1595868	0	87473	456622	7055842	0	541796	1211718480	[m²]	LU_C
1	2	2	3	1	1	2	3	1	2	2	4	1	2	4		LU_C_Q
10	14	17	19	15	14	13	22	16	12	13	22	15	16	25		SUM_Q

10792	10790	10788	10787	10786	10785	10783	10772	10770	10768	10767	10766	10765	10762	10761	10760		HPPD_ID
13	2	2	5	15	1	620	320	200	372	202	68	124	108	86	132	[MW]	Cap
278	1	1	0	7	0	935	83372	196	19	5	2701	11	1386	599	1417	[million m³]	r_vol
40	0	0	0	1	0	70	2626	18	2	1	391	3	46	21	87	[million m²]	r_area
28	44	44	44	44	111	138	509	44	19	19	19	19	33	33	33	[%]	RRI_04
2	3	3	3	3	3	3	4	3	1	1	1	1	2	2	2		RRI_04_Q
92	72	72	72	72	27	50	36	72	75	75	75	75	40	40	40	[%]	RFI_04
4	3	3	3	3	1	2	1	3	3	3	3	3	1	1	1		RFI_04_Q
10943	342	147	26	338	8	593	51394	3457	99	58	10549	170	185	290	939	count	Res
4	2	1	1	2	1	2	4	3	1	1	4	1	1	1	2		Res_Q
			1			3	8				2		1	2	1	count	PA_No
0	0	0	17042	0	0	55703698	4382205770	0	0	0	22923904	0	21574061	22684516	89476967	[m²]	PA
1	1	1	3	1	1	4	4	1	1	1	4	1	4	4	4		PA_Q
11	3	3	3	3	3	5	5	4	6	6	5	6	6	6	6	count	MF
4	1	1	1	1	1	2	2	1	2	2	2	2	2	2	2		MF_Q
5057022	29119	39472	964	130347	2034	9813790	364860007	2176764	291952	127412	47435776	381856	5916935	2712523	11213106	[m³/year]	PE
3	1	1	1	1	1	4	4	3	1	1	4	2	3	3	4		PE_Q
481930	169442	588863	313323	1121	57	29923472	x	2317786	5697450	58438	82	12758	268765	275298	1748562	[t/year]	SE
1528	22	4	1	15458	4380	83	x	224	9	247	87125305	2208	13665	5767	2147	[year]	Lifespan
2	4	4	4	2	2	3	x	3	4	3	1	2	2	2	2		SE_Q
17343037	0	169278	0	28195	0	222954	1211718480	7947420	0	3212	69903429	704597	383657	487	844096	[m²]	LU_C
4	1	2	1	2	1	2	4	4	1	2	4	2	2	2	3		LU_C_Q
24	16	16	17	15	11	22	x	21	14	14	23	14	17	17	20		SUM_Q

10808	10807	10806	10805	10804	10803	10801	10800	10799	10798	10797	10796	10795	10794	10793		HPPD_ID
24	9	11	20	30	35	29	79	24	26	42	15	29	108	160	[MW]	Cap
1539	40	72	523	193	1039	34	317	17	53	117	15	497	177	1506	[million m³]	r_vol
247	12	19	81	49	146	12	35	6	15	25	12	57	19	109	[million m²]	r_area
89	89	89	28	28	28	28	28	28	28	28	28	28	28	28	[%]	RRI_04
3	3	3	2	2	2	2	2	2	2	2	2	2	2	2		RRI_04_Q
10	10	10	92	92	92	92	92	92	92	92	92	92	92	92	[%]	RFI_04
1	1	1	4	4	4	4	4	4	4	4	4	4	4	4		RFI_04_Q
15432	411	572	2722	14220	25083	459	3229	708	1021	1485	488	945	2110	8348	count	Res
4	2	2	3	4	4	2	3	2	2	3	2	2	3	4		Res_Q
1	1		1	1	2	2					1		2	2	count	PA_No
78030555	4448064	0	67954937	30486330	83624751	6413088	0	0	0	0	3648090	0	4947310	29048485	[m²]	PA
4	4	1	4	4	4	4	1	1	1	1	4	1	4	4		PA_Q
6	7	7	10	10	10	9	9	9	9	9	9	9	11	9	count	MF
2	3	3	4	4	4	4	4	4	4	4	4	4	4	4		MF_Q
38700561	1827766	3012853	11454389	6714911	20049459	1582931	4515729	811236	1960793	3211966	1458966	7239779	2396095	13768004	[m³/year]	PE
4	3	3	4	4	4	3	3	2	3	3	2	4	3	4		PE_Q
555	969271	861127	993161	678931	38	974500	482098	116368	213521	9834	91993	2196869	284800	185842	[t/year]	SE
7354018	110	221	1395	752	71907288	94	1740	383	663	31564	443	599	1643	21469	[year]	Lifespan
1	3	3	2	3	1	3	2	3	3	1	3	3	2	1		SE_Q
173752781	0	0	28336	1621087	7571443	0	3382729	189188	4869373	12490658	384081	3116142	3151148	18536099	[m²]	LU_C
4	1	1	2	3	4	1	3	2	3	4	2	3	3	4		LU_C_Q
23	20	17	25	28	27	23	22	20	22	22	23	23	25	27		SUM_Q

10833	10832	10831	10827	10825	10822	10820	10818	10817	10815	10813	10812	10811	10810	10809		HPPD_ID
90	90	5	14	5	60	11	2	4	3	3	4	2	8	12	[MW]	Cap
1486	68	10	x	259	759	1959	5	11	15	48	24	24	151	77	[million m³]	r_vol
261	5	3	x	108	201	294	2	3	10	15	12	6	37	21	[million m²]	r_area
146	146	32	94	20	162	146	28	28	89	103	103	28	46	89	[%]	RRI_04
3	3	2	3	2	4	3	2	2	3	3	3	2	3	3		RRI_04_Q
25	25	81	70	20	56	25	92	92	10	71	71	92	59	10	[%]	RFI_04
1	1	3	3	1	2	1	4	4	1	3	3	4	2	1		RFI_04_Q
48911	609	14428	x	8109	12625	7986	303	501	181	996	609	820	1025	1723	count	Res
4	2	4	x	4	4	4	2	2	1	2	2	2	2	3		Res_Q
4	2		x	2	1	4			1				3	1	count	PA_No
67185888	2961365	0	x	38035998	32764363	96461901	0	0	698730	0	0	0	73836361	2910818	[m²]	PA
4	4	1	x	4	4	4	1	1	3	1	1	1	4	4		PA_Q
7	7	7	x	4	4	6	10	10	7	6	7	9	7	6	count	MF
3	3	3	x	1	1	2	4	4	3	2	3	4	3	2		MF_Q
29323824	513853	289220	x	15512754	26967145	39935919	308426	421662	1510330	2216609	1870299	817168	5700694	3512921	[m³/year]	PE
4	2	1	x	4	4	4	1	2	2	3	3	2	3	3		PE_Q
917614	42138	1613960	x	19	26971417	4265403	377481	534614	1263588	467776	197544	290645	82	345918	[t/year]	SE
4291	4279	16	x	36127970	75	1217	35	53	31	273	327	218	4865722	590	[year]	Lifespan
2	2	4	x	1	4	3	4	4	4	3	3	3	1	3		SE_Q
241172188	343970	2244093	x	4221473	1706711	71417679	0	0	0	1100581	3523696	1667668	1956135	5574455	[m²]	LU_C
4	2	3	x	3	3	4	1	1	1	3	3	3	3	3		LU_C_Q
25	19	21	x	20	26	25	19	20	18	20	21	21	21	22		SUM_Q

10860	10859	10858	10857	10856	10855	10853	10852	10847	10846	10845	10842	10840	10836	10835		HPPD_ID
225	3	2	150	32	2	150	156	280	2	90	21	28	91	15	[MW]	Cap
32	377	76	2005	89	12	311	108	2403	14	1851	34	76	200	110	[million m³]	r_vol
11	13	2	204	43	7	61	12	208	5	314	17	93	49	20	[million m²]	r_area
32	82	82	82	82	258	82	82	82	258	146	258	258	258	258	[%]	RRI_04
2	3	3	3	3	4	3	3	3	4	3	4	4	4	4		RRI_04_Q
88	76	76	76	76	81	76	76	76	81	25	81	81	81	81	[%]	RFI_04
4	3	3	3	3	3	3	3	3	3	1	3	3	3	3		RFI_04_Q
181	82186	2609	13539	584	804	7421	7979	1484	292	48855	1147	15466	5538	8315	count	Res
1	4	3	4	2	2	4	4	3	1	4	2	4	4	4		Res_Q
	1		2	1		3		1	3	3	1	2		1	count	PA_No
0	72456	0	44594356	14542287	0	35147975	0	14701895	5203355	54458632	7139248	18217104	0	225149	[m²]	PA
1	3	1	4	4	1	4	1	4	4	4	4	4	1	3		PA_Q
8	7	7	6	7	6	8	9	9	8	7	9	9	10	10	count	MF
4	3	3	2	3	2	4	4	4	4	3	4	4	4	4		MF_Q
1143762	1427015	177203	23272830	4955468	783919	6821144	1307808	22840478	554745	35791474	1953478	10290973	5573629	2341349	[m³/year]	PE
2	2	1	4	3	2	4	2	4	2	4	3	4	3	3		PE_Q
3569	314776	122283	4129297	12749626	1102979	530	11656430	541454	2855419	15494944	171	218	73644	4805028	[t/year]	SE
23893	3170	1641	1287	18	28	1555186	24	11761	13	317	524688	917126	7187	61	[year]	Lifespan
1	2	2	2	4	4	1	4	2	4	3	1	1	2	4		SE_Q
1880257	5279203	1564354	23609700	13368	0	39132797	7264134	206011716	169666	304418115	2264655	82288989	42062687	17076140	[m²]	LU_C
3	3	3	4	2	1	4	4	4	2	4	3	4	4	4		LU_C_Q
18	23	19	26	24	19	27	25	27	24	26	24	28	25	29		SUM_Q

10892	10891	10890	10878	10877	10876	10872	10871	10870	10868	10867	10866	10865	10863	10861		HPPD_ID
13	15	45	36	43	87	252	50	50	30	56	4	7	4	20	[MW]	Cap
x	30	30	1479	413	229	13	403	31	1720	x	540	4274	20	99	[million m³]	r_vol
x	12	12	188	146	95	2	100	12	193	x	79	414	5	43	[million m²]	r_area
32	32	32	94	94	46	32	32	32	32	32	146	258	258	32	[%]	RRI_04
2	2	2	3	3	3	2	2	2	2	2	3	4	4	2		RRI_04_Q
88	88	88	70	70	59	81	81	81	81	81	25	81	81	88	[%]	RFI_04
4	4	4	3	3	2	3	3	3	3	3	1	3	3	4		RFI_04_Q
x	1322	1322	6699	7710	7894	942	46629	2889	68347	x	3011	36639	15834	6971	count	Res
x	2	2	4	4	4	2	4	3	4	x	3	4	4	4		Res_Q
x			1						1	x	3	4		1	count	PA_No
x	0	0	30149747	0	0	0	0	0	2666477	x	8012513	40647245	0	94243	[m²]	PA
x	1	1	4	1	1	1	1	1	4	x	4	4	1	3		PA_Q
x	7	7	6	8	10	7	7	8	7	x	5	7	7	8	count	MF
x	3	3	2	4	4	3	3	4	3	x	2	3	3	4		MF_Q
x	1545124	1545124	25802348	19855855	12525100	184883	10816525	1257230	21086523	x	10375354	54681106	593013	4648416	[m³/year]	PE
x	3	2	4	4	4	1	4	2	4	x	4	4	2	3		PE_Q
x	x	885699	23	9610620	88	154074	5984517	306111	x	x	531580	32	3050	1941135	[t/year]	SE
x	x	88	167759831	114	6906617	229	178	269	x	x	2694	354820140	17077	136	[year]	Lifespan
x	x	3	1	3	1	3	3	3	x	x	2	1	1	3		SE_Q
x	86623	86623	186745	5785115	11751312	1853853	97999365	11935091	203977227	x	657411	105044498	4566649	43212169	[m²]	LU_C
x	2	2	2	3	4	3	4	4	4	x	2	4	3	4		LU_C_Q
x	x	19	23	25	23	18	24	22	x	x	21	27	21	27		SUM_Q

10915	10914	10913	10912	10911	10909	10908	10907	10906	10903	10901	10900	10899	10898	10895	10893		HPPD_ID
19	14	24	21	29	40	15	23	27	2	67	80	2	11	100	9	[MW]	Cap
18	231	1462	1069	1818	1031	56	381	751	9	244	268	3	3	189	226	[million m³]	r_vol
1	16	64	91	128	33	13	28	89	2	16	18	1	1	18	51	[million m³]	r_area
32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	[%]	RRI_04
2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2		RRI_04_Q
88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	88	[%]	RFI_04
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4		RFI_04_Q
227	3014	5897	7762	9442	2276	2352	2049	10707	385	2145	2180	289	264	2974	5465	count	Res
1	3	4	4	4	3	3	3	4	2	3	3	1	1	3	4		Res_Q
									1					1		count	PA_No
0	0	0	0	0	0	0	0	0	1646476	0	0	0	0	270785	0	[m²]	PA
1	1	1	1	1	1	1	1	1	4	1	1	1	1	3	1		PA_Q
5	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6	count	MF
2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2		MF_Q
116597	2049947	7995614	11716274	16481535	4104656	1635926	3649057	11126965	202969	2133908	2262646	105507	161903	2391767	6578856	[m³/year]	PE
1	3	4	4	4	3	3	3	4	1	3	3	1	1	3	4		PE_Q
9024	905225	294985	134618	44700	780970	15913	1433315	231	178127	1105722	54	216682	118097	589590	x	[t/year]	SE
5321	675	13130	21040	107781	3497	9358	705	8625250	136	585	13192672	40	61	848	x	[year]	Lifespan
2	3	2	1	1	2	2	3	1	3	3	1	4	4	3	x		SE_Q
448030	5311244	6662101	6125639	8783330	1039164	2949511	1172928	15391821	862771	4583932	3703124	587461	415999	11238166	2768055	[m²]	LU_C
2	3	4	3	4	3	3	3	4	3	3	3	2	2	4	3		LU_C_Q
15	21	23	21	22	20	20	21	22	21	21	19	17	17	24	x		SUM_Q

10942	10941	10933	10930	10929	10927	10926	10924	10923	10922	10921	10920	10919	10918	10917	10916		HPPD_ID
3	3	10	128	5	135	16	82	90	36	90	115	120	291	81	84	[MW]	Cap
164	1	18	1990	35	2556	25	1273	998	81	87	141	512	95	95	600	[million m³]	r_vol
23	0	5	128	9	152	10	60	35	12	8	11	40	7	7	14	[million m²]	r_area
964	32	32	98	98	32	32	32	32	32	32	32	32	32	32	32	[%]	RRI_04
4	2	2	3	3	2	2	2	2	2	2	2	2	2	2	2		RRI_04_Q
68	88	88	50	50	88	88	88	88	88	88	88	88	88	88	88	[%]	RFI_04
3	4	4	2	2	4	4	4	4	4	4	4	4	4	4	4		RFI_04_Q
3312	148	384	3614	281	5755	1080	2820	4487	2456	1819	2167	5269	2838	2838	2452	count	Res
3	1	2	3	1	4	2	3	3	3	3	3	3	3	3	3		Res_Q
		1		1	1		1								1	count	PA_No
0	0	3412561	0	9731247	16718920	0	9351874	0	0	0	0	0	0	0	1098518	[m²]	PA
1	1	4	1	4	4	1	4	1	1	1	1	1	1	1	3		PA_Q
4	5	5	5	5	5	5	5	6	6	6	6	6	5	5	5	count	MF
1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2		MF_Q
2969139	22429	653047	17709249	1289970	20274357	1324146	7869937	4547475	1574333	1028968	1395101	5138845	897100	897100	1671709	[m³/year]	PE
3	1	2	4	2	4	2	4	3	3	2	2	3	2	2	3		PE_Q
98854	1670	3363904	6516372	1664554	2042159	2324377	1708387	889907	240131	825529	8175	222146	x	592583	229057	[t/year]	SE
4393	1803	14	809	56	3317	29	1975	2971	895	279	45850	6112	x	423	6946	[year]	Lifespan
2	2	4	3	4	2	4	2	2	3	3	1	2	x	3	2		SE_Q
0	0	0	501971	0	387324	0	2458221	22580792	4902767	5171439	6956140	19844808	0	0	1303403	[m²]	LU_C
1	1	1	2	1	2	1	3	4	3	3	4	4	1	1	3		LU_C_Q
18	14	21	20	19	24	18	24	21	21	20	19	21	x	18	22		SUM_Q

10985	10984	10980	10975	10970	10969	10968	10967	10966	10965	10962	10956	10952	10946	10944		HPPD_ID
149	281	76	12	40	127	98	118	135	58	21	18	93	1	174	[MW]	Cap
27	27089	229	473	89	787	349	587	664	503	843	122	297	2	1798	[million m³]	r_vol
1	612	80	45	18	46	24	23	28	15	78	1	14	0	57	[million m²]	r_area
964	964	964	56	32	32	32	32	32	964	32	32	98	964	32	[%]	RRI_04
4	4	4	3	2	2	2	2	2	4	2	2	3	4	2		RRI_04_Q
68	68	68	30	88	88	88	88	88	68	88	88	50	68	88	[%]	RFI_04
3	3	3	1	4	4	4	4	4	3	4	4	2	3	4		RFI_04_Q
48	31603	9779	8052	2341	2081	5207	786	1121	1586	2182	155	647	55	9298	count	Res
1	4	4	4	3	3	3	2	2	3	3	1	2	1	4		Res_Q
2	4		2				1	1							count	PA_No
1896727	366265105	0	47546002	0	0	0	1412598	1216744	0	0	0	0	0	0	[m²]	PA
4	4	1	4	1	1	1	3	3	1	1	1	1	1	1		PA_Q
4	5	4	7	5	6	6	6	6	5	5	6	4	4	5	count	MF
1	2	1	3	2	2	2	2	2	2	2	2	1	1	2		MF_Q
184088	80572712	10148277	6103194	2395727	6414201	3145750	3249548	3945463	1967740	10071541	160926	1845445	42968	7175296	[m³/year]	PE
1	4	4	4	3	4	3	3	3	3	4	1	3	1	4		PE_Q
8639878	833	1468963	1418833	475	499058	379591	1941213	98579	94848	13053	25041	2198022	291770	1722702	[t/year]	SE
8	86194849	413	884	498151	4177	2436	801	17857	14051	171132	12916	358	16	2765	[year]	Lifespan
4	1	3	3	1	2	2	3	1	2	1	2	3	4	2		SE_Q
0	2421674	186578	21162041	983612	3219212	1156138	953532	1098980	373198	1677	0	0	0	4038111	[m²]	LU_C
1	3	2	4	3	3	3	3	3	2	2	1	1	1	3		LU_C_Q
19	25	22	26	19	21	20	22	20	20	19	14	16	16	22		SUM_Q

11004	11002	11001	11000	10998	10997	10996	10993	10992	10991	10990	10989	10987	10986		HPPD_ID
6	100	36	17	1	27	2	5	4	85	90	72	7	161	[MW]	Cap
83	1029	18	32	24	350	55	91	25	802	1070	806	35	3670	[million m³]	r_vol
7	225	4	11	8	69	10	23	4	106	163	153	14	220	[million m²]	r_area
56	56	56	56	56	56	56	56	56	56	56	56	56	964	[%]	RRI_04
3	3	3	3	3	3	3	3	3	3	3	3	3	4		RRI_04_Q
30	30	30	30	30	30	30	30	30	30	30	30	30	68	[%]	RFI_04
1	1	1	1	1	1	1	1	1	1	1	1	1	3		RFI_04_Q
1343	7304	103	325	483	6161	284	1851	112	2001	6861	2261	424	5532	count	Res
2	4	1	2	2	4	1	3	1	3	4	3	2	4		Res_Q
	2	1	2		2	1	1	1	2	2	2		2	count	PA_No
0	322811489	3484864	12451667	0	2821622	10786247	21774839	1239979	114380871	164964235	73494252	0	105422144	[m²]	PA
1	4	4	4	1	4	4	4	3	4	4	4	1	4		PA_Q
7	7	8	8	7	7	8	7	7	7	7	9	8	3	count	MF
3	3	4	4	3	3	4	3	3	3	3	4	4	1		MF_Q
871405	29503594	466727	1423066	1000463	8702373	1243792	2975186	495623	14173908	22027089	20985979	1932701	30374598	[m³/year]	PE
2	4	2	2	2	4	2	3	2	4	4	4	3	4		PE_Q
131899	7299209	3609100	x	74600	1207307	221293	209110	5956	324	x	3810831	555611	2166313	[t/year]	SE
1666	373	13	x	850	769	664	1156	11212	6553085	x	561	167	4490	[year]	Lifespan
2	3	4	x	3	3	3	3	2	1	x	3	3	2		SE_Q
0	841813	0	187218	334993	633144	802137	625658	0	0	15148843	0	0	8730413	[m²]	LU_C
1	3	1	2	2	2	2	2	1	1	4	1	1	4		LU_C_Q
15	25	20	x	17	24	20	22	16	20	x	23	18	26		SUM_Q

11032	11029	11024	11023	11021	11019	11017	11016	11015	11012	11011	11010	11009	11007	11005		HPPD_ID
14	25	518	150	9	2	8	7	18	48	3	6	48	5	17	[MW]	Cap
0	882	7652	144	0	103	36	1	247	36	60	13	107	66	1528	[million m³]	r_vol
0	528	480	40	0	21	14	0	31	10	4	14	25	12	146	[million m²]	r_area
56	103	32	32	32	32	32	32	32	32	32	32	32	56	56	[%]	RRI_04
3	3	2	2	2	2	2	2	2	2	2	2	2	3	3		RRI_04_Q
30	71	88	88	88	88	88	88	88	88	88	88	88	30	30	[%]	RFI_04
1	3	4	4	4	4	4	4	4	4	4	4	4	1	1		RFI_04_Q
317	23347	33879	2729	93	4072	16247	69	8474	3925	323	725	3324	995	5892	count	Res
2	4	4	3	1	3	4	1	4	3	2	2	3	2	4		Res_Q
								1		1	1				count	PA_No
0	0	0	0	0	0	0	0	3298966	0	4511673	89636	0	0	0	[m²]	PA
1	1	1	1	1	1	1	1	4	1	4	3	1	1	1		PA_Q
8	3	9	8	8	8	6	5	5	6	8	5	5	8	7	count	MF
4	1	4	4	4	4	2	2	2	2	4	2	2	4	3		MF_Q
9373	106927676	54301816	4421484	10123	2145897	1711605	18786	3513187	1063459	461150	1606522	2735909	1457922	17296524	[m³/year]	PE
1	4	4	3	1	3	3	1	3	2	2	3	3	2	4		PE_Q
x	x	859116	2829503	661	82	1904225	319059	721401	321397	28902	848136	2694221	646078	1389210	[t/year]	SE
x	x	23603	135	1580	3304699	50	7	908	299	5515	42	105	272	2915	[year]	Lifespan
x	x	1	3	2	1	4	4	3	3	2	4	3	3	2		SE_Q
0	20145429	223325879	31973698	71661	19376147	10051912	4764	28946484	7477506	0	98162	11472678	0	3153734	[m²]	LU_C
1	4	4	4	2	4	4	2	4	4	1	2	4	1	3		LU_C_Q
x	x	24	24	17	22	24	17	26	21	21	22	22	17	21		SUM_Q

11071	11069	11068	11067	11066	11051	11048	11047	11045	11042	11041	11039	11038	11036		HPPD_ID
40	360	1	25	4	1870	26	123	18	70	30	50	24	4	[MW]	Cap
22	1035	167	199	616	5005	8713	98	307	860	1095	30	662	377	[million m³]	r_vol
4	63	15	64	82	1120	744	52	81	113	107	11	263	115	[million m²]	r_area
49	118	118	212	44	142	103	103	1265	102	964	964	11	56	[%]	RRI_04
3	3	3	4	3	3	3	3	4	3	4	4	1	3		RRI_04_Q
72	64	64	49	19	1	71	71	9	20	68	68	40	30	[%]	RFI_04
3	2	2	2	1	1	3	3	1	1	3	3	1	1		RFI_04_Q
21958	10699	45573	14392	32604	157118	5492	2974	21572	1216	1901	433	12161	14701	count	Res
4	4	4	4	4	4	4	3	4	2	3	2	4	4		Res_Q
	2			3	4	7	5	1	1			1		count	PA_No
0	24307154	0	0	13327781	201191338	2720576957	55096399	556508	357805	0	0	133369496	0	[m²]	PA
1	4	1	1	4	4	4	4	3	3	1	1	4	1		PA_Q
7	8	5	5	3	8	7	7	3	3	2	3	6	7	count	MF
3	4	2	2	1	4	3	3	1	1	1	1	2	3		MF_Q
551339	9620054	2603476	11446051	15283112	150084219	124541269	9049881	13140229	17672070	15797011	1542745	37068545	17551501	[m³/year]	PE
2	4	3	4	4	4	4	4	4	4	4	2	4	4		PE_Q
420601	1476592	41953	x	214771	94	1241835	x	20784016	22984150	3327066	4975103	11725626	1470	[t/year]	SE
141	1858	10575	x	7600	140485611	18593	x	39	99	872	16	150	679541	[year]	Lifespan
3	2	2	x	2	1	1	x	4	3	3	4	3	1		SE_Q
875613	616519	14894933	3825946	37149586	131328366	137668072	22172888	48423240	35844817	12146474	0	88163079	63012907	[m²]	LU_C
3	2	4	3	4	4	4	4	4	4	4	1	4	4		LU_C_Q
22	25	21	x	23	25	26	x	25	21	23	18	23	21		SUM_Q

11090	11088	11086	11084	11083	11082	11081	11080	11079	11078	11077	11076	11075	11074	11073	11072		HPPD_ID
11	138	92	136	109	182	2192	441	9	6	1	2	700	1062	1	20	[MW]	Cap
103	x	566	1204	135	68	4942	x	694	142	129	0	x	2614	1	33	[million m³]	r_vol
55	x	101	104	41	17	439	x	76	52	10	0	x	499	6	0	[million m²]	r_area
32	49	49	49	49	49	14	142	28	28	28	118	49	49	49	49	[%]	RRI_04
2	3	3	3	3	3	1	3	2	2	2	3	3	3	3	3		RRI_04_Q
88	72	72	72	72	72	49	1	92	92	92	64	72	72	72	72	[%]	RFI_04
4	3	3	3	3	3	2	1	4	4	4	2	3	3	3	3		RFI_04_Q
16080	x	9334	8859	26820	3168	70870	x	13183	6253	141567	12	x	238484	70	91	count	Res
4	x	4	4	4	3	4	x	4	4	4	1	x	4	1	1		Res_Q
	x		1	1		3	x		2			x	2		1	count	PA_No
0	x	0	67436	60290	0	112057721	x	0	25307596	0	0	x	12962097	0	257984	[m²]	PA
1	x	1	3	3	1	4	x	1	4	1	1	x	4	1	3		PA_Q
7	x	8	9	7	8	10	x	7	7	6	7	x	8	8	7	count	MF
3	x	4	4	3	4	4	x	3	3	2	3	x	4	4	3		MF_Q
7202220	x	14212349	13468804	5376437	2115989	47677854	x	9145866	6563427	1141246	1055	x	69068581	809292	33918	[m³/year]	PE
4	x	4	4	3	3	4	x	4	4	2	1	x	4	2	1		PE_Q
47516	x	41256634	17539459	30016950	25	912281	x	x	1510260	20663	43	x	x	114802	233399	[t/year]	SE
5749	x	36	182	12	7273952	14357	x	x	249	16537	3130	x	x	12	371	[year]	Lifespan
2	x	4	3	4	1	2	x	x	3	1	2	x	x	4	3		SE_Q
51708914	x	28386399	2039941	14039984	75138	17430549	x	17121900	1875192	992706	0	x	91128126	20966	0	[m²]	LU_C
4	x	4	3	4	2	4	x	4	3	3	1	x	4	2	1		LU_C_Q
24	x	27	27	27	20	25	x	x	27	19	14	x	x	20	18		SUM_Q

11118	11115	11114	11113	11112	11111	11110	11108	11106	11105	11104	11103	11100	11098	11097	11093		HPPD_ID
2100	15	24	13	24	5	6	17	8	7	9	24	10	100	120	86	[MW]	Cap
x	x	15	13	128	33	19	1232	52	176	44	230	958	4	39	4	[million m³]	r_vol
x	x	11	3	18	6	5	125	14	37	14	49	58	1	10	4	[million m²]	r_area
x	46	46	46	46	46	46	28	28	28	28	28	504	32	32	32	[%]	RRI_04
x	3	3	3	3	3	3	2	2	2	2	2	4	2	2	2		RRI_04_Q
x	59	59	59	59	59	59	92	92	92	92	92	5	88	88	88	[%]	RFI_04
x	2	2	2	2	2	2	4	4	4	4	4	1	4	4	4		RFI_04_Q
x	x	1134	649	5706	1923	436	8388	1550	3894	1738	4859	56576	368	6415	842	count	Res
x	x	2	2	4	3	2	4	3	3	3	3	4	2	4	2		Res_Q
x	x	2	1	1		1	3				1					count	PA_No
x	x	22489587	187340	2121116	0	273410	38880389	0	0	0	13789792	0	0	0	0	[m²]	PA
x	x	4	3	4	1	3	4	1	1	1	4	1	1	1	1		PA_Q
x	x	6	6	6	7	7	8	8	7	8	8	8	8	8	8	count	MF
x	x	2	2	2	3	3	4	4	3	4	4	4	4	4	4		MF_Q
x	x	1534773	468375	2427709	838331	605187	16180282	1723633	4714368	1767357	6065310	6717375	180915	1409637	496899	[m³/year]	PE
x	x	2	2	3	2	2	4	3	3	3	3	4	1	2	2		PE_Q
x	x	996878	1049533	704230	180233	1283658	805598	192156	625707	109469	4824097	174537	428	2420	1334804	[t/year]	SE
x	x	39	33	483	485	39	4052	718	747	1053	126	14545	24544	42845	8	[year]	Lifespan
x	x	4	4	3	3	4	2	3	3	3	3	2	1	1	4		SE_Q
x	x	7897897	2142853	2121041	0	0	5906653	0	3432073	4604150	38368269	56733622	647320	7164196	1088441	[m²]	LU_C
x	x	4	3	3	1	1	3	1	3	3	4	4	2	4	3		LU_C_Q
x	x	23	21	24	18	20	27	21	22	23	27	24	17	22	22		SUM_Q

11194	11193	11191	11187	11186	11185	11178	11175	11174	11158	11157	11156	11152	11149	11148		HPPD_ID
287	147	480	150	160	238	12	10	30	63	30	38	18	12	26	[MW]	Cap
313	205	2	2406	6782	24194	1383	67	1467	1003	983	136	1	11	91	[million m³]	r_vol
4	3	0	103	203	959	35	12	36	38	39	7	0	1	3	[million m²]	r_area
33	33	97	483	483	117	109	398	398	533	533	533	533	533	533	[%]	RRI_04
2	2	3	4	4	3	3	4	4	4	4	4	4	4	4		RRI_04_Q
40	40	68	7	7	66	81	65	65	56	56	56	56	56	56	[%]	RFI_04
1	1	3	1	1	2	4	2	2	2	2	2	2	2	2		RFI_04_Q
5367	4425	27	29626	45223	13120	801	3565	21628	120890	1539	2756	35	406	719	count	Res
3	3	1	4	4	4	2	3	4	4	3	3	1	2	2		Res_Q
					5	2			1	1			1	3	count	PA_No
0	0	0	0	0	629373844	30640554	0	0	27761625	3340999	0	0	320575	1692724	[m²]	PA
1	1	1	1	1	4	4	1	1	4	4	1	1	3	4		PA_Q
6	6	2	4	4	5	1	1	1	1	1	1	1	1	1	count	MF
2	2	1	1	1	2	1	1	1	1	1	1	1	1	1		MF_Q
443152	329407	38753	13106717	25897728	132110856	4048068	1259695	3865234	4290385	4449079	777867	14470	83723	383897	[m³/year]	PE
2	1	1	4	4	4	3	2	3	3	3	2	1	1	2		PE_Q
2673	352808	x	1966688	713965	4237145	1386709	357669	80	79	1124501	1404301	283349	6177298	21643	[t/year]	SE
310179	1541	x	3242	25172	15131	2644	495	48500743	33860652	2316	256	12	5	11103	[year]	Lifespan
1	2	x	2	1	2	2	3	1	1	2	3	4	4	2		SE_Q
1570194	917657	0	37997659	108468647	43166557	7545957	3977637	26437227	22073197	5457411	505590	0	312007	550104	[m²]	LU_C
3	3	1	4	4	4	4	3	4	4	3	2	1	2	2		LU_C_Q
15	15	x	21	20	25	23	19	20	23	22	18	15	19	19		SUM_Q

11237	11233	11232	11231	11230	11229	11228	11227	11226	11225	11223	11202	11198	11197	11196		HPPD_ID
12	24	41	42	66	70	80	140	380	3	4	1	20	51	20	17	[MW]
3	1230	3	0	63	5777	1	113	291	210	3	407	x	269	13	[million m³]	Cap
1	153	1	0	6	222	0	10	19	2	1	0	31	x	51	3	[million m²]
2	102	32	596	32	2	260	90	212	x	x	596	32	32	32	32	RRI_04
1	3	2	4	2	1	4	3	4	x	x	4	2	2	2	2	RRI_04_Q
17	20	88	81	88	17	56	76	75	x	x	81	81	81	81	81	RFI_04
1	1	4	4	4	1	2	3	3	x	x	4	3	3	3	3	RFI_04_Q
77	1423	45	68	581	7968	179	805	4949	574	114	18164	x	15172	322	count	Res
1	3	1	1	2	4	1	2	3	2	1	4	x	4	2	2	Res_Q
	5		1			1			1	1		x		1	count	PA_No
0	132932304	0	175072	0	0	204498	0	0	2693002	702538	0	x	0	8307	[m²]	PA
1	4	1	3	1	1	3	1	1	4	3	1	x	1	3	3	PA_Q
4	4	9	9	9	4	2	4	3	4	4	9	x	7	7	count	MF
1	1	4	4	4	1	1	1	1	1	1	4	x	3	3	3	MF_Q
81086	24790782	81851	19519	788022	25866381	15081	1672128	2890819	194799	50496	3919485	x	5551890	274459	[m³/year]	PE
1	4	1	1	2	4	1	3	3	1	1	3	x	3	1	1	PE_Q
x	1760109	3105465	114	2167653	1025440	72487	2113873	83622263	x	x	194326	x	468713	2314401	[t/year]	SE
x	1852	2	11355	77	14930	31	141	9	x	x	5551	x	1518	15	[year]	Lifespan
x	2	4	2	4	2	4	3	4	x	x	2	x	2	4	4	SE_Q
0	92587908	15121	0	8627	146567	0	8908075	4922066	0	0	17810819	x	55173850	2934287	[m²]	LU_C
1	4	2	1	2	2	1	4	3	1	1	4	x	4	3	3	LU_C_Q
x	22	19	20	21	16	17	20	22	x	x	26	x	22	21	21	SUM_Q

HPPD_ID	11241	11239	11238	HPPD_ID
66	1	1	[MW]	Cap
92	139	65	[million m ³]	r_vol
12	6	22	[million m ³]	r_area
32	0	0	[%]	RRI_04
2	1	1		RRI_04_Q
88	52	52	[%]	RFI_04
4	2	2		RFI_04_Q
1324	304	882	count	Res
2	2	2		Res_Q
			count	PA_No
0	0	0	[m ²]	PA
1	1	1		PA_Q
8	11	6	count	MF
4	4	2		MF_Q
1736924	659846	2460543	[m ³ /year]	PE
3	2	3		PE_Q
1342242	12466	6970856	[t/year]	SE
181	29489	25	[year]	Lifespan
3	1	4		SE_Q
4753216	371018	661451	[m ²]	LU_C
3	2	2		LU_C_Q
22	15	17		SUM_Q

Table A.5: Proposed hydropower plants of Type Reservoir and unknown. Each hydropower plant (HPP) can be identified with the respective HPPD_ID from the Renewable Power Plant Database (RePP) Africa (Peters et al., 2023). Rankings including all indicators for the entire continent (Ranking_all continent), and the major basins Congo, Niger, Nile, Volta, Zambezi (Ranking_all basin); rankings leaving out one indicator (ex_...) at a time (River Regulation (RRI), River Fragmentation (RFI), Resettlement (Res), Protected Areas (PA), Megafauna (MF), Potential Evaporation (PE), Sediment Entrapment (SE), and Land Use Change Cropland (LU_C); and rankings for different indicator compositions with A including PA, Res, and PU; B including MF, and SE; and C including PE, RFI, and RRI. Quartile values are indicated with 1 (low impact, ≤ 1 st quartile), 2 (moderate impact, > 1 st to ≤ 2 nd quartile), 3 (heavy impact, > 2 nd to ≤ 3 rd quartile), and 4 (severe impact, > 3 rd quartile). Colour intensity increases with impact magnitude.

HPPD_ID	10007	10008	10015	10016	10017	10018	10019	10020	10021	10022	10024	10025	10027
Ranking_all continent	2	2	4	3	2	4	2	2	2	1	2	3	4
HYBAS_ID	1030020050	1030020050	1030020050	1030020050	1030020050	1030020050	1030020050	1030020050	1030020050	1030040190	1030022420	1030022420	1030022420
Basin name											Niger	Niger	Niger
Ranking_all basin													
Ex_RRI	2	2	4	3	3	4	2	2	2	1	1	3	3
Ex_RFI	2	2	4	2	2	4	2	2	2	1	1	3	4
Ex_Res	2	2	4	3	2	4	2	3	3	1	2	3	3
Ex_PA	2	2	4	3	2	4	2	2	2	1	2	4	4
Ex_MF	1	1	4	2	2	3	1	2	2	1	1	3	3
Ex_PE	2	2	4	2	2	3	2	2	2	1	2	3	4
Ex_SE	1	1	4	3	2	3	1	2	2	1	1	3	4
Ex_LU_C	2	2	4	2	2	4	2	2	2	1	2	4	4
Ranking A	1	1	4	2	2	2	1	1	1	1	1	2	3
Ranking B	4	4	4	2	4	4	4	4	4	3	4	3	3
Ranking C	2	2	2	3	2	3	2	2	2	1	2	4	3

10090	10084	10076	10074	10071	10070	10069	10066	10065	10064	10063	10060	10059	10058	10051	10049	10047	10043	10038	10037	10036	10035	10034	10033	10028	HPPD_ID
3	1	1	3	1	1	3	2	1	2	1	1	1	3	1	4	4	3	2	1	2	2	3	3	4	Ranking_all continent
103002 0050	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0050	103002 0050	103002 0040	103002 0040	103002 0040	103002 0050	103002 0040	103002 0050	103002 0050	103002 2420	HYBAS_ID
	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo			Congo	Congo	Congo		Congo			Niger	Basin name
	1	1	4	2	1	4	3	2	4	2	1	1	4	2			4	4	2		3			4	Ranking_all basin
3	1	1	4	2	1	3	2	2	3	2	1	1	4	1	4	4	3	3	1	2	2	3	3	4	Ex_RRI
3	1	1	4	2	1	4	2	2	3	2	1	1	4	1	4	4	3	3	1	2	2	3	3	4	Ex_RFI
4	1	1	4	2	1	3	2	2	2	2	1	1	4	1	4	4	3	2	1	1	2	3	3	4	Ex_Res
2	1	1	2	1	1	2	1	1	2	2	1	1	2	1	4	3	3	2	1	2	1	4	4	4	Ex_PA
3	1	1	3	1	1	3	2	1	2	1	1	1	3	1	4	4	2	2	1	2	2	3	3	4	Ex_MF
3	1	1	3	2	1	3	2	1	2	1	1	1	3	1	4	4	2	2	1	2	1	3	3	4	Ex_PE
2	1	1	3	1	1	3	2	2	2	1	1	1	3	1	4	4	2	2	1	2	2	4	3	4	Ex_SE
3	1	1	3	1	1	2	2	1	2	1	1	1	3	1	4	4	3	2	1	1	2	3	4	4	Ex_LU_C
3	1	1	3	2	1	4	3	3	2	2	1	1	4	1	4	4	1	2	1	3	3	3	2	3	Ranking A
3	3	1	4	4	4	3	1	1	3	2	2	4	3	2	1	1	4	3	3	1	1	2	4	3	Ranking B
2	1	1	2	1	1	1	1	1	2	1	1	1	2	1	3	3	2	2	2	1	2	3	3	4	Ranking C

10139	10138	10137	10136	10135	10134	10133	10132	10131	10128	10126	10124	10123	10122	10119	10118	10117	10115	10114	10112	10111	10109	10103	10093	10091	HPPD_ID
2	1	1	1	2	3	2	3	3	2	2	1	2	3	1	2	2	1	2	1	1	1	2	2	1	Ranking all continent
103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	HYBAS_ID
Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Basin name
3	1	1	2	3	4	4	4	4	3	3	2	3	4	2	4	4	2	3	1	1	1	4	3	2	Ranking all basin
2	1	1	1	2	3	3	3	3	2	2	1	2	3	1	3	3	2	2	1	1	1	3	2	1	Ex_RRI
2	1	1	1	2	3	3	3	3	2	2	1	2	3	1	2	2	2	2	1	1	1	2	2	1	Ex_RFI
2	1	1	1	2	2	2	2	3	2	2	1	2	3	1	2	2	1	1	1	1	1	2	2	1	Ex_Res
2	1	1	1	2	3	2	3	3	2	2	1	2	3	1	2	2	2	1	1	1	1	2	2	1	Ex_PA
1	1	1	1	1	2	2	2	2	1	1	1	1	2	1	2	2	1	2	1	1	1	2	2	1	Ex_MF
2	1	1	1	2	3	2	3	2	1	1	1	2	2	1	2	2	1	1	1	1	1	2	1	1	Ex_PE
2	1	1	1	1	2	3	2	2	2	2	1	1	2	1	2	2	1	2	1	1	1	3	2	1	Ex_SE
2	1	1	1	2	3	2	3	3	2	1	1	2	2	1	3	2	1	2	1	1	1	2	1	1	Ex_LU_C
2	1	1	1	1	3	3	3	2	2	2	1	1	2	1	1	2	2	3	1	1	1	3	3	1	Ranking A
2	1	3	2	4	4	2	4	4	2	2	2	4	4	2	3	1	2	1	2	1	3	2	1	2	Ranking B
2	2	1	2	1	2	2	2	2	2	2	1	2	2	2	2	2	1	1	1	1	1	2	2	1	Ranking C

10206	10204	10203	10201	10185	10184	10176	10175	10174	10167	10158	10156	10155	10154	10153	10152	10151	10150	10149	10148	10147	10146	10145	10143	10140	HPPD_ID
2	1	3	1	2	1	1	1	1	3	1	3	1	1	2	2	2	1	3	2	2	1	3	3	2	Ranking_all continent
103002 0040	103002 0040	103003 4260	103002 0040	103002 0040	103002 0040	103002 0050	103002 0050	103002 0050	103002 0050	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103003 4260	103002 0040	103002 0040	103002 0040	103003 4260	103003 4260	103002 0040	HYBAS_ID
Congo	Congo	Nile	Congo	Congo	Congo					Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Nile	Congo	Congo	Congo	Nile	Nile	Congo	Basin name
3	2	2	2	4	1					1	4	2	2	4	4	3	1	2	3	1	1	2	2	4	Ranking_all basin
2	1	3	1	2	1	2	1	1	3	1	3	2	1	2	2	2	1	2	2	1	1	3	2	3	Ex_RRI
2	2	3	2	3	1	1	1	1	3	1	3	1	1	2	3	2	1	2	2	1	1	3	2	2	Ex_RFI
1	1	3	1	2	1	2	1	1	2	1	2	2	1	1	2	1	1	3	1	1	1	4	3	2	Ex_Res
2	2	4	2	2	1	1	1	1	2	1	2	2	1	2	2	2	1	3	2	1	1	2	2	2	Ex_PA
2	1	4	1	2	1	1	1	1	2	1	2	1	1	2	2	2	1	2	2	1	1	3	2	2	Ex_MF
2	1	3	2	2	1	1	1	1	3	1	2	1	1	2	2	2	1	3	2	1	1	4	3	2	Ex_PE
2	2	4	1	2	1	2	1	1	3	1	3	1	1	2	2	1	1	2	1	1	1	3	2	3	Ex_SE
1	1	3	1	2	1	1	1	1	2	1	3	1	1	1	2	2	1	3	1	1	1	4	3	2	Ex_LU_C
3	3	3	2	3	1	2	1	2	4	1	4	1	1	3	3	2	2	1	2	1	2	2	1	2	Ranking A
1	1	1	3	1	2	1	4	1	2	2	1	3	4	1	2	3	1	4	2	3	1	4	3	2	Ranking B
1	1	4	1	2	1	1	2	1	1	1	2	1	1	2	1	1	1	3	1	1	1	3	3	2	Ranking C

10283	10282	10281	10280	10257	10250	10249	10248	10247	10246	10245	10243	10241	10240	10239	10238	10235	10234	10233	10232	10215	10214	10213	10212	10211	HPPD_ID
4	2	4	4	3	2	1	3	1	1	1	1	4	4	4	2	2	1	4	2	4	2	3	4	4	Ranking_all continent
103003 4260	103003 4260	103003 4260	103000 8110	103003 4260	103000 8100	103003 4260	103004 0260	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	103004 0260	103004 0260	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	103000 8100	103004 0260	103003 4260	103003 4260	HYBAS_ID
Nile	Nile	Nile		Nile					Nile	Nile	Nile	Nile	Nile			Nile	Nile	Nile	Nile	Nile			Nile	Nile	Basin name
4	1	4		2				1	1	1	1	4	3			1	1	3	1	3			4	4	Ranking_all basin
4	2	4	3	2	1	1	3	1	1	1	1	4	3	4	2	2	1	3	1	3	2	2	3	3	Ex_RRI
4	2	4	4	2	2	1	3	1	1	1	1	4	3	4	2	2	1	3	2	3	2	3	4	4	Ex_RFI
4	3	4	3	3	1	1	4	1	1	1	1	4	3	4	2	2	1	3	2	3	2	2	4	4	Ex_Res
4	2	4	3	3	2	1	2	1	1	1	1	4	4	4	2	2	2	4	2	4	1	3	4	3	Ex_PA
4	2	4	4	3	2	1	3	1	1	1	1	4	4	4	3	3	2	4	2	4	2	3	4	4	Ex_MF
4	3	4	4	4	1	1	3	1	1	1	1	4	4	4	3	3	2	4	2	4	2	2	4	4	Ex_PE
4	2	4	4	2	2	1	3	1	1	1	1	4	3	4	2	2	1	3	2	4	1	3	4	3	Ex_SE
4	2	4	3	3	2	1	4	1	1	1	1	4	4	4	2	2	2	4	2	3	2	4	4	4	Ex_LU_C
4	2	3	4	2	2	1	2	2	1	1	1	4	3	4	2	2	1	2	2	3	3	2	3	3	Ranking A
1	1	2	1	3	1	1	2	1	3	3	2	1	1	1	2	1	1	2	1	1	2	1	1	2	Ranking B
4	3	4	2	3	2	2	4	1	1	1	1	4	4	4	2	3	3	4	3	4	1	4	4	4	Ranking C

10388	10358	10357	10356	10354	10350	10348	10344	10343	10342	10341	10340	10323	10322	10314	10311	10309	10302	10301	10300	10299	10294	10293	10292	10290	HPPD_ID
3	1	1	2	1	1	1	1	1	1	1	1	1	1	4	3	2	2	2	2	3	3	4	2	4	Ranking_all continent
103003 4260	103003 5180	103003 5180	103003 5180	103003 5180	103003 5180	103003 5180	103003 5180	103003 5180	103003 5180	103003 5180	103003 5180	103003 5180	103003 5180	103000 8110	103000 8110	103000 8110	103000 8110	103004 0260	103004 0260	103004 0260	103003 4260	103003 4260	103003 4260	103003 4260	HYBAS_ID
Nile																					Nile	Nile	Nile	Nile	Basin name
2																					2	4	1	4	Ranking_all basin
3	2	2	3	1	1	1	1	1	1	1	1	1	1	4	3	2	2	1	2	3	3	4	2	4	Ex_RRI
3	1	1	2	1	1	1	1	1	1	1	1	1	1	4	3	2	2	2	2	3	3	4	2	4	Ex_RFI
3	1	1	2	1	1	1	1	1	1	1	1	1	1	4	3	2	2	2	3	3	4	4	3	4	Ex_Res
4	2	2	2	1	1	1	1	1	1	1	1	1	1	3	3	2	2	2	2	2	3	4	2	4	Ex_PA
4	2	2	3	1	1	1	1	1	1	1	1	1	1	4	3	2	3	2	3	4	3	4	2	4	Ex_MF
4	1	1	2	1	1	1	1	1	1	1	1	1	1	4	3	2	2	2	3	4	4	4	3	4	Ex_PE
3	2	2	2	1	1	1	1	1	1	1	1	1	1	4	3	1	2	2	2	3	3	4	2	4	Ex_SE
3	1	1	2	1	1	1	1	1	1	1	1	1	1	4	2	2	2	2	2	3	4	4	2	4	Ex_LU_C
3	3	3	3	1	1	1	3	2	1	2	1	1	1	4	3	2	3	2	2	4	2	4	1	3	Ranking A
1	1	1	2	1	1	1	1	1	1	1	2	2	1	1	1	2	1	1	2	1	3	2	3	2	Ranking B
4	2	2	2	1	1	1	1	2	1	1	1	1	1	4	3	2	2	2	2	3	3	4	3	4	Ranking C

10522	10521	10486	10479	10475	10474	10469	10467	10459	10454	10452	10434	10433	10431	10421	10414	10412	10410	10402	10398	10395	10393	10392	10390	10389	HPPD_ID
4	2	4	4	2	1	1	1	2	1	2	1	1	2	3	4	3	3	1	2	4	1	1	3	3	Ranking all continent
103003 4260	103003 4260	103003 4260	103003 4260	103001 1660	103001 1660	103001 1660	103001 1660	103000 8110	103000 8110	103000 8110	103002 0040	103002 0040	103001 1660	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	103002 0040	103002 0040	103003 4260	103003 4260	HYBAS_ID
Nile	Nile	Nile	Nile	Zambezi	Zambezi	Zambezi	Zambezi				Congo	Congo	Zambezi	Nile	Nile	Nile	Nile	Nile	Nile	Nile	Congo	Congo	Nile	Nile	Basin name
3	1	4	3	3	1	1	1				1	2	3	2	4	2	2	1	1	3	2	2	2	2	Ranking all basin
3	2	4	3	2	1	1	1	1	1	2	1	1	1	3	4	2	2	2	2	3	1	1	2	2	Ex_RRI
3	2	4	3	3	1	1	1	2	1	2	1	1	2	3	4	3	2	2	2	3	1	1	2	2	Ex_RFI
4	3	4	4	2	1	1	1	2	1	2	1	1	2	3	4	3	3	1	2	3	1	1	3	2	Ex_Res
4	2	4	4	2	1	1	1	1	1	1	1	1	2	4	4	3	2	2	2	4	1	1	3	3	Ex_PA
4	2	4	3	3	1	1	1	2	1	2	1	1	2	3	4	3	2	2	3	4	1	1	3	3	Ex_MF
3	2	4	4	2	1	1	1	2	1	2	1	1	1	3	4	3	3	1	3	3	1	1	4	3	Ex_PE
3	2	4	3	2	1	1	1	2	1	2	1	1	2	4	4	3	2	2	2	4	1	1	3	3	Ex_SE
4	3	4	4	2	1	1	1	2	1	2	1	1	2	3	4	3	3	1	2	3	1	1	3	2	Ex_LU_C
2	1	4	2	3	1	1	2	3	1		1	2	2	3	3	2	3	3	2	3	1	2	3	3	Ranking A
2	3	2	4	1	1	1	1	1	2	1	3	1	1	4	4	1	2	1	1	1	3	1	2	1	Ranking B
4	4	4	3	2	2	2	2	2	2	2	1	1	3	4	4	4	4	2	3	4	1	1	3	4	Ranking C

10584	10583	10581	10579	10578	10577	10576	10575	10574	10573	10572	10571	10570	10569	10567	10550	10547	10545	10542	10539	10538	10537	10535	10533	10526	HPPD_ID
1	1	3	1	1	2	1	4	1	2	1	1	1	3	1	1	2	2	4	4	3	4	4	2	2	Ranking_all continent
103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103002 0040	103004 0260	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	103003 4260	HYBAS_ID
															Congo		Nile	Nile	Nile	Nile	Nile	Nile	Nile	Nile	Basin name
															1		1	3	2	4	3	1	4	1	Ranking_all basin
1	1	2	1	1	2	1	4	1	1	1	1	1	2	1	1	2	2	3	2	3	3	1	4	1	Ex_RRI
1	1	3	1	1	2	1	4	1	1	1	1	1	2	1	1	2	2	3	2	4	3	1	4	1	Ex_RFI
1	1	2	1	1	2	1	4	1	2	1	1	1	2	1	1	2	2	3	3	4	4	2	4	2	Ex_Res
1	2	3	1	1	2	1	3	1	2	1	1	1	3	1	1	2	2	4	3	4	3	2	4	2	Ex_PA
1	2	3	1	1	2	1	4	1	2	1	1	1	3	1	1	3	2	3	3	4	3	2	4	2	Ex_MF
1	1	2	1	1	1	1	4	1	1	1	1	1	2	1	1	3	3	4	3	4	4	2	4	2	Ex_PE
1	1	3	1	1	2	1	4	1	2	1	1	1	3	1	1	2	2	4	3	4	4	2	4	2	Ex_SE
1	2	2	1	1	1	1	4	1	2	1	1	1	2	1	1	2	2	4	3	4	4	2	4	2	Ex_LU_C
1	1	3	1	1	3	1	4	1	1	1	1	1	2	1	1	2	1	3	2	3	3	1	3	1	Ranking A
1	1	1	1	1	1	1	1	1	1	1	2	1	1	3	1	2	2	2	1	3	3	1	4	1	Ranking B
2	2	2	1	2	2	1	4	2	3	2	2	2	4	1	1	2	3	4	4	4	3	3	4	3	Ranking C

10647	10645	10644	10642	10638	10637	10636	10618	10615	10611	10610	10609	10608	10606	10605	10604	10603	10602	10601	10599	10597	10596	10595	10594	10585	HPPD_ID
2	4	4	2	1	2	1	2	4	1	1	1	1	2	1	2	1	1	3	1	1	1	1	1	1	Ranking all continent
103001 1660	103001 1660	103001 1660	103001 1660	103001 1660	103001 1660	103001 1660	103001 2600	103001 2600	103002 0040	103002 0040	103002 0040	103002 0040	103001 8110	103001 1660	103004 0200	103004 0200	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	103001 8110	HYBAS_ID
Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi			Congo	Congo	Congo	Congo		Zambe zi											Basin name
3	4	4	3	2	2	1			2	1	1	1		1											Ranking all basin
1	3	3	2	1	1	1	1	3	1	1	1	1	2	1	2	1	1	2	1	1	1	1	1	1	Ex_RRI
2	4	4	3	2	2	1	2	4	1	1	1	1	2	1	3	2	1	3	1	1	1	1	1	1	Ex_RFI
2	3	4	2	1	2	1	4	4	1	1	1	1	2	1	2	1	1	2	1	1	1	1	1	1	Ex_Res
2	3	3	2	2	1	1	3	3	1	1	1	1	2	1	2	2	2	3	1	1	1	1	1	1	Ex_PA
2	4	4	3	1	2	1	2	4	1	1	1	1	2	1	3	2	2	3	1	1	1	1	1	1	Ex_MF
2	3	4	2	2	2	1	2	4	1	1	1	1	1	1	2	1	1	2	1	1	1	1	1	1	Ex_PE
1	4	4	2	1	1	1	1	4	1	1	1	1	2	1	2	2	2	3	1	1	1	1	1	1	Ex_SE
2	3	4	2	1	2	1	2	3	1	1	1	1	2	1	2	1	2	2	1	1	1	1	1	1	Ex_LU_C
2	4	4	2	1	2	1	4	4	2	1	1	1	1	1	3	2	1	3	1	1	1	1	1	1	Ranking A
2	1	1	1	2	2	2	1	1	2	1	2	2	1	1	1	1	1	1	2	3	3	3	1	2	Ranking B
2	3	3	2	2	2	2	2	3	1	1	1	1	4	2	2	2	3	4	1	1	1	1	1	2	Ranking C

10754	10751	10749	10748	10745	10744	10743	10742	10741	10722	10680	10678	10675	10672	10670	10669	10668	10666	10659	10658	10657	10653	10651	10650	10649	HPPD_ID
1	1	3	1	1	1	3	1	1	4	2	2	1	4	1	2	1	1	3	1	1	3	4	1	1	Ranking_all continent
103001 1660	103001 1660	103001 1660	103001 1660	103001 1660	103001 1660	103001 1660	103001 1660	103001 1660	103001 1660	103001 8110	103004 0200	103001 1670	103001 1660	103001 1660	103001 1660	103000 8110	103000 8110	103001 1670	103000 8110	103000 8110	103001 1660	103001 1660	103001 1660	103001 1660	HYBAS_ID
Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi	Zambe zi				Zambe zi	Zambe zi	Zambe zi						Zambe zi	Zambe zi	Zambe zi	Zambe zi	Basin name
1	1	4	3	1	1	4	1	2	4				4	2	2						3	4	2	1	Ranking_all basin
1	1	3	2	1	1	1	1	1	4	1	2	1	4	1	1	1	1	2	1	1	2	3	1	1	Ex_RRI
1	1	4	2	1	1	1	1	1	4	2	3	1	4	1	2	1	1	2	1	1	4	4	2	1	Ex_RFI
1	1	4	1	1	1	3	1	2	4	2	2	1	4	2	2	1	1	2	1	1	3	3	2	1	Ex_Res
1	1	2	1	1	1	3	1	1	4	1	2	1	4	2	2	1	1	2	1	1	3	3	1	1	Ex_PA
1	1	3	2	1	1	4	1	2	4	2	2	1	4	1	2	1	1	3	1	1	3	4	2	1	Ex_MF
1	1	3	1	1	1	3	1	2	4	2	2	1	4	2	1	1	1	3	1	1	2	3	1	1	Ex_PE
1	1	3	2	1	1	3	1	1	4	2	2	1	4	1	2	1	1	3	1	1	3	4	1	1	Ex_SE
1	1	3	2	1	1	3	1	1	4	2	3	1	4	2	2	1	1	2	1	1	2	3	2	1	Ex_LU_C
1	1	3	3	1	1	4	1	2	4	2	2	1	4	1	1	1	2	4	1	1	3	4	2	2	Ranking A
1	1	3	1	2	2	1	1	2	1	1	3	1	1	3	1	2	1	1	2	1	1	1	1	1	Ranking B
2	2	2	2	1	1	3	2	1	3	3	2	2	4	2	3	1	1	2	1	1	3	3	2	2	Ranking C

10797	10796	10795	10794	10793	10792	10790	10788	10787	10786	10785	10783	10770	10768	10767	10766	10765	10762	10761	10760	10759	10758	10757	10756	10755	HPPD_ID
3	4	4	4	4	4	1	1	2	1	1	3	3	1	1	4	1	2	2	3	1	1	2	2	1	Ranking all continent
103002 2430	103002 2430	103002 2430	103002 2430	103002 2430	103002 2430	103001 1670	103001 1670	103001 1670	103001 1670	103001 2590	103001 1660	103001 1670	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103002 0040	103001 1660	103001 1660	103002 0040	HYBAS_ID
											Zambezi		Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Congo	Zambezi	Zambezi	Congo	Basin name
											4		1	1	4	1	3	3	4	1	1	2	3	2	Ranking all basin
3	4	4	4	4	4	1	1	1	1	1	3	3	1	1	4	1	2	2	3	1	1	1	2	1	Ex_RRI
3	3	3	4	4	4	1	1	1	1	1	4	3	1	1	4	1	2	2	3	1	1	2	2	1	Ex_RFI
3	4	4	4	4	4	1	2	2	1	1	4	3	1	1	3	1	2	2	3	1	1	1	2	1	Ex_Res
4	3	4	4	4	4	2	2	1	1	1	2	3	1	1	3	1	1	1	2	1	1	2	2	1	Ex_PA
3	3	3	4	4	3	2	2	2	1	1	3	3	1	1	4	1	2	2	3	1	1	2	2	1	Ex_MF
3	4	3	4	4	4	2	2	2	1	1	3	3	1	1	3	1	1	1	2	1	1	1	2	1	Ex_PE
4	3	3	4	4	4	1	1	1	1	1	3	3	1	1	4	1	2	2	3	1	1	2	3	1	Ex_SE
3	4	4	4	4	4	2	1	2	1	1	4	2	1	1	3	1	2	2	2	1	1	2	2	1	Ex_LU_C
3	3	2	4	4	3	1	1	1	1	1	3	3	1	1	4	1	2	2	3	1	1	2	3	1	Ranking A
2	4	4	3	2	3	2	2	2	1	1	2	1	3	2	1	1	1	1	1	1	1	1	1	3	Ranking B
3	2	4	3	4	3	2	2	2	2	1	3	3	1	1	2	2	2	2	2	1	2	3	2	2	Ranking C

10835	10833	10832	10831	10825	10822	10820	10818	10817	10815	10813	10812	10811	10810	10809	10808	10807	10806	10805	10804	10803	10801	10800	10799	10798	HPPD_ID
4	4	2	3	3	4	4	2	3	2	3	3	3	3	3	4	3	2	4	4	4	4	3	3	3	Ranking_all continent
103002 3310	103002 3310	103002 3310	103002 3310	103002 3300	103002 3300	103002 3310	103002 2430	103002 2430	103002 2420	103002 2420	103002 2420	103002 2430	103002 3300	103002 2420	103002 2420	103002 2420	103002 2420	103002 2430	103002 2430	103002 2430	103002 2430	103002 2430	103002 2430	103002 2430	HYBAS_ID
				Volta	Volta				Niger	Niger	Niger		Volta	Niger	Niger	Niger	Niger								Basin name
				1	4				1	2	2		2	3	3	2	1								Ranking_all basin
4	4	2	3	3	4	4	2	3	2	2	3	3	3	3	3	2	1	4	4	4	4	3	3	3	Ex_RRI
4	4	3	3		4	4	2	2	2	2	3	2	3	4	4	3	2	4	4	4	3	3	2	3	Ex_RFI
4	4	2	2	2	4	4	2	3	2	3	3	3	3	3	3	3	2	4	4	4	4	3	3	4	Ex_Res
4	4	2	3	2	4	4	2	3	2	3	3	3	2	2	3	2	2	4	4	4	3	4	3	4	Ex_PA
4	4	2	3	3	4	4	2	2	2	3	3	2	3	3	4	2	1	4	4	4	3	3	2	3	Ex_MF
4	4	2	4	2	4	4	3	3	2	2	3	3	3	3	3	2	1	4	4	4	4	3	3	3	Ex_PE
4	4	2	2	3	4	4	2	2	1	2	3	3	3	3	4	2	1	4	4	4	3	3	2	3	Ex_SE
4	4	2	3	2	4	4	3	3	2	2	3	3	3	3	3	3	2	4	4	4	4	3	3	3	Ex_LU_C
4	4	3	3	4	4	4	1	1	1	2	2	2	3	4	4	2	1	3	4	4	2	2	1	2	Ranking A
4	2	2	4	1	2	2	4	4	4	2	3	4	1	2	1	3	3	3	4	2	4	3	4	4	Ranking B
4	2	2	2	4	4	2	2	2	2	3	3	2	2	2	2	2	2	4	4	4	3	3	2	3	Ranking C

10890	10878	10877	10876	10872	10871	10870	10866	10865	10863	10861	10860	10859	10858	10857	10856	10855	10853	10852	10847	10846	10845	10842	10840	10836	HPPD_ID
2	4	4	4	2	4	3	3	4	3	4	2	4	2	4	4	4	2	4	4	4	4	4	4	4	Ranking all continent
103002 3310	103002 3300	103002 3300	103002 3300	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	HYBAS_ID
	Volta	Volta	Volta																						Basin name
	2	4	2																						Ranking all basin
2	3	4	3	2	4	3	3	4	2	4	2	3	2	4	4	2	4	4	4	4	3	4	4	4	Ex_RRI
2	4	4	4	2	4	3	4	4	3	4	1	4	2	4	4	2	4	4	4	4	4	4	4	4	Ex_RFI
2	3	4	3	2	4	3	3	4	2	4	2	3	2	4	4	2	4	4	4	4	4	4	4	4	Ex_Res
2	3	4	4	2	4	4	2	4	3	4	2	3	2	4	3	2	4	4	4	4	4	3	4	4	Ex_PA
2	4	4	3	2	4	3	3	4	3	4	1	3	2	4	4	2	4	4	4	4	4	3	4	4	Ex_MF
2	3	4	3	2	4	4	2	4	3	4	2	4	3	4	4	2	4	4	4	4	4	4	4	4	Ex_PE
2	4	4	4	2	4	3	3	4	3	4	2	4	2	4	3	2	4	4	4	4	4	4	4	4	Ex_SE
2	4	4	3	2	4	3	3	4	3	4	2	4	2	4	4	3	4	4	4	4	4	4	4	4	Ex_LU_C
1	4	3	3	2	3	3	3	4	3	4	1	4	2	4	3	1	4	3	4	4	4	3	4	3	Ranking A
3	1	4	2	3	3	4	1	1	1	4	2	2	2	1	4	3	2	4	3	4	3	2	2	3	Ranking B
2	4	4	3	2	3	2	2	4	3	3	2	2	2	4	3	3	4					4	4	4	Ranking C

10927	10926	10924	10923	10922	10921	10920	10919	10917	10916	10915	10914	10913	10912	10911	10909	10908	10907	10906	10903	10901	10900	10899	10898	10895	HPPD_ID
4	2	4	3	3	3	2	3	2	3	1	3	4	3	3	3	3	3	3	3	3	2	2	2	4	Ranking_all continent
103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	HYBAS_ID
																									Basin name
																									Ranking_all basin
4	2	4	3	3	3	2	3	2	3	1	3	4	3	3	3	3	3	3	3	3	2	2	2	4	Ex_RRI
4	1	4	2	2	2	1	2	3	3	1	2	3	2	3	2	2	2	3	2	2	1	1	4	4	Ex_RFI
4	2	4	3	3	2	2	3	2	3	1	3	3	2	3	2	2	3	3	3	3	2	2	2	4	Ex_Res
3	2	3	3	3	3	2	3	2	3	1	3	4	3	4	3	3	3	4	2	3	2	2	2	4	Ex_PA
4	2	4	3	3	3	2	3	2	3	1	3	4	3	3	3	3	3	3	3	3	2	2	2	4	Ex_MF
4	2	4	3	3	3	2	3	2	3	1	3	3	2	3	2	2	3	3	4	3	2	2	2	4	Ex_PE
4	1	4	3	3	2	3	3	2	3	1	3	4	3	4	3	3	3	4	3	3	3	1	1	4	Ex_SE
4	2	4	2	3	2	2	2	2	3	1	3	3	3	3	2	2	3	3	3	3	2	2	2	4	Ex_LU_C
4	1	4	3	2	2	3	3	1	3	1	2	3	3	3	2	2	2	3	3	2	2	1	1	4	Ranking A
1	3	1	1	2	2	1	1	2	1	1	2	1	1	1	1	1	2	1	2	2	1	3	2	2	Ranking B
4	2	4	3	3	2	2	3	2	3	2	3	4	4	4	3	3	3	4	2	3	3	2	2	3	Ranking C

10992	10991	10989	10987	10986	10985	10984	10980	10975	10970	10969	10968	10967	10966	10965	10962	10956	10952	10946	10944	10942	10941	10933	10930	10929	HPPD_ID
1	3	4	2	4	2	4	3	4	2	3	3	3	3	3	2	1	1	1	3	2	1	3	3	2	Ranking all continent
103002 2420	103002 2420	103002 2420	103002 2420	103002 7410	103002 7410	103002 7410	103002 7410	103002 2420	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 7410	103002 3310	103002 3310	103002 3310	103002 7410	103002 3310	103002 7410	103002 3310	103002 3310	103002 3310	103002 3310	HYBAS_ID
Niger	Niger	Niger	Niger					Niger																	Basin name
1	2	3	1					4																	Ranking all basin
1	2	3	2	4	2	4	3	4	2	3	3	3	3	2	2	1	1	1	3	1	1	3	2	2	Ex_RRI
2	3	4	2	4	2	4	3	4	2	2	2	3	2	2	2	1	1	1	3	2	1	2	3	2	Ex_RFI
2	2	4	2	4	3	4	3	4	2	3	2	4	3	2	2	1	1	2	3	2	1	3	2	3	Ex_Res
1	2	3	2	4	2	4	4	4	2	3	3	3	2	3	2	1	2	2	4	2	1	2	3	2	Ex_PA
1	2	3	1	4	3	4	4	4	2	3	3	3	3	3	2	1	2	2	3	2	1	3	3	2	Ex_MF
1	2	3	2	4	3	4	3	4	2	2	2	3	2	2	2	1	1	2	3	2	1	3	2	2	Ex_PE
1	3	3	2	4	2	4	3	4	3	3	3	3	3	3	3	1	1	1	3	2	1	2	2	2	Ex_SE
2	3	4	2	4	3	4	4	4	2	3	2	3	2	3	2	1	2	2	3	2	1	4	3	3	Ex_LU_C
1	3	3	1	4	2	4	2	4	2	2	2	3	3	2	2	1	1	1	3	1	1	2	2	2	Ranking A
2	1	4	4	1	2	1	1	3	1	1	1	2	1	1	1	1	1	2	1	1	1	3	2	3	Ranking B
2	2		2	4	2	4	4	2	3	4	3	3	3	4	4	2	2	2	4	4	2	2	3	2	Ranking C

11042	11041	11039	11038	11036	11024	11023	11021	11019	11017	11016	11015	11012	11011	11010	11009	11007	11005	11004	11002	11001	10998	10997	10996	10993	HPPD_ID
3	4	2	4	3	4	4	2	3	4	2	4	3	3	3	3	2	3	1	4	3	2	4	3	3	Ranking_all continent
103002 7410	103002 7410	103002 7410	103002 2420	103002 2420	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 3310	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	HYBAS_ID
			Niger	Niger												Niger	Niger	Niger	Niger	Niger	Niger	Niger	Niger	Niger	Basin name
			3	2												1	2	1	4	2	1	4	2	3	Ranking_all basin
3	3	1	4	3	4	4	2	3	4	2	4	3	3	3	3	1	3	1	4	2	1	4	2	3	Ex_RRI
4	4	2	4	4	4	4	1	3	4	1	4	2	2	3	3	2	4	1	4	3	2	4	3	4	Ex_RFI
3	4	2	3	2	4	4	2	3	4	2	4	3	3	4	3	2	2	1	4	3	2	4	3	3	Ex_Res
2	4	2	3	3	4	4	2	4	4	2	4	3	2	3	4	2	3	1	4	2	2	3	2	2	Ex_PA
3	4	2	4	3	3	3	1	3	4	2	4	3	2	3	3	1	3	1	4	2	1	4	2	3	Ex_MF
2	3	2	3	2	4	4	2	3	4	2	4	3	3	3	3	2	2	1	4	3	2	4	3	3	Ex_PE
3	3	1	3	3	4	4	2	4	3	1	4	3	3	3	3	1	3	1	4	2	1	4	2	3	Ex_SE
2	3	2	3	2	4	4	2	3	4	2	4	2	4	4	3	2	3	1	4	3	2	4	3	4	Ex_LU_C
3	3	1	4	3	3	3	1	3	3	1	4	3	2	2	3	1	3	1	4	2	1	4	2	3	Ranking A
1	1	2	2	1	2	4	3	2	3	3	2	2	3	3	2	4	2	2	3	4	3	3	4	3	Ranking B
2	4	3	2	2	4	3	2	3	3	2	3	2	2	3	3	2	2	2	2	2	2	2	2	2	Ranking C

11105	11104	11103	11100	11098	11097	11093	11090	11086	11084	11083	11082	11081	11078	11077	11076	11073	11072	11071	11069	11068	11066	11051	11048	11045	HPPD_ID
3	4	4	4	2	3	3	4	4	4	4	3	4	4	2	1	3	2	3	4	3	4	4	4	4	Ranking_all continent
103002 2430	103002 2430	103002 2430	103002 3300	103002 3310	103002 3310	103002 3310	103002 3310	103002 2420	103002 2420	103002 2420	103002 2420	103002 0050	103002 2430	103002 2430	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	103002 2420	103002 7410	HYBAS_ID
			Volta				Niger	Niger	Niger	Niger	Niger				Niger	Niger	Niger	Niger	Niger	Niger	Niger	Niger		Basin name	
			3				4	4	4	4	2				1	2	1	3	4	2	3	4	4	Ranking_all basin	
3	4	4	3	2	3	3	4	4	4	4	2	4	4	2	1	2	2	3	4	3	3	4	4	Ex_RRI	
3	3	4	4	1	3	3	4	4	4	4	2	4	4	2	1	2	2	3	4	3	4	4	4	Ex_RFI	
3	4	4	4	2	3	4	4	4	4	4	2	4	4	2	1	3	2	3	4	2	3	4	4	Ex_Res	
4	4	4	4	2	4	4	4	4	4	4	3	4	4	2	1	3	2	4	4	3	3	4	4	Ex_PA	
3	3	4	3	1	3	3	4	4	4	4	2	4	4	2	1	2	2	3	4	3	4	4	4	Ex_MF	
3	4	4	4	2	4	4	4	4	4	4	2	4	4	2	1	3	2	4	4	3	3	4	4	Ex_PE	
3	3	4	4	2	4	3	4	4	4	4	3	4	4	3	1	2	2	3	4	3	4	4	4	Ex_SE	
3	4	4	4	2	3	3	4	4	4	4	3	4	4	2	1	3	2	3	4	2	3	4	4	Ex_LU_C	
2	2	4	3	1	3	2	3	3	4	4	2	4	4	3	1	1	1	3	4	3	4	4	4	Ranking A	
3	4	4	3	2	2	4	4	4	4	4	2	3	3	1	2	4	3	3	3	1	1	2	1	Ranking B	
3	3	3	3	2	2	2	4	4	4	3	3	2	4	2	2	2	2				2	4	3	Ranking C	

11226	11202	11197	11196	11194	11193	11187	11186	11185	11178	11175	11174	11158	11157	11156	11152	11149	11148	11114	11113	11112	11111	11110	11108	11106	HPPD_ID
3	4	3	3	1	1	3	3	4	4	2	3	4	3	2	1	2	2	4	4	4	2	3	4	3	Ranking_all continent
103003 4260	103003 4260	103002 3310	103002 3310	103002 0040	103002 0040	103001 1660	103001 1660	103001 1660	103002 9810	103002 7430	103002 7430	103002 7430	103002 7430	103002 7430	103002 7430	103002 7430	103002 7430	103002 3300	103002 3300	103002 3300	103002 3300	103002 3300	103002 2430	103002 2430	HYBAS_ID
Nile	Nile			Congo	Congo	Zambe zi	Zambe zi	Zambe zi										Volta	Volta	Volta	Volta	Volta			Basin name
2	4			2	2	3	3	4										2	2	3	1	1			Ranking_all basin
3	4	3	3	1	1	2	2	4	3	2	2	3	3	1	1	2	2	3	3	4	2	2	4	3	Ex_RRI
3	4	3	3	1	1	4	3	4	3	2	3	4	4	2	1	2	2	4	3	4	2	3	4	2	Ex_RFI
3	4	3	3	1	1	2	2	4	4	2	2	3	3	2	1	2	2	4	3	4	2	3	4	3	Ex_Res
4	4	4	2	1	1	3	3	4	3	2	3	3	2	2	1	2	2	3	2	3	2	2	4	3	Ex_PA
4	4	3	3	1	1	3	3	4	4	3	3	4	4	2	1	3	3	4	3	4	2	2	4	2	Ex_MF
3	4	3	4	1	1	2	2	4	4	2	2	4	3	2	1	3	2	4	3	4	2	3	4	3	Ex_PE
3	4	3	2	1	1	3	3	4	4	2	3	4	3	2	1	2	2	3	2	4	2	2	4	3	Ex_SE
3	4	3	3	1	1	2	2	4	3	2	2	3	3	2	1	2	2	3	3	4	2	3	4	4	Ex_LU_C
2	3	3	3	2	2	3	3	4	4	2	3	4	4	2	1	2	3	4	3	4	1	2	4	1	Ranking A
2	3	2	4	1	1	1	1	1	1	1	1	1	1	1	2	2	1	3	3	2	3	4	3	4	Ranking B
4	4	2	2	1	1	3	3	3	4	2	3	3	3	2	2	2	2	2	2	2	2	2	4	3	Ranking C

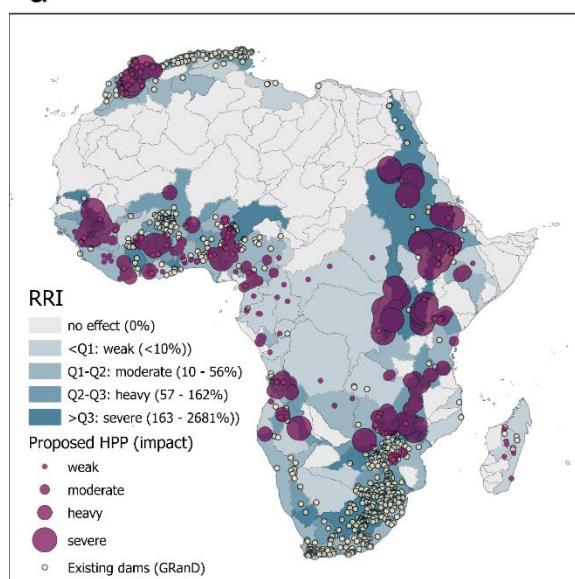
11241	11239	11238	11233	11232	11231	11230	11229	11228	11227	HPPD_ID
3	1	2	3	2	3	3	1	2	3	Ranking_all continent
1030023310	1030020040	1030020040	1030027410	1030023310	1030034260	1030023310	1030020040	1030015850	1030008110	HYBAS_ID
	Congo	Congo			Nile		Congo			Basin name
	2	3			2		2			Ranking_all basin
3	1	2	3	2	2	3	2	1	2	Ex_RRI
3	1	2	4	2	2	2	2	2	2	Ex_RFI
4	1	2	3	3	3	3	1	2	3	Ex_Res
4	1	2	2	2	2	3	2	1	3	Ex_PA
3	1	2	4	2	2	2	2	2	3	Ex_MF
3	1	1	3	3	3	3	1	2	2	Ex_PE
3	1	1	3	2	3	2	1	1	2	Ex_SE
3	1	2	3	2	3	3	1	2	2	Ex_LU_C
2	1	1	4	1	1	1	2	1	2	Ranking A
4	2	3	1	4	3	4	1	2	1	Ranking B
3	1	2	2	2	3	2	2	2	3	Ranking C

Table A.6: Spearman's correlation coefficients for correlations between the individual indicators including reservoir size. Dataset 1 includes hydropower plants of type reservoir and unknown type. Dataset 2 only includes hydropower plants of type reservoir.

	Reservoir Size		River Regulation		River Fragmentation		Resettlement		Protected Area		Megafauna		Potential Evaporation		Sediment Entrapment (Lifespan)		Land Use Change (Cropland)	
Dataset	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Reservoir size	1	1	0.177	0.211	0.177	0.211	0.500	0.286	0.756	0.841	-0.037	0.018	0.996	0.995	0.283	0.293	0.647	0.602
River Regulation	0.177	0.211	1	1	-0.071	0.044	0.148	0.198	0.173	0.219	-0.246	-0.242	0.189	0.228	0.002	-0.029	0.132	0.154
River Fragmentation	-0.071	0.003	0.044	0.123	1	1	-0.076	0.015	-0.021	-0.003	0.193	0.150	-0.069	0.004	-0.041	-0.019	-0.109	-0.041
Resettlement	0.500	0.286	0.148	0.198	-0.076	0.015	1	1	0.093	0.194	-0.040	-0.045	0.488	0.281	0.078	0.077	0.842	-0.487
Protected Area	0.756	0.841	0.173	0.219	-0.021	-0.003	0.093	0.194	1	1	-0.012	0.023	0.795	0.881	0.079	0.071	0.365	0.709
Megafauna	-0.037	0.018	-0.246	-0.242	0.193	0.150	-0.040	-0.045	-0.012	0.023	1	1	-0.039	0.016	-0.025	-0.005	-0.053	0.020
Potential Evaporation	0.996	0.995	0.189	0.228	-0.096	0.004	0.488	0.281	0.795	0.881	-0.039	0.016	1	1	0.254	0.253	0.645	0.619
Sediment Entrapment (Lifetime)	0.283	0.293	0.002	-0.029	-0.041	-0.019	0.078	0.077	0.079	0.071	-0.025	-0.005	0.255	0.253	1	1	0.034	0.019
Land Use Change (Cropland)	0.647	0.602	0.132	0.154	-0.109	-0.041	0.842	0.487	0.365	0.709	-0.053	0.020	0.645	0.619	0.034	0.019	1	1

River Regulation

a



b

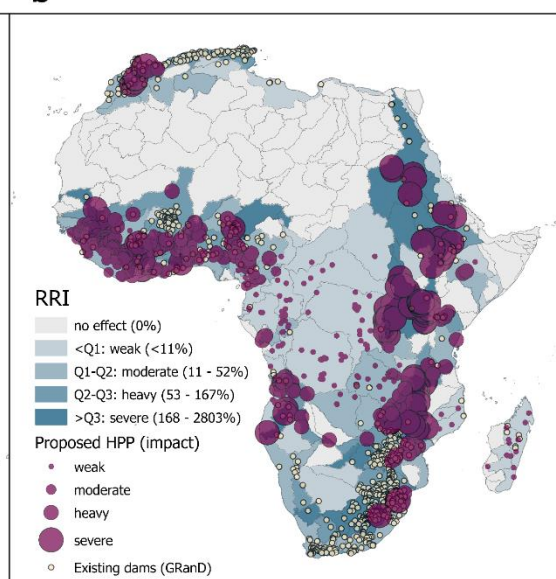
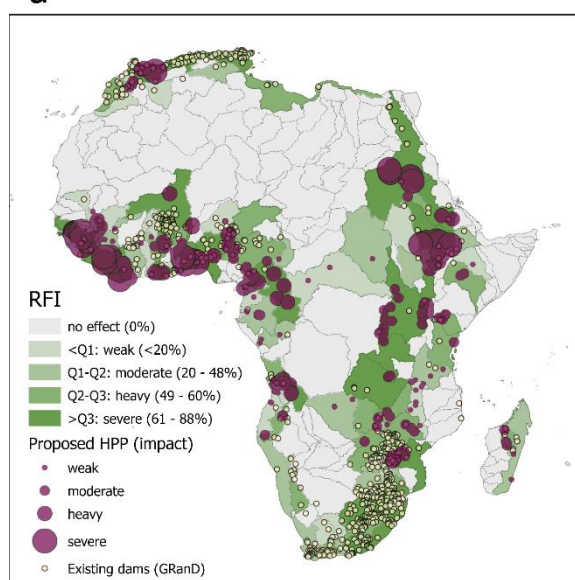


Figure A.1: Results of impact assessment for the indicator River Regulation (RRI: River Regulation Index) for hydropower plants (HPPs) of type reservoir (a) and of type reservoir and unknown (b). Purple circles indicate proposed HPPs. Small yellow circles indicate existing dam infrastructure (GRanD). Impact of proposed HPPs increases with circle size. The base map shows RRI values divided according to the quartile values (Q) for sub-basins (HydroBASIN Level 4).

River Fragmentation

a



b

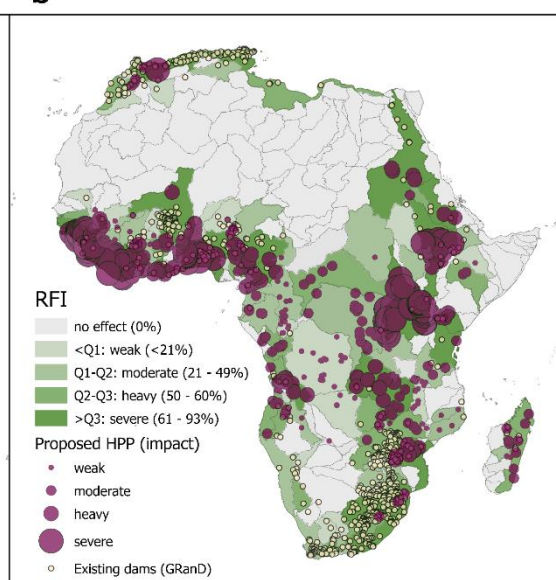


Figure A.2: Results of impact assessment for the indicator River Fragmentation (RFI: River Regulation Index) for hydropower plants (HPPs) of type reservoir (a) and of type reservoir and unknown (b). Purple circles indicate proposed HPPs. Small yellow circles indicate existing dam infrastructure (GRanD). Impact of proposed HPPs increases with circle size. The base map shows RFI values divided according to the quartile values (Q) for sub-basins (HydroBASIN Level 4).

Sediment Entrapment

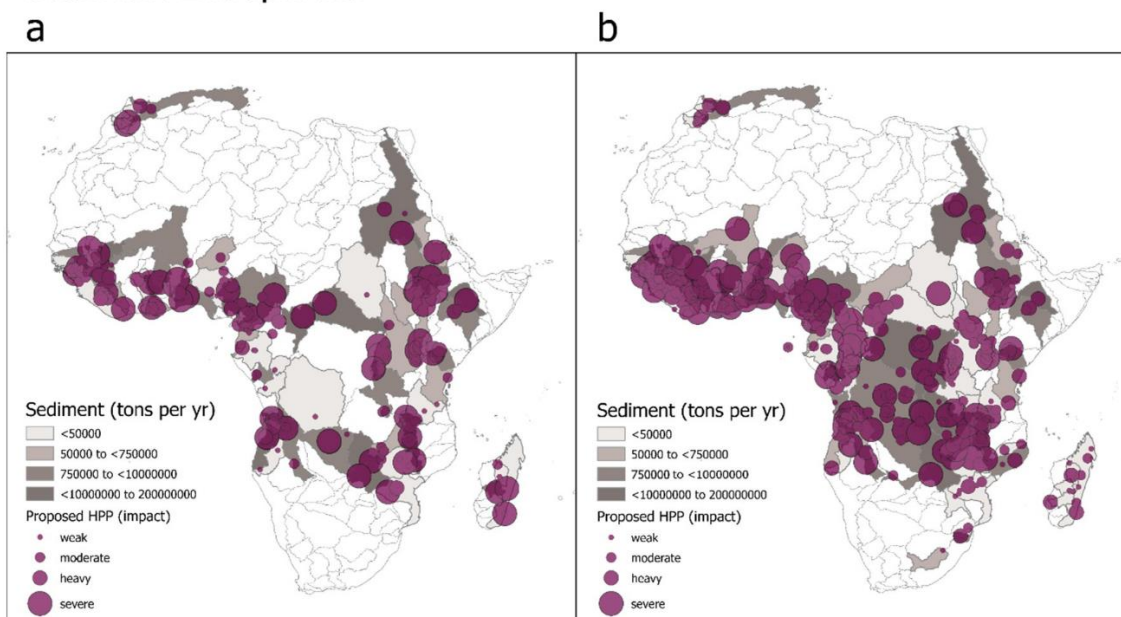


Figure A.3: Results of impact assessment for the indicator Sediment Entrapment for hydropower plants (HPPs) of type reservoir (a) and of type reservoir and unknown (b). Purple circles indicate proposed HPPs. Impact of proposed HPPs increases with circle size. The base map shows the entrapped sediment per sub-basin (HydroBASIN, Level 10) [tons/year].

Megafauna

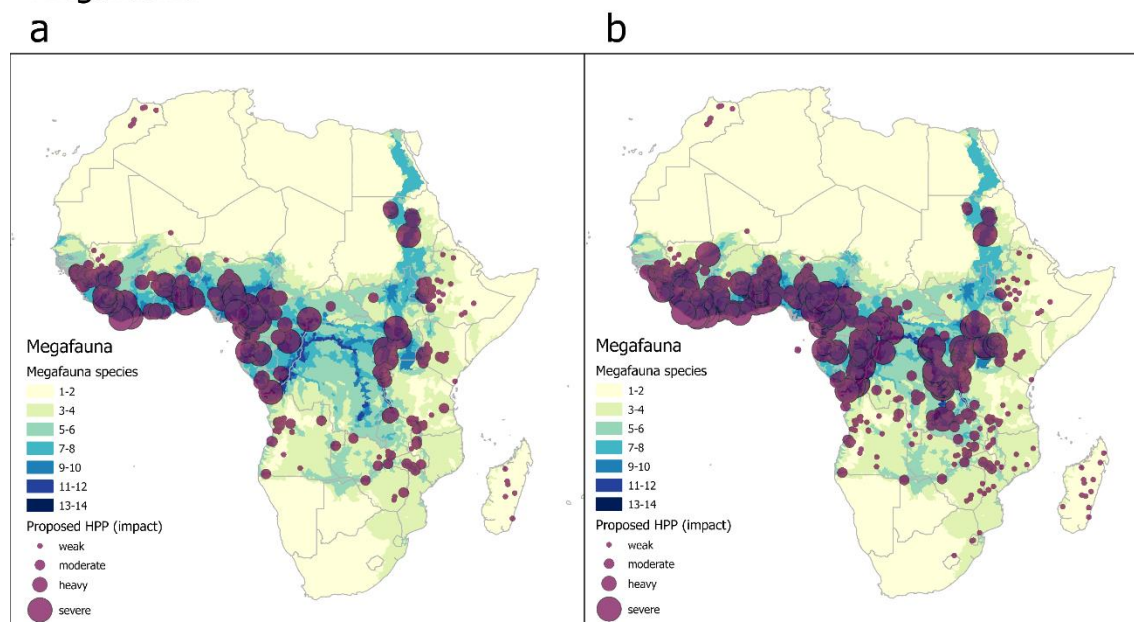
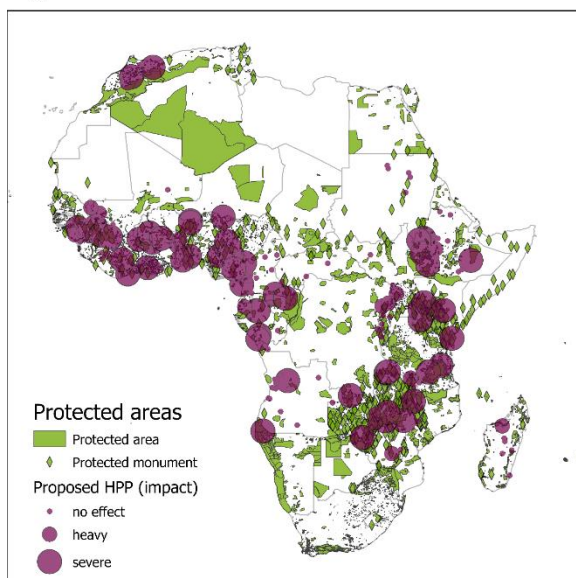


Figure A.4: Results of impact assessment for the indicator Megafauna for hydropower plants (HPPs) of type reservoir (a) and of type reservoir and unknown (b). Purple circles indicate proposed HPPs. Impact of proposed HPPs increases with circle size. The base map shows the number of freshwater megafauna species. Colour intensity increases from yellow to dark blue with number of available megafauna species.

Protected Area

a



b

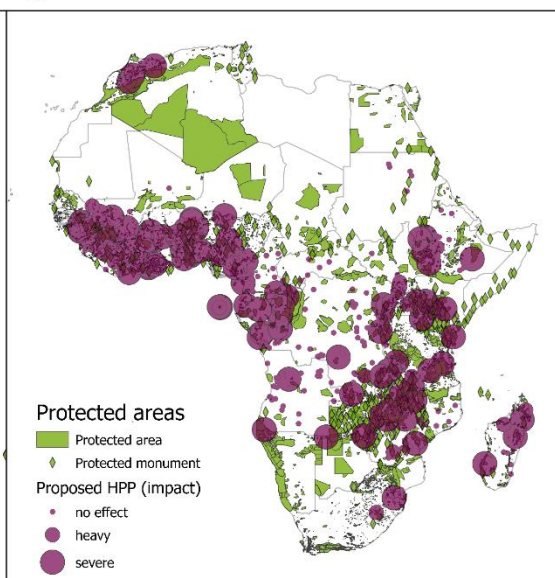
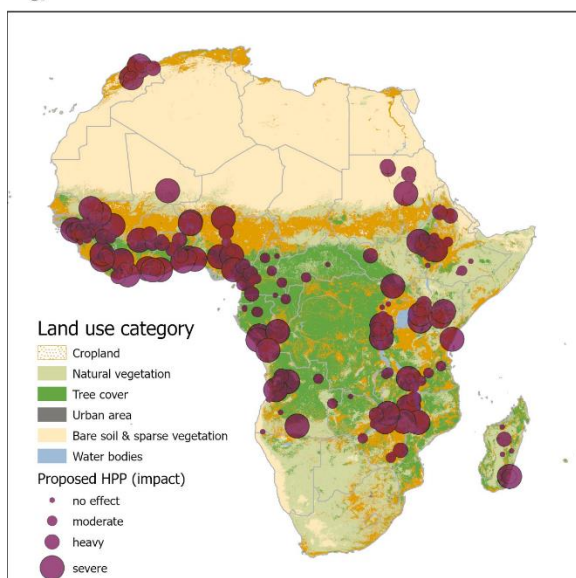


Figure A.5: Results of impact assessment for the indicator Protected Area for hydropower plants (HPPs) of type reservoir (a) and of type reservoir and unknown (b). Purple circles indicate proposed HPPs. Impact of proposed HPPs increases with circle size. The base map shows protected areas and protected natural monuments (diamonds).

Land Use Change (cropland)

a



b

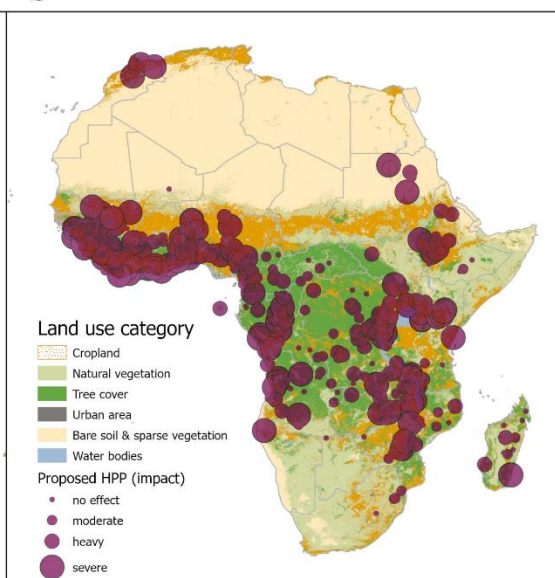


Figure A.6: Results of impact assessment for the indicator Land Use Change (cropland) for hydropower plants (HPPs) of type reservoir (a) and of type reservoir and unknown (b). Purple circles indicate proposed HPPs. Impact of proposed HPPs increases with circle size. The base map shows the different land use categories. The impact assessment is based on the category cropland.

Resettlement

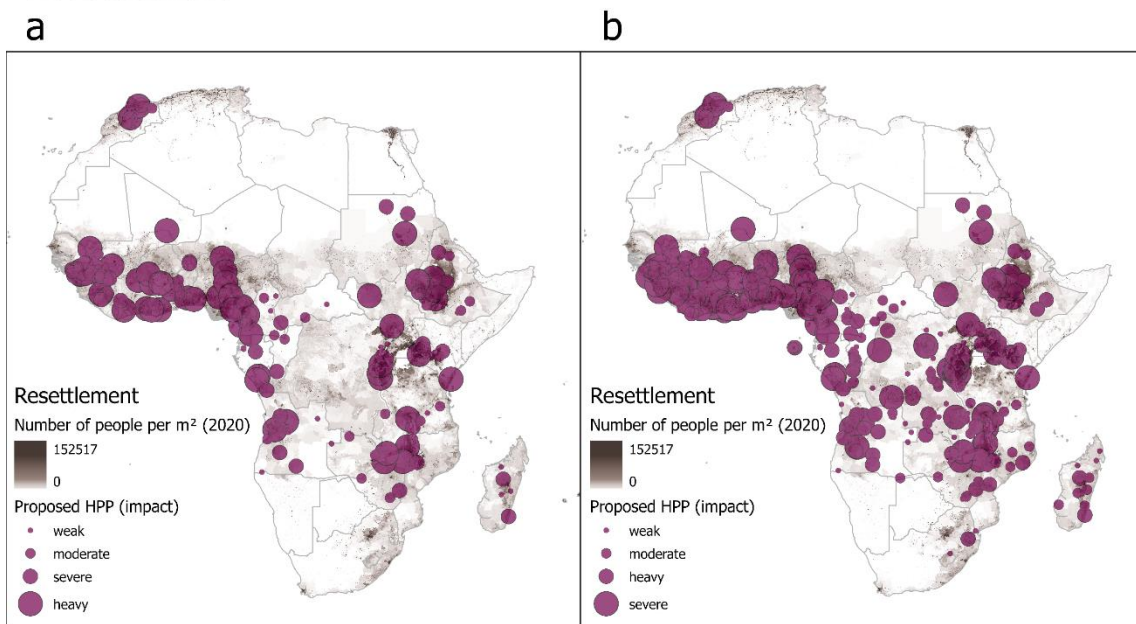


Figure A.7: Results of impact assessment for the indicator Resettlement for hydropower plants (HPPs) of type reservoir (a) and of type reservoir and unknown (b). Purple circles indicate proposed HPPs. Impact of proposed HPPs increases with circle size. The base map shows the population density in 2020.

Potential Evaporation

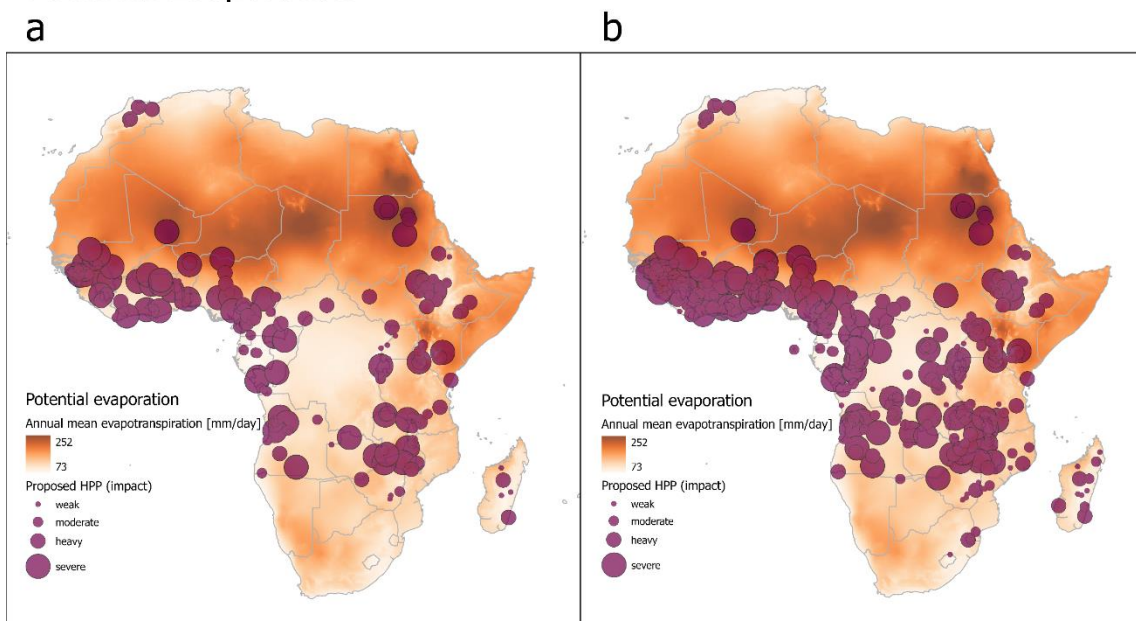


Figure A.8: Results of impact assessment for the indicator Potential Evaporation for hydropower plants (HPPs) of type reservoir (a) and of type reservoir and unknown (b). Purple circles indicate proposed HPPs. Impact of proposed HPPs increases with circle size. The base map shows potential evaporation values [mm/year].

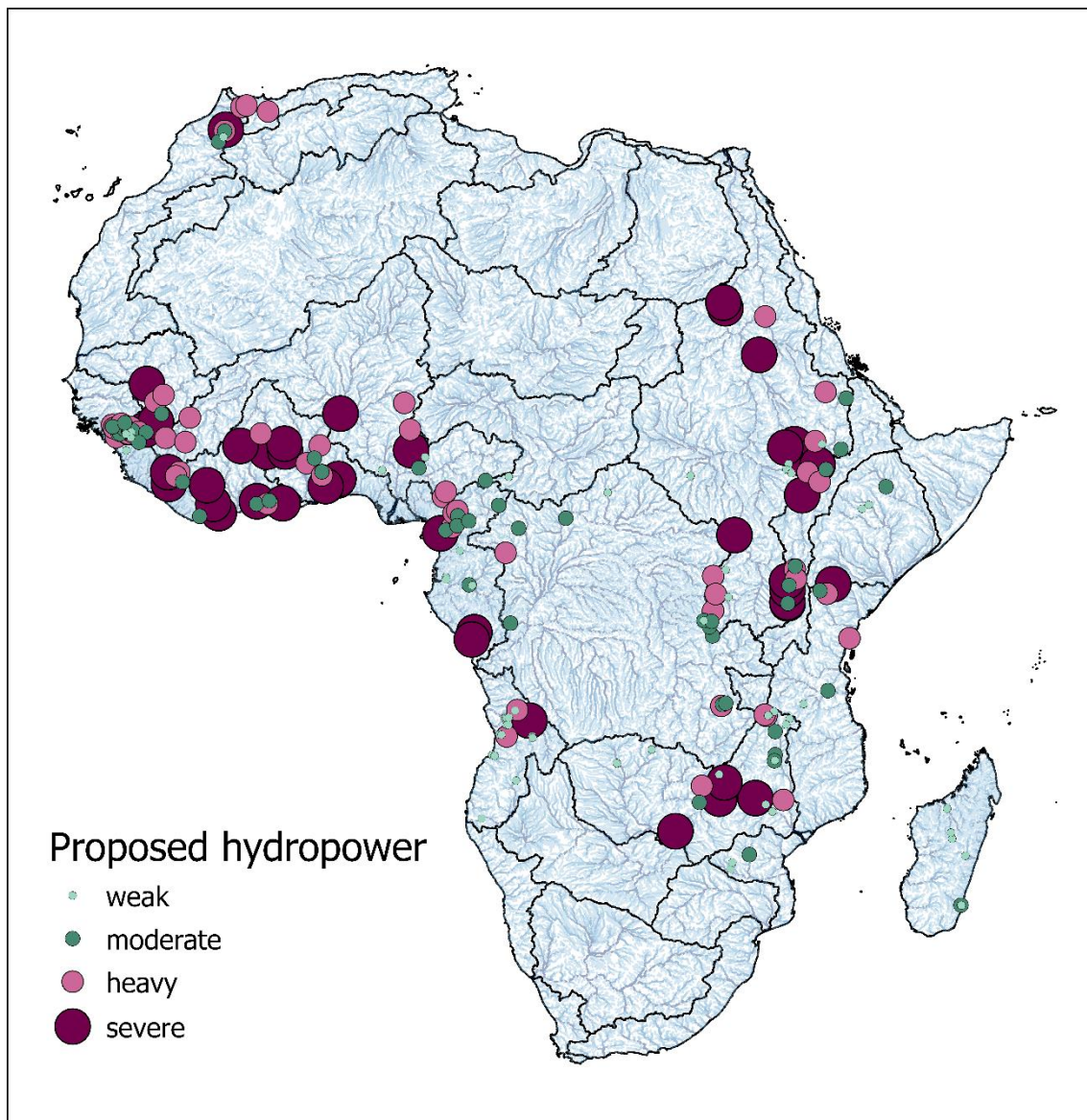


Figure A.9: Results of the continental impact assessment including all indicators for hydropower plants of type reservoir (dataset 2): Circles indicate proposed hydropower plants and size increases with indicated quarter value from weak (<Quartile(Q) 1), moderate (Q1-Q2), heavy (Q2-Q3) to severe (>Q4). Boundaries represent major river basins (HydroBASIN Level 3).

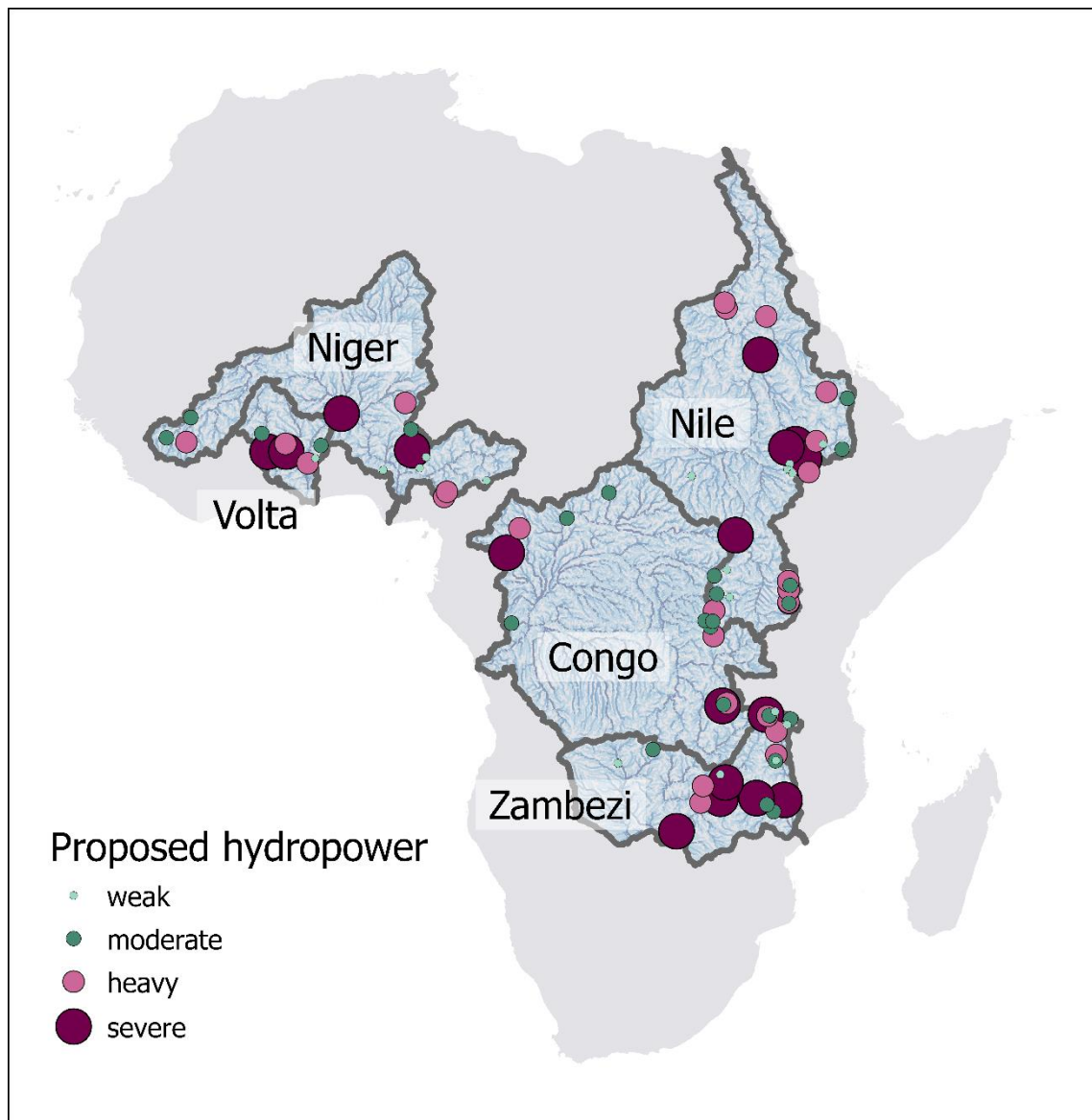


Figure A.10: Results of the impact assessment at basin-scale including all indicators for hydropower plants of type reservoir (dataset 2). Basin-scale assessments were conducted for the Congo, Niger, Nile, Volta, and Zambezi river basins (HydroBASIN Level 3). Circles indicate proposed hydropower plants and circle size increases from weak (<Quartile(Q) 1), moderate (Q1-Q2), heavy (Q2-Q3) to severe (>Q4) cumulative impact.

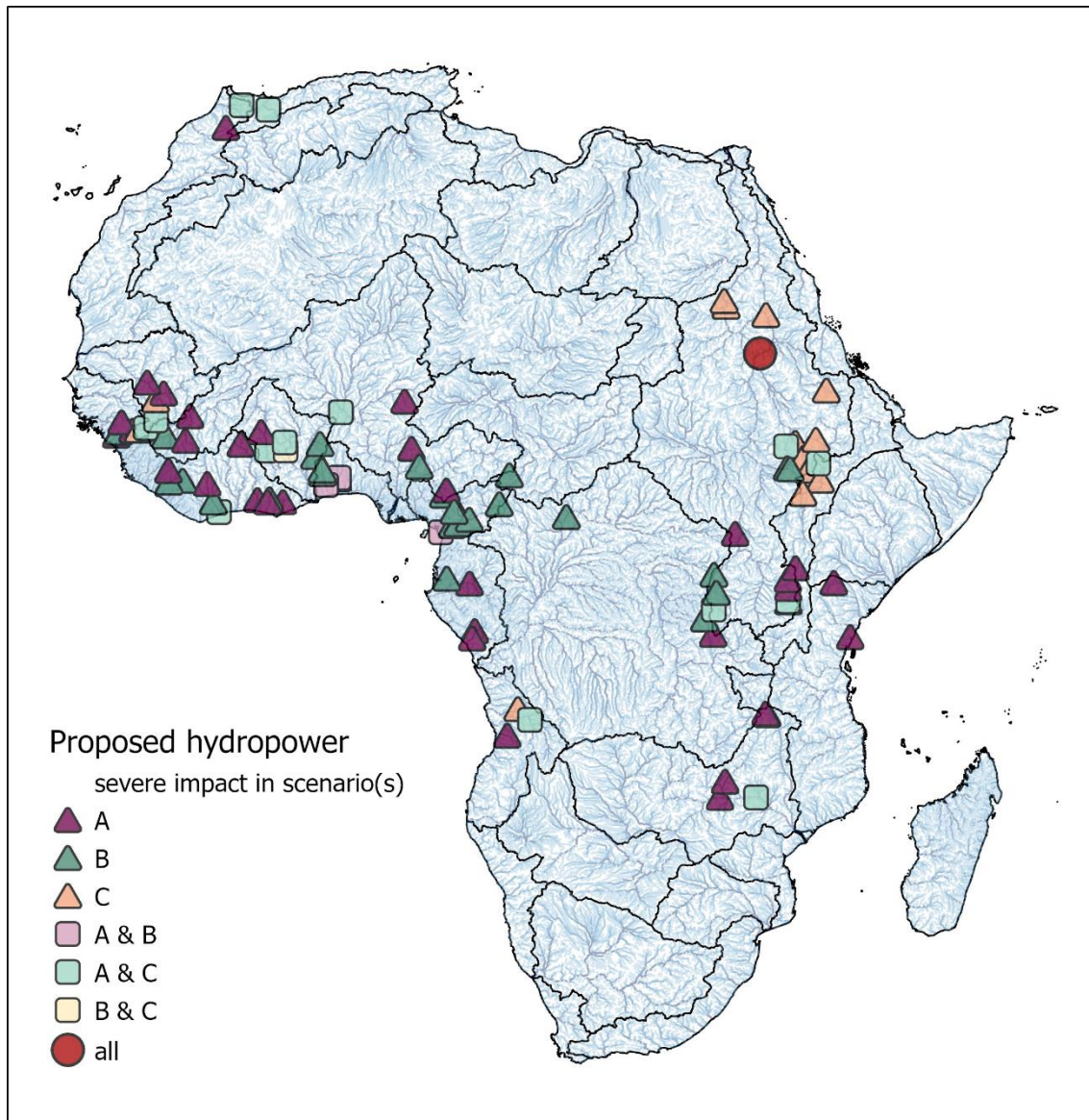


Figure A.11: Results of the impact assessment for dataset 2 by applying three different scenarios of indicator consideration (Scenario A: Protected Area, Resettlement, Land Use Change; Scenario B: Megafauna, Sediment Entrapment; Scenario C: River Regulation, River Fragmentation, Potential Evaporation). Symbols indicate proposed hydropower plants (HPPs). Proposed HPPs in the top quarter (>Quartile 4; severe impact) of one (triangle), two (square), or all scenario(s) (circle) are of different shapes and colours.

B.

Supporting information – Chapter 4

B.1. Supplementary figures

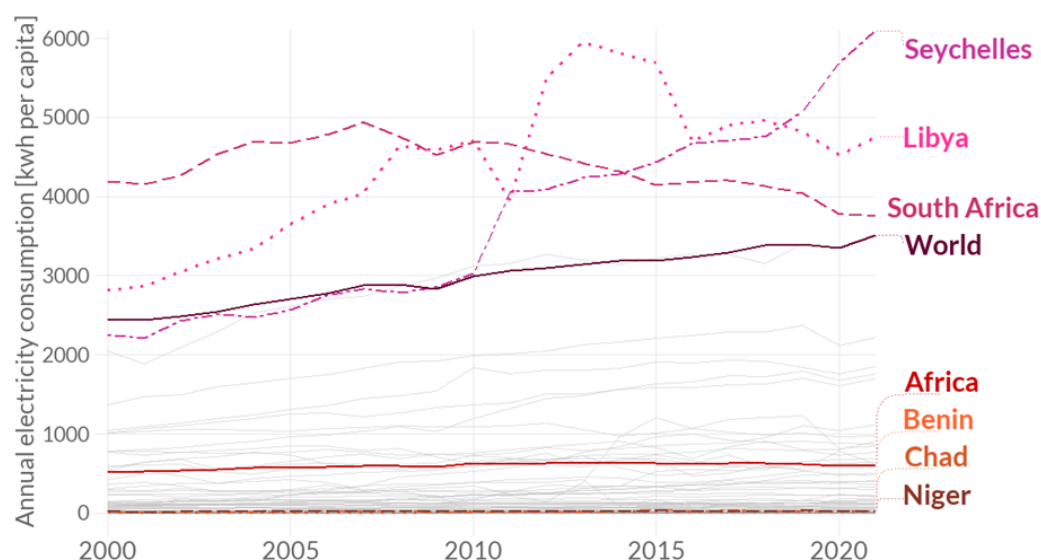


Figure B.1: Development of annual electricity consumption [kwh] per capita in African countries. Highlighted are the countries with lowest (Niger, Chad, Benin) and highest (Seychelles, Libya, South Africa) annual electricity-per-capita rates for 2021. Annual per capita electricity consumption of all other African countries is of grey colour. Average World and Africa annual per capita electricity consumption serve as reference. Data: Our World in Data (Ritchie et al., 2020)

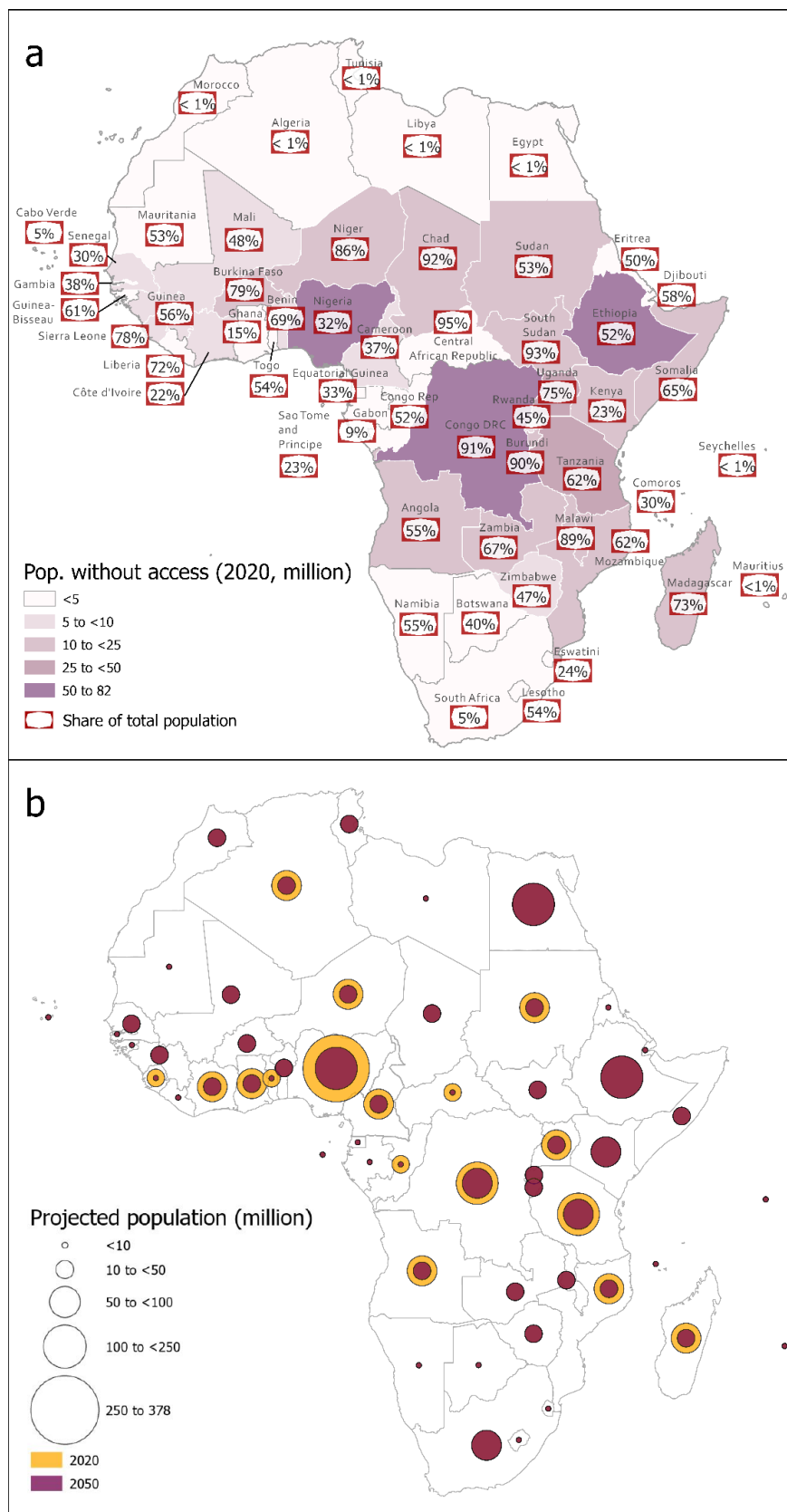


Figure B.2: Electricity access and population size in African countries. a. Country polygons are coloured according to the number of people without access to electricity, darker colours indicate more people lacking access. Red framed boxes indicate the share of total population without access to electricity. b. Purple circles indicate the total population size in million for 2020 and increase with population count. Orange circles indicate the total population size in million projected for 2050. If the orange circle is visible, projected population is larger than the current population size. If no orange circle is visible, the projected population size is equal to current population size. No African country is projected to have a decreased population size by 2050. Data: IEA (IEA, 2021b), UN (UN, 2022)

B.2. Supplementary methods

Estimation of national coverage of electricity demand by renewable electricity generation

The installed and proposed capacity of renewable electricity plants needs to be compared with the actual electricity demand in each country to assess if existing and proposed plants will be able to cover the actual electricity demand or if a shortfall or surplus can be expected. Thus, the **coverage** of the electricity demand of each country by existing and proposed plants for renewable electricity generation is calculated as follows:

$$Coverage[GWh] = Demand[GWh] - Generation [GWh]$$

Since electricity **demand** is hard to project it was estimated from annual per-capita electricity consumption (see details below) and (projected) national population count for 2021 and 2050, respectively:

$$Demand [GWh] = Annual\ electricity\ consumption \left[\frac{GWh}{capita} \right] * Population [capita]$$

To calculate the maximum possible electricity **generation** in gigawatt hours [GWh] by renewable plants per country, we used peak installed capacity [MW] from RePP Africa (Peters et al., 2023), an open accessible dataset with georeferenced information on hydro-, wind, and solar power plants. We assume, that all capacity is explicitly used for renewable electricity production. Electricity generation is calculated for 2021 by including power plants that are categorized as existing (E) or under construction (U) while production in 2050 also includes power plants that are proposed (P), i.e. in addition to E and U.

We multiplied the cumulated capacity values [MW] for each country and renewable type (hydro, wind, solar) with the respective average capacity factor estimated for Africa:

$$Generation [GWh] = Power\ plant\ peak\ capacity [MW] * Capacity\ factor * 8760\ h * 0.001$$

The capacity factor describes the efficiency of a plant in exploiting its installed technical capacity; this depends e.g. on environmental conditions and natural variability. Estimated capacity factors are 60% for hydro-, 35% for wind, and 25% for solar power plants (IRENA, 2022a, 2022b, 2022c). 0.001 is the conversion factor from MW to GW. Finally, calculated values for electricity generation per renewable type were summed up for each African country and give the overall generation in GWh.

Six different scenarios were calculated (a – f, Table B.1; results are visualized in Figure 4.4), that combine a 2021 and 2050 scenario (specified in population count and renewable power plants) with three different assumptions on annual electricity consumption, i.e. the national average for each country, the African average and the world average. For detailed parameter values and calculation results please consider Table B2.

Table B.1: Scenario composition for estimating the (potential) coverage of the national electricity demand for each African country by renewable electricity generation. Please see Table B.2 for parameter values and results.

		Annual per-capita consumption [GWh per capita and year]		
		National average	African average	World average
National population count and implemented RE power plants in	2021	a	c	e
	2050	b	d	f

Table B.2: Parameter values and estimation results for the (potential) coverage of the national electricity demand for each African country by renewable electricity generation. Surplus: Coverage <-1000 kWh; Sufficient: Coverage +/-1000 kWh; Shortfall: Coverage >1000 kWh. Used abbreviation: Congo DRC – The Democratic Republic of Congo.

	Algeria	World	Africa	Data source	Parameter	Parameter (short)
Angola	476.2	3512.7	602.3	Our World in Data(Ritchie et al., 2020)	Annual electricity consumption rate (2021) [kWh per capita]	Electricity rate 2021
	35	44		UN(UN, 2022)	Population 2021 [million]	Population 2021
	72	60		UN(UN, 2022)	Projected population 2050 [million]	Population 2050
	16430	77540		RePP Africa(Peters et al., 2023)	Demand 2021 [GWh]	Demand 2021
	-17831	74813			Coverage 2021 [GWh]	Coverage 2021
	+	-			Surplus (+), Sufficient (±), Shortfall (-)	+ / ± / -
	34441	105312		RePP Africa(Peters et al., 2023)	Demand 2050 [GWh]	Demand 2050
	-33760	101942			Coverage 2050 [GWh]	Coverage 2050
	+	-			Surplus (+), Sufficient (±), Shortfall (-)	+ / ± / -
	-13480	23879			Coverage 2021 [GWh] based on African average annual electricity consumption	Coverage 2021 – Africa
	+	-			Surplus (+), Sufficient (±), Shortfall (-)	+ / ± / -
	-24642	32766			Coverage 2050 [GWh] based on African average annual electricity consumption	Coverage 2050 – Africa
	+	-			Surplus (+), Sufficient (±), Shortfall (-)	+ / ± / -
	86940	152456			Coverage 2021 [GWh] based on World average annual electricity consumption	Coverage 2021 – World
	-	-			Surplus (+), Sufficient (±), Shortfall (-)	+ / ± / -
	185864	207394			Coverage 2025 [GWh] based on World average annual electricity consumption	Coverage 2050 – World
	-	-			Surplus (+), Sufficient (±), Shortfall (-)	+ / ± / -

Cote d'Ivoire	Congo DRC	Congo	Comoros	Chad	Central African Republic	Cape Verde	Cameroon	Burundi	Burkina Faso	Botswana	Benin	Parameter (short)
399.6	115.1	688.8	170.4	18.0	27.5	765.4	296.0	28.7	79.2	846.1	18.5	Electricity rate 2021
27	96	6	1	17	5	1	27	13	22	3	13	Population 2021
51	217	10	1	36	12	1	51	24	41	4	25	Population 2050
10980	11040	4020	140	310	150	450	8050	360	1750	2190	240	Demand 2021
5561	-4899	2664	133	-38	-11	339	248	-9	945	2078	-592	Coverage 2021
-	+	-	±	±	±	±	±	±	±	-	±	+ / ± / -
20522	25039	7150	212	658	317	557	15177	694	3210	3113	467	Demand 2050
6450	-214592	-32940	125	-644	-3151	204	-45879	-2492	1444	2828	-4114	Coverage 2050
-	+	+	±	±	+	±	+	+	-	-	+	+ / ± / -
11129	41814	2159	488	9999	3125	244	8579	7190	12505	1447	6996	Coverage 2021 – Africa
-	-	-	±	-	-	±	-	-	-	-	-	+ / ± / -
16859	-108644	-33839	663	20651	3478	85	-30173	11394	22650	1931	10635	Coverage 2050 – Africa
-	+	+	±	-	-	±	+	-	-	-	-	+ / ± / -
91103	320906	19144	2880	59999	19008	1955	87738	43719	76828	8980	44822	Coverage 2021 – World
-	-	-	-	-	-	-	-	-	-	-	-	+ / ± / -
166333	524355	-3632	4290	126742	37045	2202	119072	81851	140643	12639	84164	Coverage 2050 – World
-	-	+	-	-	-	-	-	-	-	-	-	+ / ± / -

Libya	Liberia	Lesotho	Kenya	Guinea-Bissau	Guinea	Ghana	Gambia	Gabon	Ethiopia	Eswatini	Eritrea	Equatorial Guinea	Egypt	Djibouti	Parameter (short)
4754.1	177.1	219.2	223.2	38.8	205.4	637.8	113.6	978.1	122.1	620.7	124.3	868.8	1851.1	54.3	Electricity rate 2021
7	5	2	53	2	14	33	3	2	120	1	4	2	109	1	Population 2021
9	9	3	85	3	24	52	5	4	215	2	6	3	160	2	Population 2050
32020	920	500	11830	80	2780	20940	300	2290	14690	740	450	1420	202250	60	Demand 2021
31722	432	-467	4121	80	-3761	10291	300	-86	-47558	395	434	-311	175456	-247	Coverage 2021
-	±	±	-	±	+	-	±	±	+	±	±	±	-	±	+ / ± / -
40600	1575	635	19018	134	4871	33312	531	3675	26235	1027	741	2424	296797	82	Demand 2050
39196	-3475	-7410	-741	-22	-23719	13456	69	-2448	-109508	-230	707	617	238534	-1194	Coverage 2050
-	+	+	±	±	+	-	±	+	+	±	±	±	-	+	+ / ± / -
3758	2640	407	24214	1241	1609	9125	1590	-966	10193	373	2164	-746	39010	359	Coverage 2021 – Africa
-	-	±	-	-	-	-	-	±	-	±	-	±	-	±	+ / ± / -
3739	304	-6299	31560	1920	-14310	11601	2353	-3861	-6371	-260	3557	-127	38302	-371	Coverage 2050 – Africa
-	±	+	-	-	+	-	-	+	+	±	-	±	-	±	+ / ± / -
23360	17755	7047	178483	7239	40992	104683	9273	5848	360267	3843	12701	4011	357009	3576	Coverage 2021 – World
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+ / ± / -
28594	26180	2136	279562	11947	54701	163617	15956	7074	618823	4557	20915	7995	504958	4002	Coverage 2050 – World
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+ / ± / -

Sao Tome and Principe	Rwanda	Nigeria	Niger	Namibia	Mozambique	Morocco (Western Sahara)	Mauritius	Mauritania	Mali	Malawi	Madagascar	Parameter (short)
418.5	63.1	147.5	17.8	620.5	620.7	1113.9	2217.2	407.4	154.8	71.4	72.3	Electricity rate 2021
0	13	213	25	3	32	38	1	5	22	20	29	Population 2021
0	23	377	67	4	63	46	1	9	47	37	52	Population 2050
93	850	31470	450	1570	19910	41930	2880	1880	3390	1420	2090	Demand 2021
62	232	1121	-258	-623	6988	22761	2273	1283	528	-1055	527	Coverage 2021
±	±	-	±	±	-	-	-	-	±	+	±	+ / ± / -
153	1454	55663	1195	2346	39131	51124	2719	3632	7342	2653	3729	Demand 2050
-26	337	-41733	-1613	-4747	3925	21295	1912	3023	1830	-9158	-13149	Coverage 2050
±	±	+	+	+	-	-	-	-	-	+	+	+ / ± / -
103	7489	98173	14500	-669	6396	3501	175	2182	10330	9504	15851	Coverage 2021 – Africa
±	-	-	-	±	-	-	±	-	-	-	-	+ / ± / -
42	12753	129931	37569	-4816	2762	-2188	-69	4761	23059	10569	14194	Coverage 2050 – Africa
±	-	-	-	+	-	+	±	-	-	-	-	+ / ± / -
753	46669	719261	87996	6695	99754	113056	3955	15614	74083	67392	100008	Coverage 2021 – World
-	-	-	-	-	-	-	-	-	-	-	-	+ / ± / -
1109	79780	1228498	23269 ₄	6185	186248	131388	3500	30706	161129	118718	164351	Coverage 2050 – World
-	-	-	-	-	-	-	-	-	-	-	-	+ / ± / -

Zimbabwe	Zambia	Uganda	Tunisia	Togo	Tanzania	Sudan	South Sudan	South Africa	Somalia	Sierra Leone	Seychelles	Senegal	Parameter (short)
502.7	909.5	96.0	1706.8	72.9	128.5	363.4	53.0	3758.1	24.0	24.9	6104.1	332.4	Electricity rate 2021
16	19	46	12	9	64	46	11	59	17	8	0	17	Population 2021
26	37	88	14	15	130	84	17	74	36	14	0	33	Population 2050
8040	17710	4400	20930	630	8170	16590	570	223200	410	210	650	5610	Demand 2021
2004	791	-4794	19686	171	-6111	4852	567	186686	325	-178	616	4525	Coverage 2021
-	±	+	-	±	+	-	±	-	±	±	±	-	+ / ± / -
13291	34069	8408	24434	1128	16694	30702	926	276330	876	339	712	10824	Demand 2050
-10018	-10072	-15061	10436	-566	-13803	6121	-11125	169518	791	-3343	670	8548	Coverage 2050
+	+	+	-	±	+	-	+	-	±	+	±	-	+ / ± / -
3596	-5191	18421	6141	4747	24015	15760	6470	-745	10193	4683	31	9079	Coverage 2021 – Africa
-	+	-	-	-	-	-	-	±	-	-	±	-	+ / ± / -
-7386	-21580	29302	-5376	7628	47755	26307	-1535	-62528	21875	4506	28	17335	Coverage 2050 – Africa
+	+	-	+	-	-	-	+	+	-	-	±	-	+ / ± / -
50144	51484	151875	41831	29907	209084	148641	37752	172111	59861	29191	341	58197	Coverage 2021 – World
-	-	-	-	-	-	-	-	-	-	-	±	-	+ / ± / -
69562	87445	284319	36289	52678	425910	272220	49283	151474	127997	44073	368	112106	Coverage 2050 – World
-	-	-	-	-	-	-	-	-	-	-	±	-	+ / ± / -

C.

Supporting information – Chapter 5

Table C.1: Results for electricity generation by complementing existing hydropower plant (HPP) reservoirs with floating photovoltaic (FPV) (Co-use potential). National summaries are given for a 40% coverage. Sensitivity is tested by running the scenario for an FPV coverage of 20% and 60% respectively.

Country	Total area of included HPP reservoirs	FPV area (40% coverage)	Total electricity generation FPV (40% coverage)	Total electricity generation FPV (20% coverage)	Total electricity generation FPV (60% coverage)	Proposed hydropower electricity (average capacity factor)	Replacement (40% FPV)
	[10 ⁶ m ²]	[10 ³ m ²]	[GWh]	[GWh]	[GWh]	[GWh]	[GWh]
Algeria	33	13085	26203	13102	39305	x	x
Angola	295	118102	256929	128465	385394	24986	231943
Burkina Faso	434	173464	371259	185629	556888	433	370825
Burundi	1	478	817	409	1226	2131	-1313
Cameroon	749	299780	630438	315219	945657	46274	584163
Central African Republic	14	5793	11499	5750	17249	2621	8878
Congo	106	42270	79660	39830	119491	35506	44154
Congo DRC	412	164741	362996	181498	544494	203236	159760
Côte d'Ivoire	1138	455363	840726	420363	1261090	7057	833669
Egypt	1040	416061	1060456	530228	1590684	10118	1050338
Equatorial Guinea	11	4229	7358	3679	11037	x	x
Eswatini	12	4801	9494	4747	14242	636	8858
Ethiopia	719	287497	653653	326826	980479	62289	591364
Gabon	14	5556	8892	4446	13338	3362.964	5529
Ghana	6396	2558325	4728503	2364252	7092755	3334.056	4725169
Guinea	88	35333	72492	36246	108739	18748.77	53744
Kenya	100	40003	83181	41590	124771	7362.386	75818
Lesotho	24	9470	21822	10911	32733	385.44	21437
Madagascar	0	11	20	10	31	10883	-10862
Malawi	0	61	131	65	196	5917	-5786
Mali	771	308466	668134	334067	1002200	1243	666891
Morocco	242	96962	205388	102694	308082	1150	204238
Mozambique	2332	932925	2089867	1044933	3134800	11960	2077907
Nigeria	2207	882878	1804012	902006	2706018	35610	1768402
Rwanda	0	169	306	153	458	295	10
Sierra Leone	8	3206	6172	3086	9258	2159	4012
South Africa	506	202308	482162	241081	723242	x	x
Sudan	2290	915849	2181237	1090619	3271856	10874	2170363

Tanzania	557	222908	516707	258353	775060	7663	509044
Togo	130	52017	100069	50035	150104	781	99289
Tunisia	56	22321	43524	21762	65286	x	x
Uganda	3	1398	2805	1403	4208	4788	-1983
Zambia	419	167653	387972	193986	581958	12749	375223
Zimbabwe	5259	2103722	4880010	2440005	7320016	5615	4874395
SUM	26371	10548282	22596994	11298497	33895491	540168	

Table C.2: Data on future reservoirs area is provided from reservoir projection calculations implemented in Chapter 3. The reservoir area could not be calculated for the proposed Qattara Depression hydropower plant in Egypt (2100 MW), which is why no reservoir area is indicated for Egypt.

Country	Reservoir Area	Proposed hydropower	Proposed hydropower	MSR Area (Solar PV)	MSR potential (Solar PV)	MSR potential (Solar PV)	MSR Area (onshore wind)	MSR potential (onshore wind)	MSR potential (onshore wind)	Available electricity considering hydropower replacement
	[km ²]	[MW]	[GWh]	[km ²]	[MW]	[GWh]	[km ²]	[MW]	[GWh]	[GWh]
Algeria	x	x	x	115446	380971	648769	115758	340328	1392550	x
Angola	4757	5186	24986	62501	206252	373336	20896	61435	177468	525818
Benin	993	692	3336	5347	17646	27944	532	1563	4564	29172
Botswana	x	x	x	28699	94707	168659	28561	83971	293353	x
Burkina Faso	603	90	433	13448	44377	73419	13626	40061	121510	194496
Burundi	69	442	2131	1008	3327	5311	x	x	x	3180
Cabo Verde	x	x	x	x	x	x	180	529	2489	x
Cameroon	938	9604	46274	23144	76376	128025	7207	21188	64051	145802
Central African Republic	214	544	2621	31136	102748	168033	256	752	2139	167551
Chad	x	x	x	63236	208678	350506	63521	186751	872428	x
Congo	2796	7370	35506	16905	55786	82337	8	23	64	46895
Congo DRC	1349	42183	203236	116800	385439	602476	626	1840	5884	405124
Côte d'Ivoire	1867	1465	7057	16163	53339	85716	8	25	68	78727
Djibouti	x	x	x	746	2462	4398	922	2710	13408	x
Egypt	failed	2100	10118	48774	160953	295917	48986	144018	623998	909797
Equatorial Guinea	x	x	x	1273	4202	5885	x	x	x	x
Eritrea	x	x	x	5913	19515	36146	5878	17280	70863	x
Eswatini	39	132	636	405	1337	2009	385	1132	3360	4734
Ethiopia	4536	12982	62289	56760	187307	345555	56538	166222	636859	920125

Gabon	28	698	3363	13048	43058	60090	x	x	x	56727
Gambia	x	x	x	516	1702	2840	75	221	503	x
Ghana	789	692	3334	11770	38842	61513	1811	5323	15939	74118
Guinea	3305	3891	18749	12052	39772	64988	15	45	127	46366
Guinea-Bissau	x	x	x	1424	4701	7571	x	x	x	x
Kenya	385	1528	7362	28964	95581	17536 9	29222	85913	412227	580234
Lesotho	0	80	385	1513	4993	8591	534	1571	5507	13713
Liberia	542	720	3471	4798	15835	23152	x	x	x	19681
Libya	x	x	x	80578	26590 8	47931 5	80949	23799 0	100562 0	x
Madagascar	165	2259	10883	29420	97086	16944 7	29450	86584	344765	503329
Malawi	4558	1228	5917	5712	18850	32416	5956	17512	64488	90988
Mali	1371	258	1243	62884	20751 7	34429 5	62677	18427 0	718899	106195 1
Mauritania	x	x	x	51743	17075 3	29165 7	51666	15189 8	672992	x
Morocco	170	239	1150	33914	11191 7	19850 2	33504	98501	432545	629897
Mozambique	4801	2482	11960	39418	13007 8	20988 7	26007	76461	222337	420264
Namibia	21	632	3046	40946	13512 2	25499 6	41269	12133 1	424423	676373
Niger	795	149	715	58782	19398 2	33756 8	59166	17394 8	717344	105419 7
Nigeria	2693	7391	35610	45381	14975 7	25402 2	45645	13419 5	460323	678735
Rwanda	189	61	295	1229	4054	6293	x	x	x	5998
Senegal	128	128	617	9749	32171	54148	9758	28687	89698	143229
Sierra Leone	88	448	2159	3474	11466	17369	x	x	x	15210
Somalia	x	x	x	31681	10454 9	19614 7	31852	93646	374427	x
South Africa	x	x	x	61202	20196 5	36890 3	61037	17945 0	676887	x
South Sudan	49	176	846	31510	10398 3	17073 7	22702	66744	207147	377038
Sudan	223	2257	10874	92520	30531 6	54811 0	92685	27249 3	129795 8	183519 4
Tanzania	107	1590	7663	47266	15597 7	28322 0	47050	13832 8	539302	814858
Togo	339	162	781	2736	9029	14369	254	747	2048	15636
Tunisia	x	x	x	7264	23971	39001	7559	22225	85197	x
Uganda	194	994	4788	12148	40089	69860	1085	3190	9985	75057
Zambia	4549	2646	12749	37550	12391 4	21562 5	26021	76501	249395	452271
Zimbabwe	2717	1166	5615	19332	63796	11150 2	19233	56546	189144	295031
SUM (all countries)	46368	114666	552198	1488229	4911156	8475943	1151071	3384149	13504285	21428030
SUM (HPP countries)	x	x	x	1039780	3431275	5882031	703292	2067680	8046058	371320

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Figure 1.1. Structure of thesis. Chapter 2 “Integrated impact assessment for proposed hydropower plants in Africa” is intended for publication and its methodology has been adapted from Peters et al. (Sustainability, 2021). Chapter 3 “RePP Africa – a georeferenced and curated database on existing and proposed wind, solar, and hydropower plants” is published as Peters et al. (Scientific data, 2023). Chapter 4 “Sustainable pathways towards universal renewable electricity access in Africa” is published in Peters et al. (Nature Reviews Earth & Environment, 2023). Chapter 5 “Towards a renewable electricity mix that avoids the increasing fragmentation of African rivers” is intended for publication, but has not yet been submitted. Icons of four Sustainable Development Goals (SDG) of the Agenda 2030 are included: SDG 7 in yellow stands for “affordable and clean energy”. SDG 13 in dark green stands for “climate action”. SDG 6 in light blue stands for “clean water and sanitation”, as Chapter 5 specifically addresses SDG 6.6 which aims to “protect and restore water-related ecosystems”. SDG 15 in light green stands for “life on land”, as Chapter 5 specifically addresses SDG 15.1, which aims to “conserve and restore terrestrial and freshwater ecosystems” 8

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List of abbreviation

AHA	African Hydropower Atlas
AKP	African Knowledge Platform
CAPP	Central African Power Pool
COMELEC	Comité Maghrébin de l'Electricité (Maghreb Electricity Committee/North African Power Pool)
COP 27	United Nations Framework Convention on Climate Change, 27th Conference of the Parties
CPV	Concentrating photovoltaic
CSP	Concentrated solar power
DEM	Digital elevation model
E	Existing
EAPP	East African Power Pool
ECOWAS	Economic Community of West African States
ECOWREX	ECOWAS observatory for Renewable Energy and Energy Efficiency
EIA	Environmental Impact Assessment
FHReD	Future Hydropower Reservoirs and Dams Database
FPV	Floating photovoltaic
GDP	Gross domestic product
GERD	Grand Ethiopian Renaissance Dam
GHG	Greenhouse gas
GPPD	Global Power Plant Database
GRanD	Global Reservoir and Dam Database
GTI	Global tilted irradiation
GW	Gigawatt
GWED	The Global Wind Energy Council
GWh	Gigawatt hour
HPP	Hydropower plant
HPPD	Hydropower Plant Database
HSAP	Hydropower Sustainability Assessment Protocol
HSS	Hydropower Sustainability Standard
IEA	International Energy Agency
IHA	International Hydropower Association
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
kWh	Kilowatt hour
MW	Megawatt
MWh	Megawatt hour
N	Total number
NDC	Nationally Determined Contribution
OIM	Open Infrastructure Map
P	Proposed
PV	Photovoltaic
Q	Quartile
RBO	River basin organisation
RE	Renewable energy
RePP	Renewable Power Plant Database
RoR	Run-of-river
SAPP	Southern African Power Pool
SDG	Sustainable Development Goal
SPP	Solar power plant
SPPD	Solar Power Plant Database
TWh	Terawatt hour
U	Under construction
USLE	Universal Soil Loss Equation
WAPP	West African Power Pool
WPP	Wind power plant
WPPD	Wind Power Plant Database

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