A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030

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A cost optimal resolution for Sub-Saharan Africa powered by 100% renewables in 2030

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A R T I C L E   I N F O

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Sub-Saharan Africa
Hourly resolution
Energy system model
Grid integration
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A B S T R A C T

This paper determines a least cost electricity solution for Sub-Saharan Africa (SSA). The power system discussed in this study is hourly resolved and based on 100% Renewable Energy (RE) technologies. Sub-Saharan Africa was subdivided into 16 sub-regions. Four different scenarios were considered involving the setup of a high voltage direct current (HVDC) transmission grid. An integrated scenario that considers water desalination and industrial gas production was also analyzed. This study reveals that RE is sufficient to cover 866.4 TWh estimated electricity demand for 2030 and additional electricity needed to fulfill 319 million m³ of water desalination and 268 TWhHV of synthetic natural gas demand. Existing hydro dams can be used as virtual batteries for solar PV and wind electricity storage, diminishing the role of other storage technologies. The results for total levelised cost of electricity (LCOE) decreases from 57.8 €/MWh for a highly decentralized to 54.7 €/MWh for a more centralized grid scenario. For the integrated scenario, including water desalination and synthetic natural gas demand, the levelised cost of gas and the levelised cost of water are 113.7 €/MWhHV and 1.39 €/m³, respectively. A reduction of 6% in total cost and 19% in electricity generation was realized as a result of integrating desalination and power-to-gas sectors into the system. A review of studies on the energy future of Sub-Saharan Africa provides the basis for a detailed discussion of the new results presented.

1. Introduction

The need for a revolution in the energy sector globally is vital, in view of tackling the problems of global warming, pollution, climate change, and energy security. The usage of and further dependence on fossil fuels in the pursuit of energy generation will engender an increase of greenhouse gas emissions and more extreme climate impacts. The energy sector accounts for roughly two-third of all anthropogenic greenhouse gas emissions, and there is imminent need for a paradigm shift from conventional to renewable energy resources that are sustainable, clean and cost effective [39,52,57]. Investment in sustainable energy infrastructure is a crucial link between economic growth, development, and climatic action. Renewable electricity generation will ensure the reduction of carbon dioxide emissions and meet climatic targets. A renewable energy optimization solution will reduce the dependency on fossil fuels as the predominant energy sources in the power system, and address socio-economic development needs and vulnerability to environmental change [23,46].

The region of Sub-Saharan Africa (SSA) continues to face significant energy crises. Despite the unique potential of energy sources in the region, a severe energy shortage has yet to be conquered, and access to electricity eludes millions of people [48]. Billions of dollars are spent annually on inefficient and often dangerous alternatives such as kerosene lamps, candles, flashlights, or other fossil-fueled powered stopgap technologies. In 2012 almost 16 TWh of electricity demand was served by backup generators for service and industrial activities in SSA [48,8]. The current energy challenge in Africa requires a rapid increase in energy supply (growth and development of energy) for the continent due to growing population, unprecedented economic progress and a need for reliable, modern energy services. Supply of energy is expected to at least double by 2030 and might even triple for electricity [56].

Africa’s electricity generation varies significantly among African countries. North Africa (more than 99% electricity access) dominates in terms of electricity generation from a continental perspective [58], while Sub-Saharan Africa is starved for electricity. Only seven countries, Cameroon, Côte d’Ivoire, Gabon, Ghana, Namibia, Senegal and South Africa have electricity access rates exceeding 50%. The average annual consumption in Sub-Saharan Africa (except South Africa) is only about 150 kWh/capita [20]. Electricity demand in Africa was 385 TWh and 621 TWh in 2000 and 2012, respectively, and estimated to increase to about 1258 TWh and 1869 TWh by 2030 and 2040, respectively. The Sub-Saharan African demand will be about 812 TWh and 1297 TWh by...
2030 and 2040, respectively [48]. According to Greenpeace [39], 95% of the electricity produced in Africa will come from renewable energy sources by 2050. Moreover, wind, solar photovoltaics (PV), concentrating solar thermal power (CSP), and geothermal energy will contribute 80% to total electricity generation. Already by 2020 the share of renewable electricity production will be 31%, and 65% by 2030. Consequently, the installed capacity of renewables will reach about 380 GW in 2030 and 1390 GW by 2050.

A brief summary of various studies on the trend of renewable energy share in African energy systems is presented in Table 1. Greenpeace [39] reveals the possibility of achieving 100% renewable energy in Africa by 2050 and WWF [81] affirms this possibility. The 2030 renewable energy map for Africa by IRENA [56] reports that the renewable share in the generation mix in the power sector can grow by 50% while the New Policies Scenario of the IEA [48] for 2040 reveals that hydropower may account for 26% of electricity generation, and other renewables will reach 12 GW (15%).

Energy demand grows as population increases in the world [3]. Africa is expected to contribute more than half of the global population growth between now and 2050, i.e. 1.3 billion people will be added in Africa of the 2.4 billion projected increase in global population between 2015 and 2050, and even more for the following decades [75]. Most developing countries and Africa need to plan a secure and sustainable means of meeting the current energy shortage problem and satisfy future energy demand, due to this fast growing and projected increase. In particular, the lack of access to affordable electricity in the Sub-Saharan Africa region requires a massive expansion of access to electricity [56,20]. Over 620 million people in Sub-Saharan Africa lack access to electricity, and nearly 730 million rely on the traditional use of solid biomass for cooking [48].

Sub-Saharan Africa has a huge untapped potential of renewable energy resources, widely spread across the region, which could provide affordable, sufficient and secure supplies of energy for the continental need. Therefore, investments in the energy system in Sub-Saharan Africa with a focus on increasing energy accessibility and affordability will improve quality of life, life expectancy and economic growth [55,75]. Africa’s energy sector is vital to its development; therefore, effective energy planning, optimal design, wise utilisation of all available renewable energy (RE) resources and maximum synergy between various resources and different regions (regional electricity networking due to disperse energy resources) of Africa will have a positive impact on energy systems of the continent [56]. In view of designing and optimizing a renewable based energy system, several studies have been carried out with the aim of increasing utilisation of renewables in renewable energy rich regions (such as Northeast Asia) by utilizing high voltage direct current grids (HVDC) for interconnections within the regions [10].

Access to modern energy services can be secured by RE, especially solar PV [48]. Globally, solar PV installations have shown high growth rates, and solar PV is one of the fastest growing renewable technologies

### Table 1

<table>
<thead>
<tr>
<th>Reference</th>
<th>Scope</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenpeace [39]</td>
<td>Global</td>
<td>The Energy [R]evolution scenario 2015 reveals a growing share of renewables in the African energy system till year 2050: 31%, 65%, and 100% by 2020, 2030 and 2050, respectively, in electricity generation. Increase in installed capacity from 380 GW (2030) to 1390 GW (2050).</td>
</tr>
<tr>
<td>IRENA [56]</td>
<td>Africa</td>
<td>Reduction of about 310 Mt of CO₂eq emission by 2030 with 50% share of RE in the power sector. Solar capacity could reach 90 GW, hydropower and wind 100 GW each.</td>
</tr>
<tr>
<td>WWF [81]</td>
<td>Uganda</td>
<td>Transition to 100% RE in Uganda requires adoption of on- and off-grid solar energy and increasing use of other RE. With a target of 60% RE system in 2030 and close to 100% by 2050.</td>
</tr>
<tr>
<td>Teske et al. [73]</td>
<td>Tanzania</td>
<td>Scenario design is based on Greenpeace [39] complemented by an Energy Access Scenario. 100% RE in Tanzania is technically and economically possible with 44.8 GW (PV), 30.0 GW (wind) installed in 2050.</td>
</tr>
<tr>
<td>IEA [48]</td>
<td>Sub-Saharan Africa</td>
<td>Electricity generation according to the 2040 New Policies Scenario is 1540 TWh; hydro accounts for 26% of the total generation and other renewable including solar, wind, bioenergy, geothermal and CSP will reach 12 GW (15%) by 2040</td>
</tr>
<tr>
<td>IRENA [53,54]</td>
<td>Africa</td>
<td>RE presents the least-cost option and provides electricity access to millions of Africans through renewable off-grid systems. RE share projected to increase from 50% to 73% by 2030 and 2050, respectively.</td>
</tr>
<tr>
<td>Bazilian et al. [5]</td>
<td>Sub-Saharan Africa</td>
<td>Reports on various levels of access and required installed capacities in Sub-Saharan Africa (excluding South Africa) by 2030. The access levels include business-as-usual, Trendline, Moderate Access, Full Access and Full Enhanced Access and required capacities are 79 GW, 374 GW, 501 GW and 1002 GW, respectively. Universal access by 2030 considering 2°C target, renewable energy will contribute about 275 GW.</td>
</tr>
</tbody>
</table>
with continuously decreasing generation cost \([13,67]\). PV in Africa has transcended the government-donor niche to become a commercial based market development \([43]\). Solar PV technology currently plays a dominant role in the off-grid market, 4 million solar products were sold globally in the last half of 2015, and Sub-Saharan African sales accounted for 2.2 million (54.3\%) \([38]\). PV will play a crucial role towards a 100\% renewable energy system in Africa and requires the adoption of on- and off-grid solar energy as well as increasing the use of other RE resources \([81]\). In the New Policies Scenario 2040 \([48]\), mini-grids and other off-grid technologies account for 26 TWh and 12 TWh of power generation, respectively, in Sub-Saharan Africa, and solar PV contributes 37\% and 47\% of the technology mix, respectively. Solar home systems and mini-grids provide technically feasible and economical solutions to energy challenges, where the cost of grid extension is not economical \([66]\). In Africa, solar energy has the largest RE resource potential and the high quality resource is widely available. Therefore, the PV and CSP technical potential could be as high as 6567 TWh and 4719 TWh, respectively. The rapid cost reduction for solar PV has led to increasing annual capacity additions and enhancing off-grid access \([53,54]\). The Sub-Saharan Africa energy sector is vital to its development. Therefore, effective energy planning, optimal design, and wise utilisation of the untapped, abundant renewable energy resources across Sub-Saharan Africa will have a positive impact on energy systems of the region.

The idea of a super grid has recently attracted more attention by Gobitec and the Northeast Asian Super Grid initiative, influenced by EU-MENA Desertec \([25,63]\). The super grid approach enables connections within a region or continent to attain synergetic effects by the harnessing of RE resources. This can help realize a 100\% RE electricity supply system which can set the path for a 100\% RE supply \([10]\).

The main focus of this paper is to design an optimal energy system in Sub-Saharan Africa which is cost efficient and competitive. This will be found via a 100\% RE-based system with optimal design and wise utilisation of all available RE resources, supportive storage and grid technologies.
calculated as the sum of self-generation, annual cost, and cost of electricity consumed from the grid, less benefits from selling excess energy. The model flow diagram that has all the considered input data, system models and model output data is presented in Fig. 1.

2.2. Input data

Additional information to Bogdanov and Breyer [10] about geothermal data, water desalination, and industrial gas demand are defined in this section. The geothermal potential is evaluated based on available information on the surface heat flow rate [1,45] and surface ambient temperature for the year 2005 globally. For areas where surface heat flow data are not available, an extrapolation of existing heat flow data was performed. Based on that, temperature levels and available heat at the middle depth point of each 1 km thick plate, between depths of 1 km and 10 km [21,22,85] globally with 0.45° x 0.45” spatial resolution, are derived.

Water desalination demand is projected based on water consumption levels and future water stress [86]. Water stress occurs when the water demand exceeds renewable water availability during a given period. It is assumed that water stress greater than 50% shall be covered by seawater reverse osmosis (SWRO) desalination. Transportation costs are also taken into account, as described by Caldera et al. [18]. The energy consumption of horizontal and vertical pumping are 0.04 kWh/(m³ h 100 km) and 0.36 kWh/(m³ h 100 m), respectively [18].

Present industrial gas consumption is based on natural gas demand data from the International Energy Agency statistics [49]. Natural gas consumption projections for the year 2030 were calculated considering annual industrial growth projections based on the World Energy Outlook [48].

2.3. Applied technologies

The technologies applied in the cost optimization for Sub-Saharan Africa can be classified into four main categories: conversion of RE resources into electricity, energy storage, energy sector bridging (for definition, see later), and electricity transmission. The technologies for converting RE resources into electricity applied in the model are ground-mounted (optimally tilted and single-axis north-south oriented horizontal continuous tracking) and rooftop solar PV systems, concentrating solar thermal power (CSP), wind onshore turbines, hydropower (run-of-river and dams), biomass plants (solid biomass and biogas), waste-to-energy power plants and geothermal power plants.

The energy storage technologies used in this study are battery storage, pumped hydro storage (PHS), adiabatic compressed air energy storage (A-CAES), thermal energy storage (TES) and power-to-gas (PtG) technology. PtG includes synthetic natural gas (SNG) synthesis technologies: water electrolysis, methanation, CO₂ scrubbing from air, gas storage, and both combined and open cycle gas turbines (CCGT, OCGT). SNG synthesis process technologies have to be operated in synchronization because of hydrogen and CO₂ storage absence. Additionally, there is a 48 h biogas buffer storage, and a part of the biogas can be upgraded to biomethane and injected into the gas storage.

The energy sector bridging technologies give more flexibility to the entire energy system, thus reducing the overall cost. One bridging technology available in the model is PtG technology for the case that the produced gas is consumed in the industrial sector and not as a storage option for the electricity sector. The second bridging technology is seawater reverse osmosis (SWRO) desalination, which couples the water sector to the electricity sector. The technologies are represented on two levels: power distribution and transmission within the sub-regions are assumed to be based on standard alternating current (AC) grids which are not part of the model, and inter-regional transmission grids modeled by applying high voltage direct current (HVDC) technology.

Power losses in the HVDC grids consist of two main elements: length dependent electricity losses of the power lines and losses in the converter stations at the interconnection with the AC grid. An energy system mainly based on RE and in particular intermittent solar PV and wind power requires different types of flexibility for an overall balanced and cost optimized energy mix. The four broad categories are generation management (e.g. hydro dams or biomass plants), demand side management (e.g. PtG, SWRO desalination), storage of energy at one location and energy shifted in time (e.g. batteries), and transmission grids connecting different areas and energy shifted to the site (e.g. HVDC transmission). The full model block diagram is presented in Fig. 2.

3. Scenario assumptions

3.1. Regions subdivision and grid structure

This study considered 51 countries that are merged or subdivided into 16 sub-regions of the Sub-Saharan Africa super regional network based on area, population, and national grid connections. The 16 interconnected sub-regions include: West-West (Senegal, Gambia, Cape
Verde Islands, Guinea Bissau, Guinea, Sierra Leone, Liberia, Mali, Mauritania and Western Sahara), West-South (Ghana, Côte d’Ivoire, Benin, Burkina Faso and Togo), West-North (Niger and Chad), South-Nigeria (South Nigeria), North-Nigeria (North Nigeria), Sudan-Eritrea (Sudan and Eritrea), Ethiopia (Ethiopia), Somalia (Djibouti and Somalia), Kenya-Uganda (Kenya and Uganda), Tanzania (Rwanda, Burundi, Tanzania), Central (Central African Republic, Cameroon, Equatorial Guinea, Sao Tome and Principe, Democratic Republic of the Congo [Kinshasa], Republic of the Congo [Brazzaville] and Gabon), South-West (Angola, Namibia and Botswana), South Africa (the Republic of South Africa and Lesotho), South-East (Malawi, Mozambique, Zambia, Zimbabwe and Swaziland) and Indian Ocean (Comoros Islands, Mauritius, Mayotte, Madagascar and Seychelles).

In this paper four scenarios for energy system development options are discussed:

1. Regional-wide, which assumes that the sub-regions operate independently (with no HVDC grid interconnections), and the electricity demand has to be covered by the respective regions’ supply;
2. Country-wide energy system, which assumes that the sub-regions are interconnected via HVDC lines but within the borders of nations;
3. Area-wide energy system, which assumes that all sub-regions are interconnected via HVDC lines;
4. Integrated scenario, which takes into account additional demand sectors (SWRO desalination and industrial gas demand) to the area-wide energy system scenario. In this scenario, RE sources combined with PtG technology are used not only for electricity generation and storage options within the system but also as energy sector bridging technologies to cover water desalination and industrial gas demand, increasing the flexibility of the system.

The subdivision and grid configuration of Sub-Saharan Africa are presented in Fig. 3. Existing HVDC interconnections of Sub-Saharan Africa are shown by dashed lines. The structure of the HVDC grid for the scenarios (solid lines) is based on the existing configuration of Sub-Saharan Africa Power Pools. A typical existing line is Cahora-Bassa (1920 MW as 533 kVA and 1800 A).

3.2. Financial and technical assumptions

The model optimization is undertaken based on cost assumptions derived from technological status for the year 2030 and the overnight building approach, which is also applicable to nuclear energy [19]. The financial assumptions for capital expenditures (CAPEX), operational expenditures (OPEX) and lifetimes of all components are provided in the Supplementary material (in Table I). CAPEX and OPEX are quantified estimates by weighting the hourly LCOE per technology (generation, transmission, and storage) balanced with hourly demand for 2030. Weighted average cost of capital (WACC) is set at 7% for all scenarios, but for residential PV self-consumption, WACC is set to 4%, due to lower financial return requirements. The technical assumptions of power to energy ratios for storage technologies, efficiency numbers for generation and storage technologies, and power losses in HVDC power lines and converters are provided in the Supplementary material (Tables II, III, and IV, respectively). The electricity prices for residential, commercial, and industrial consumers in most of the Sub-Saharan Africa countries for the year 2030 are obtained from Gerlach et al. [36] and aggregated based on population weighted estimates as presented in the Supplementary material (Table V). Prosumers will use PV to supply a portion of their electricity needs. Thus, prosumers will cut the slice of electricity demand and get remunerated for any surplus generation, which does not top their annual consumption. The operation cost for prosumers depends on market conditions for the year 2030 and covers the cost of new rooftop PV systems and batteries. Excess generation, which cannot be self-consumed by the solar PV prosumers, is assumed to be fed into the grid for a transfer selling price of 2 €cents/kWh.

3.3. Feed-in for solar and wind energy

The feed-in profiles for solar CSP, PV optimally tilted and single-axis tracking, and wind energy were calculated according to Bogdanov and...
Breyer [10]. The aggregated profiles of solar PV generation (optimally tilted and single-axis tracking), wind energy power generation, and CSP solar field, normalized to the maximum capacity averaged for Sub-Saharan Africa are presented in Fig. 4. The computed average full load hours (FLH) for optimally tilted, single-axis tracking PV systems, wind power plants, and CSP are provided in the Supplementary material (Table VI). The feed-in values for hydropower are computed based on the monthly resolved precipitation data for the year 2005 as a normalized sum of precipitation in the regions. Such an estimate leads to a good approximation of the annual generation of hydropower plants.

3.4. Biomass and geothermal heat potentials

Biomass and waste resource potentials are mainly taken from DBFZ et al. [24] and classified as described in Bogdanov and Breyer [10]. Costs for biomass are calculated using data from the International Energy Agency [46] and Intergovernmental Panel on Climate Change [51]. For solid wastes a 100 €/ton gate fee for incineration is assumed. Calculated solid biomass, biogas, solid waste, and geothermal heat potentials are provided in the Supplementary material (Table VII). Prices for biomass fuels are provided in the Supplementary material (Table VIII), and price differences between countries are explained by various waste and residue component shares. Heating values are based on lower heating values (LHV). Regional geothermal heat potentials are calculated based on spatial data for available heat, temperature, and geothermal plants for depths of 1–10 km [83]. For each 0.45° x 0.45° area and depth, geothermal LCOE is calculated and optimal well depth is determined. It is assumed that only 25% of available heat will be used as an upper resource limit. The total available heat in the region is calculated using the same weighted average formula as for solar and wind feed-in explained in Bogdanov and Breyer [10], except for the fact that areas with geothermal LCOE exceeding 100 €/MWh are excluded.

3.5. Upper and lower limitations on installed capacities

Lower limits are taken from Farfan and Breyer [31] and upper limits were estimated based on Bogdanov and Breyer [10]. Lower limits on already installed capacities in Sub-Saharan Africa are provided in the Supplementary material (Table IX) and all upper limits of installable capacities are summarized in the Supplementary material (Table X). For all other technologies, upper limits are not specified. However, for biomass residues, biogas, and waste-to-energy plants it is assumed, due to energy efficiency reasons, that the available and specified amount of the fuel is used during the year, except for solid biomass which can be used up to the full resource potential.

Fig. 4. Aggregated feed-in profiles for PV optimally tilted (top left), PV single-axis tracking (top right), 3 MW 150 m hub height wind turbine (bottom left) and CSP solar field (bottom right).
3.6. Load

The synthetic load data are generated based on hourly load data on a national level and takes into account local phenomena such as gross domestic product, population, temperature, and power plant structure. Fig. 5 represents the area-aggregated demand of all sub-regions in Sub-Saharan Africa. Electricity demand increase by the year 2030 is estimated using IEA data [48] and population weighted on the countries close border proximity. Solar PV self-consumption prosumers have a significant impact on the extra load of the energy system as illustrated in Fig. 5 (right). The total electricity demand and the peak load are reduced by 11.2% and 5.2%, respectively.

Industrial gas demand values (expressed as gas demand excluding electricity generation and residential sectors) and desalinated water demand for Sub-Saharan Africa sub-regions are presented in the Supplementary material (Table XI). Gas demand values are based on [49]. Desalination demand numbers are based on water stress and water consumption projections obtained from [18].

Table 2 displays the financial results for all four analyzed scenarios. The role of HVDC transmission is important in achieving the least cost solution for Sub-Saharan Africa for the year 2030. It can be observed that the installation of HVDC transmission lines leads to a significant reduction of electricity cost of the entire system; a comparison of the region-wide and area-wide scenario shows a 5.4% and 5.8% decrease in LCOE and the annual expenses of the system, respectively. The same conclusion can be drawn regarding grid utilisation, which shows a reduction in primary generation cost. A comparison of the area-wide and integrated scenario emphasizes the increased flexibility in the system by an additional PtG capacity of 47.0 GW. This occurs despite the availability of low cost biogas since the biogas resource potential cannot cover the full gas demand in the energy system as tabled in the Supplementary material (Tables VII and XI). The numeric values for LCOE components in all sub-regions and scenarios are summarized in the Supplementary material (Table XIV). The integration of water desalination and industrial gas sectors results in a further reduction in LCOE by 23.4% compared to the area-wide open trade scenario. The cost reduction benefits are a result of a massive reduction in cost of storage and a minor decrease in the cost of curtailment. Storage cost is reduced by 48.3% since industrial gas and desalination sectors decrease the need for long-term storage utilisation, giving additional flexibility to the system. The utilisation of low-cost wind and solar electricity results in increased system flexibility as can be seen in Table 3. This results in an 8.7% decrease in primary electricity generation cost. A comparison of the area-wide and integrated scenario emphasizes the increased flexibility in the system by an additional PtG capacity of 47.0 GW. This occurs despite the availability of low cost biogas since the biogas resource potential cannot cover the full gas demand in the energy system as tabled in the Supplementary material (Tables VII and XI). The numeric values for LCOE components in all sub-regions and scenarios are summarized in the Supplementary material (Table XIV). Regarding the RE installed capacities, all the RE technologies present a reduction of total installed capacity with an increase of grid utilisation (Table 3). Moreover, in all scenarios, solar PV technologies have the largest overall share compared to alternative technologies. The share of PV dominates as a result of interconnectivity reaching 55.5%, as the share of wind drops to 30.8%. The rest of the RE technologies make up the remainder, with hydro, biomass and geothermal taking slight shares that range from 4.7% to 6.6%, 4.5 to 7.2%, and 1.0 to 1.3%, respectively. The share for hydro and geothermal show some minor changes as a result of interconnection and integration of gas and desalination sectors. Hydro dams also act as virtual storage for the

![Fig. 5. Aggregated load curve (left) and system load curve with prosumers influence (right) for the year 2030.](image-url)
Table 2
Financial results for the four scenarios applied in Sub-Saharan Africa.

<table>
<thead>
<tr>
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<td>Region-wide</td>
<td>58</td>
<td>38</td>
<td>2</td>
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<td>Country-wide</td>
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<td>15</td>
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<td>47</td>
<td>416</td>
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Table 3
Overview on installed RE technologies and storage capacities for the four scenarios.

<table>
<thead>
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<th>RE Technology</th>
<th>Units</th>
<th>Region-wide</th>
<th>Country-wide</th>
<th>Area-wide</th>
<th>Integrated</th>
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<td>PV self-consumption</td>
<td>[GW]</td>
<td>61.3</td>
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<tr>
<td>PV optimally tilted</td>
<td>[GW]</td>
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<td>PV single-axis tracking</td>
<td>[GW]</td>
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<td>133.9</td>
<td>111.5</td>
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<tr>
<td>PV total</td>
<td>[GW]</td>
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<td>196.7</td>
<td>174.2</td>
<td>301.9</td>
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<td>CSP</td>
<td>[GW]</td>
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<td>Wind energy</td>
<td>[GW]</td>
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<td>Biogas power plants</td>
<td>[GW]</td>
<td>4.5</td>
<td>4.2</td>
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<td>1.3</td>
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<td>Biomass power plants</td>
<td>[GW]</td>
<td>1.7</td>
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<td>MSW incinerator</td>
<td>[GW]</td>
<td>23.1</td>
<td>23.2</td>
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<td>Geothermal energy</td>
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<td>Hydro dams</td>
<td>[GW]</td>
<td>20.4</td>
<td>20.4</td>
<td>20.4</td>
<td>20.4</td>
</tr>
<tr>
<td>Battery PV self-consumption</td>
<td>[GWh]</td>
<td>72.2</td>
<td>72.2</td>
<td>72.2</td>
<td>72.2</td>
</tr>
<tr>
<td>Battery total</td>
<td>[GWh]</td>
<td>262.6</td>
<td>268.6</td>
<td>240.3</td>
<td>218.4</td>
</tr>
<tr>
<td>PHS</td>
<td>[GWh]</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>A-CAES</td>
<td>[GWh]</td>
<td>623.2</td>
<td>579.7</td>
<td>432.5</td>
<td>335.0</td>
</tr>
<tr>
<td>Gas storage</td>
<td>[GWhel]</td>
<td>25,754</td>
<td>25,948</td>
<td>18,936</td>
<td>24,304</td>
</tr>
<tr>
<td>PtG electrolyzers</td>
<td>[GWel]</td>
<td>9.1</td>
<td>9.1</td>
<td>6.5</td>
<td>53.9</td>
</tr>
<tr>
<td>CCOT</td>
<td>[GW]</td>
<td>16.9</td>
<td>16.7</td>
<td>13.6</td>
<td>9.8</td>
</tr>
<tr>
<td>OCGT</td>
<td>[GW]</td>
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<td>13.0</td>
<td>10.3</td>
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<tr>
<td>Steam Turbine</td>
<td>[GW]</td>
<td>30.1</td>
<td>29.7</td>
<td>23.9</td>
<td>25.1</td>
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</table>

Fig. 6. Electricity generation duration curves for the area-wide open trade scenario for Sub-Saharan Africa.
Fig. 7. Installed capacities of RE generation (left) and storages (right) for region-wide (top), area-wide (center) integrated (bottom) scenarios.
system and provide required flexibility. Interconnection and integration have considerable impacts on storage capacities.

The cost of most RE technologies has declined, and additional expected technical advances would result in further cost reductions. A PV self-consumption overview is given in the Supplementary material (Table XII). Self-generation plays a crucial role in Sub-Saharan Africa owing to high electricity prices throughout the region and low self-consumption LCOE. Self-consumption covers 84.7% of residential prosumer demand, 88.0%, and 89.4% of generated PV electricity for commercial and industrial prosumers, respectively.

Despite the fact that an upper limit 50% higher than the current capacity was considered for hydro dams and hydro RoR plants, the total hydropower plant installed capacity practically did not change in all the studied scenarios. It is not necessary to utilize all the available hydropower capacities as PV and wind seemed to be more cost competitive options for Sub-Saharan Africa.

As seen in results for the area-wide scenario, the interconnection of sub-regions in Sub-Saharan Africa has considerable impacts on storage capacities. Gas storage dominates the proportions for storage capacities in all the scenarios followed by A-CAES. However, when the storage throughputs are considered, there is a complete shift of dominance to battery storage, which is utilized especially during the night hours and in the absence of solar PV. Gas storage has a moderately low throughput of 45.9 TWh compared to battery storage, with the highest throughput of 77.5 TWh. Besides gas and batteries, other storage solutions utilized include: PHS, which has the lowest throughput of 0.83 TWh and is only utilized in the South African sub-region, and A-CAES at 10.5 TWh, which is still surpassed by batteries and gas storage. The storage capacities of batteries, PHS, A-CAES, PtG and gas turbines decrease as a result of interconnection and integration of gas and desalination sectors. However, gas storage increases from 18.9 TWh to 24.3 TWh as a consequence of the integration of gas and desalination sectors. PtG electrolyser have a rather low installed capacity in the area-wide and area-wide scenarios since PtG is not needed much for seasonal storage.

4.2. Main findings on the optimized energy system structure in a sub-region analysis

Considering a sub-regional analysis, as presented in Fig. 7, noticeable differences can be observed between the scenarios, especially between the area-wide and the integrated scenarios. More demand in the area-wide scenario can be seen in Fig. 6. All 8760 h of the year are sorted according to the net hourly supply (generation minus load), which is represented by the black line. Higher electricity generation than demand can be observed for 4400 h of the year, and this is used for charging storage. This is caused by high electricity generation from inflexible energy sources, due to high shares of solar PV and wind energy in Sub-Saharan Africa energy mix and a higher solar irradiation and wind speed in the region during these hours of the year. As a consequence, flexible electricity generation options (such as hydro dams, biomass, and biogas) and discharge of storage plants are needed. The inflexible electricity generation is significantly reduced in comparison to the decrease in electricity demand for the remaining hours of the year, thus increasing the need for flexible electricity generation, energy storage discharge and grid utilisation. The storage plants are deployed for about 4400 h of the year in charging mode and about 4200 h in discharging mode. Electricity curtailment occurs for only about 1000 h over the entire year and is seen at relatively low levels. This is due to the existence of storage options within sub-regions and HVDC transmission lines, which enable further storage in other sub-regions as well as effective electricity exchange between sub-regions.
case of a RE-based energy system can change the entire system structure because of shifting optimal cost structure parameters and sub-regions being confronted with their upper resource limits. For region-wide and area-wide scenarios, the share of PV dominates in almost all the sub-regions considered. The exceptions are Kenya-Uganda, Somalia-Djibouti, and West-North, where wind energy plays a key role due to favorable wind resources. Wind plays a key role in the integrated scenario, as an additional electricity demand for water desalination and industrial SNG production was included. This was especially noticeable in the sub-regions that have excellent wind conditions and, therefore, low cost wind energy.

Broad cost saving opportunities appear available as a result of HVDC interconnection. Firstly, as water desalination and industrial gas sectors are integrated, the power system increases the electricity demand but, importantly, also the energy system flexibility. Therefore the, total installed capacities are reduced due to HVDC transmission grid interconnection, as seen in Fig. 7 and Table 3. This decrease occurs mainly because of a reduction in capacity by 17.2\% for PV single-axis in Sub-Saharan Africa, which is seen when region-wide to area-wide scenarios are compared. The exceptions are North-Nigeria and West-North, which showed increases in total RE installed capacities by 9.9\% and 898\%, respectively. The significant reduction in PV shares is countered by an increase in wind capacities by 10.2\% in the West-North sub-region, which shows a 20-fold increase from 0.49 GW to 10.4 GW. This result highlights the role played by wind as more sectors are integrated into the system. Secondly, the structure of HVDC power lines and utilized RE resources strongly influences the total storage capacity needed. In this context, the already installed hydro dams are an important RE source that can act as virtual batteries for long-term storage and seasonal balancing. The regional capacities also vary between sub-regions. Data of storage systems' discharge capacities, annual energy throughput, and full load cycles per year are summarized in the Supplementary material (Table XIII). The generation capacities of storage technologies decrease with the geographic integration and utilization of HVDC transmission lines. State-of-charge profiles for the area-wide scenario for battery, PHS, A-CAES, gas storage and hydro dams are provided in the Supplementary material (Fig. 4 and Fig. 5). The state-of-charge diagrams show the system optimized operation mode of the different storage technologies: mainly daily (battery, PHS), mainly weekly (A-CAES) and mainly seasonal (gas, hydro dams). Additionally, the absolute and percentage hourly grid capacity profiles in the integrated scenario for the different times of a day and days of a year are as presented in the Supplementary material (Fig. 6).

4.3. Electricity import/export

In the case of the region-wide open trade scenario, all sub-regions of Sub-Saharan Africa need to match demand using only their own RE resources. Nonetheless, in the case of the country-wide and area-wide open trade scenarios, a division of sub-regions into net exporters and net importers with interregional electricity flows can be observed. An annual import and export diagram for area-wide open trade is presented in Fig. 8. Differences in generation and demand are mainly due to export and import, but also somewhat due to storage losses. For the area-wide integrated scenario, differences are due to energy consumption for SNG production. Fig. 8 also gives a good overview of sub-regional RE resources; net exporters are sub-regions with the best renewable resources and net importers are sub-regions with moderate ones.

The results in the Supplemental material (Table XIV) summarize the import/export shares in all sub-regions and for all scenarios. The share of export is defined as the ratio of net exported electricity to the generated primary electricity of a sub-region, and the share of import is defined as the ratio of imported electricity to the electricity demand.
The area average is composed of sub-regional values weighted by the electricity demand. West-North, located in the Sahara Desert, emerges as the major net exporter in Sub-Saharan Africa; the sub-region depicts a surprisingly favorable wind and solar generation with a low electricity demand. West-North exports 36 TWh of electricity to the more highly populated South-Nigeria, the major net importer in Sub-Saharan Africa. The rest of the net importing sub-regions include Tanzania, West-West, Congo, and South-East. The remaining sub-regions are classified as balancing sub-regions since electricity is both imported and exported over the short-term (hourly) and over the long-term (annually). Hourly resolved profiles of generation in an importer sub-region (South-Nigeria), a balancing sub-region (South Africa), and an exporting region (West-North) are presented in the Supplementary material (Figs. 1–3, respectively). For the integrated scenario a drastically increased electricity demand for the desalination and SNG producing sectors changes the picture dramatically; SNG producing sub-regions tend to increase the intra-regional electricity generation to fulfill the growing demand.

The Sankey flow in Fig. 9 diagram reveals more about the energy flows, all the way from generation to end use, and the efficiency of each energy conversion. The Sankey flow diagram summarizes the integrated scenario and is comprised of the primary RE resource generators, the energy storage technologies, HVDC transmission grids, the total demand for each sector and system losses. The potentially usable heat and ultimate system losses include the difference between the primary power generation and final electricity demand. Both are comprised of curtailed electricity; the heat produced by biomass, biogas, and waste-to-energy power plants; the heat of transforming power-to-hydrogen in the electrolyzers, hydrogen-to-methane in methanation and methane-to-power in the gas turbines; and the efficiency losses in A-CAES, PHS, battery storage, as well as by the HVDC transmission grid. At the same time, the end use is comprised of the electricity, gas, and desalination sectors. Additional sectors in the integrated scenario cause additional capacity for generation from renewables, mainly wind energy and solar PV. An overview of the power transmission lines, their key parameters, and the percentage of grid utilisation can be found in the Supplementary material (Table XV and Fig. 6). The energy flow for the region-wide and area-wide scenarios are presented in the Supplementary material (Figs. 7 and 8).

5. Discussion

5.1. Cost implications for large-scale HVDC interconnections

From the presented results for Sub-Saharan Africa, it can be confirmed that different grid configurations as witnessed in the different scenarios will lead to several cost ramifications. Appropriate approaches for institutional, technical, and economic design and implementation are crucial to carrying out grid expansion programs in Sub-Saharan Africa. The electricity consumption in most Sub-Saharan countries is low due to a variety of reasons amidst a poorly developed grid infrastructure [84]. Thus, for the region to engage in large-scale energy projects, there must be calls for additional investment in HVDC power lines to facilitate cross-border transmission. The majority of Sub-Saharan countries have recurrent power shortages, almost 40% of the grid was built or refurbished decades ago, and it is estimated that 18 bUSD is required for the renovation of the existing grid [72].

In an effort to tackle the inefficiencies associated with the Sub-Saharan Africa power supply, joining national markets can provide the economy of scale to overcome them. Regional power pools need to be established to promote cross-border trade in electricity and incentivize capacity investment. HVDC interconnectors could enhance renewable electricity trade between power pools with diverse energy mixes [70]. Indeed, there are already discussions about interconnection across the continent and facilitating the creation of a Pan African power market [42]. The power market will be comprised of a consolidation of regional power pools, namely, Southern African power pool (SAPP), West African Power Pool (WAPP), Central African Power Pool (PEAC) and the East African Power Pool (EAPP). This study has, however, subdivided the power pools further and highlights 16 sub-regions as discussed in Section 3.1.

The linkage of these sub-regions via HVDC transmission lines can address the challenges of intermittency in RE technologies. The installation of HVDC transmission lines between sub-regions leads to a significant reduction of overall cost, storage requirements, and RE installed capacities in the 100% RE-based system. A comparison of the region-wide and country-wide scenarios shows negligible difference regarding cost since only Nigeria (with an enormous population) was subdivided. Moreover, a slight drop in the total levelized cost of electricity from 57.8 €/MWh to 57.7 €/MWh is noticeable. The same argument is feasible when the annualized cost is also compared. The annualized cost shows a slight decrease from 50.3 b€/a to 50.2 b€/a. However, when the country-wide or the region-wide scenario are compared to the area-wide scenario, a sizeable reduction in LCOE of 5.5% is observed, from about 57.8 €/MWh to 54.6 €/MWh. In addition, annualized cost decreases from around 50.2 b€/a to 47.3 b€/a. In parallel, the CAPEX requirements are also reduced in a similar manner by 3.0%, from 429.7 b€ to 416.8 b€, which is a lower reduction than the one seen for the annualized cost since the biomass fuel cost remain stable. Additional costs of HVDC transmission lines (23.1 b€/a annual cost for the area-wide scenario) are compensated by a substantial decrease in generation and storage capacities enabled by lower losses and costs of energy transmission compared to energy storage, access to low-cost electricity generation in other regions, and finally a more efficient use of energy system components.

Transmission and distribution (T&D) investments are key for any developing power grid system, particularly for systems that are expanding to meet universal access goals [5]. Eberhard and Shkaratan [28] estimate about 37% of the investment cost is used for new transmission and distribution networks. Unfortunately, the use of HVDC transmission line interconnections may have limited impact in improving electricity access, especially in rural localities in Sub-Saharan Africa because of the complexity of rural settlement (geographical constraints), poorly developed infrastructure, and the cost of extending grid infrastructure. Sub-Saharan Africa has generally lagged behind other regions of the world in terms of infrastructure as well as power sector investment and performance [28].

5.2. Role of off-grid PV

The traditional approaches to electrification of Sub-Saharan Africa by grid extensions have not contributed to the eradication of rural poverty [72]. Over the years, the substantial subsidies provided by the region’s utilities leave millions of African households in the dark because such a limited number of households are connected to the grid [84]. This means that much more investment would be required to achieve full electrification in Sub-Saharan Africa through grid extension options. Based on World Bank [83] calculations, a total of 280 bUSD is required for 200 million new connections to provide 100% electrification by 2030. Off-grid renewable energy technology systems, especially solar PV based technologies (solar home system and mini-grid), provide technically feasible and economical solutions to energy challenges where the cost of grid extension is not cost-effective [11,66]. Furthermore, the choice of technologies for rural electrification should consider the economic viability, geographical potential, and compatibility of (renewable) technology options. Furthermore, spatial and technological analysis helps in identifying least cost electrification options for remote areas [71,72]. Access to modern energy services can be enhanced by RE, especially solar PV. Access to clean and reliable energy constitutes an important prerequisite for fundamental determinants of human development, contributing, among other things, to economic activity, income generation, poverty alleviation, health, education, and gender equality. Due to their decentralized nature, solar PV can play a...
major role in fostering rural electrification [51]. Solar PV technologies dominate the off-grid market. Recent market research conducted in the last half of 2015 on sales of pico-PV and solar home systems reveals that about 4 million products have been sold globally, and Sub-Saharan Africa accounts for about 2.2 million (54.3%) [61]. Additionally, mini-grid and off-grid technology account for 26 TWh and 12 TWh of power generation, respectively, in Sub-Saharan Africa, and solar PV contributes 37% and 47% of the technology mix in the New Policies Scenario 2040 [48]. Mini-grids and off-grid PV capacity are predicted to reach 100 GW, representing about 5% of total capacity by 2030 (2% by 2050), which would be a significant increase from current trends [47]. Such a low PV off-grid share seems unrealistic compared to the results for SSA, whereas the overall global installed PV capacity may reach several tens of terawatts, as indicated by Breyer et al. [15]. One of the most recent approaches for electrification planning using geospatial tools was elaborated by Berthoue et al. [7], who modeled two scenarios to investigate the effects of future grid extension plans in Sub-Saharan Africa. In the first scenario based on the existing grid, 76.6 million people (12%), 290.3 million people (47%) and 252 million people (41%) could be electrified by mini-grids, grid extensions and solar home systems, respectively. The second scenario, in which modeling was based on the planned grid, 50.5 million people (8%), 381.5 million people (62%) and 187.6 million people (30%) can be electrified by mini-grids, grid extensions and solar home systems, respectively, hence more by grid extensions. Berthoue et al. (2017) carried out a sensitivity analysis varying grid buffer and population threshold. Results of the sensitivity analysis show that varying the grid electrification radius has a significant impact on the share of solar home systems and mini-grids. While varying the population threshold increased the relevance of mini-grids. Another study on electrification planning in Sub-Saharan Africa by 2030 [65] indicates that 850 million people (77%), 180 million people (16%) and 70 million people (6%) can be electrified by grid extensions, mini-grids and standalone systems in 2030, respectively, based on Tier 5 electrification criteria. For instance, in Uganda, on-grid electricity will become an increasingly important supplier of energy, though will still account for less than 25% of the overall energy supply by 2050 [81]. This means that 75% of Ugandans will not rely on grid connectivity for the provision of energy. Off-grid based RE solutions like mini-grids, and in particular solar home systems (SHS) provide a least cost solution for realizing the full electrification of rural people in Sub-Saharan Africa [11,12,17,6,81]. PV-based mini-grids can be established for initial electrification but also for upgrading existing and costly off-grid diesel-grids [16]. Furthermore, SHS can act as an interim solution until a grid is planned and constructed, or economic power makes the establishment of mini-grids feasible. This is due to the fact that there are no financial drawback for operators due to the very low amortization periods of SHS of 6–18 months [11,12].

5.3. Relevance of PV prosumers

PV self-consumption influences the energy sector in an interesting way. To measure the impacts of PV prosumers, region-wide, country-wide, and area-wide open trade scenarios are also calculated without PV self-consumption and the total demand is assumed to be covered by a more centralized system. A comparison of self-consumption-scenarios to base scenarios shows the following additions in the annualized costs; 48.6 €c compared to 50.3 €c for region-wide scenarios (+ 3.4%), 48.5 €c compared to 50.2 €c for country-wide scenarios (+ 3.4%), and 45.6 €c compared to 47.3 €c for area-wide scenarios (+ 3.6%). PV self-consumption induces additional costs because of a different target function of prosumers. However, prosumers reach their minimum annual electricity cost. The LCOE for PV self-consumption then must be lower than the grid electricity selling price, but can be higher than the total system LCOE. The cost of PV installations is projected to drop because of technological innovation, product optimization, and economies of scale, among other reasons. This trend will prompt a further cut of LCOE for PV self-consumption. PV self-consumption can also reduce the stress on local distribution and transmission grids in particular in combination with batteries, as also documented by a reduction in the Sub-Saharan African peak-load by 5.2%. Due to the high electricity prices in most of the Sub-Saharan African countries, the value of the savings brought about by PV self-consumption expands and improves the return on investment, which is further accelerated by broad use of diesel generation, even used occasionally as a substitute for base load power plants. So, the prolonged or avoided distribution and transmission capacity may result in a fast growing base of PV prosumers which could set up a component of competition with monopoly utilities in Sub-Saharan Africa.

A comparison between self-consumption and base scenarios also depicts additional battery storage demand because of PV prosumers. Electricity generation from prosumers causes some positive and negative distortion in the system demand profile (Fig. 5), i.e. the system reacts by installing more flexibility granting capacities, such as low-cost RE or further storage capacities, which increase the system costs as well. However, due to some slight inflexibility caused by constrained PV use mainly during the daytime, the impact of prosumers is constrained to a reduction of daytime peaks as opposed to night peaks. Thus, the most expensive peak hours throughout the year are substantially reduced by 5.2% by PV self-consumption, which exhibits a substantial economic value. The electricity consumption in the centralized system is higher from the morning hours till the evenings compared to a system with PV prosumers influence. For the region-wide scenario, a comparable low-cost increase due to the decentralized generation can be explained by the fact that additional disturbance cost in the system (provoked by prosumers) is compensated by access to low-cost residential electricity (for residential consumers WACC is assumed to be 4%). Finally, PV self-consumption is of particular benefit in region-wide and country-wide scenarios, particularly in areas with zero impact on rooftops. PV use for local electricity generation reduces the need to develop long-distance transmission to transmit remote RE sources to load centers. Some countries may have to carry out PV self-consumption as a policy measure for the creation of local value chains and less supply risk due to higher electricity imports.

5.4. Demand for desalination and industrial gas

The integration of water desalination and industrial gas sectors results in additional electricity generation that covers projected renewable water and natural gas demand by SWRO desalination and SNG generation, respectively. In parallel with supplying demand, such integration gives the system additional flexibility, especially for seasonal fluctuation compensation. The availability of RE in Sub-Saharan Africa is sufficient to cover additional electricity demand for producing 320 million m³ of renewable water and 268 TWhLHV of SNG. Moreover, the cost of renewable water seems to be quite affordable at 1.4 €/m³. Adding 357 TWhLHV for SWRO desalination and gas synthesis induces an additional installation of RE generation capacities of 128 GW of PV and about 48 GW of wind energy. As well, former long-term gas storage is partly substituted by short-term battery storage. Additional effects as a result of the integration of water desalination and industrial gas sectors include an 8.4 TWhLHV (-17.2%) reduction of efficiency losses of storage turbines, a 15.6 €c increase in annual system cost, 357 TWh increase in the electricity demand, and a 10.6 TWh increase in curtailed electricity. Despite the extra cost for the generation, transmission, and integrating water desalination and gas sectors, the combined benefits as a result of integration result in a 37.2% reduction in LCOE; likewise, the total LCOE decreases by 7.7 €/MWh (-14.2%). This decrease in total LCOE can be confirmed by the substantial reduction of 37.1% in the cost of storage due to the more flexibility provided to the system by the desalination and industrial gas synthesis sectors. These results are reaffirmed by Castellano et al. [20], who determine that significantly
increasing regional integration could save more than 40 bUSD in capital spending, and save African consumers nearly 10 bUSD per year by 2040, as the levelized cost of energy falls from 70 USD/MWh to 64 USD/MWh. At the same time, the cost impacts of the surplus of energy on the total cost are minimal.

5.5. Overall relevance of solar PV

Solar PV technologies emerge as the dominant technologies in Sub-Saharan Africa for the year 2030. IRENA [53,54] estimates that Sub-Saharan Africa has a technical potential of 9261 TWh for both CSP and PV with around plus or minus 50% certainty. This demonstrates that, single-handedly, solar technology is sufficient enough to power about 10 times the electricity demand for Sub-Saharan Africa (886 TWh) based on our estimates. As seen in the area-wide scenario, PV technologies generate 364.9 TWh (38%). Castellano et al. [20] conclude that higher levels of integration would result in larger regional gas options being favored over some of the smaller, in-country solar and wind additions, leading to an increase in carbon emissions. However, the results of this study show that solar PV still dominates with the integration of the desalination and gas sectors for the 100% RE case. As seen in the area-wide integrated scenario, PV technologies generate 635.6 TWh (47.8%). The high share of PV can be explained by the fact that PV is the least cost RE technology in most of Sub-Saharan Africa and the decreasing cost of battery storage further pushes this trend. The vast and desert countries, with the top five being Chad, the Democratic Republic of the Congo [Kinshasa], Mali, Niger and Sudan, hold about 40% of the solar PV potential capacity [20]. However, winds prevail in Kenya-Uganda, Somalia-Djibouti, and West-North because of the excellent wind resources. Solar PV is followed by wind onshore, which generates 138.7 TWh (36.3%). The rest of the RE technologies (including hydro, geothermal and biomass) take up the remaining 18.1% of the energy supply. Based on Breyer and Gerlach [13] and Vartiainen et al. [77], solar PV LCOE are projected to decline by a further 30–40% from 2020 to 2040 as a consequence of progressive efforts to reduce material use, improved efficiency and the development of the manufacturing processes. It is also expected that the end results of a steady decline in PV cost will be the further dominance of PV technologies in the market beyond the year 2030 [14,15,20]. These revelations are in line with the Greenpeace [39] Advanced Energy Revolution scenario, which projects that hydropower generation capacity will be outstripped by solar energy after the year 2020 and that hydropower will have a smaller generation proportion of 41 GW (11%) compared to solar energy at 177 GW (47%) by 2030.

All three wind energy dominated sub-regions are net-exporters. Compared to the net-importers like South-Nigeria, the net-exporters have a more favorable renewable resource mix. Cross-border energy supply often also provides greatly enhanced diversification of energy sources, a key component of energy security [42]. The results show that the gains from electricity trade differ between sub-regions depending on resource availability and the resource mix. However, electricity trade in Sub-Saharan Africa requires significant cooperation and coordination among countries. Hence, achieving optimal power trade will require a range of important political, legal, and economic commitments [28]. As the penetration levels for variable renewables connected to the grid rises, it also becomes important to consider the impact on grid stability and reliability. Africa needs a strategic approach to improve its economy based on energy security-development linkage policies. However, diversification of renewable resources, spreading their location over different climate zones, and grid interconnections with neighboring countries can all play major roles in ensuring grid stability and energy security [53,54]. In order to facilitate electricity trade exporting and importing sub-regions, the national utilities will need to engage in long-term bilateral contracts for the sourcing and consumption of electrical energy.

5.6. Large-scale hydropower in Sub-Saharan Africa

The Grand Inga project on the Congo River envisages the installation of 40 GW of hydro generating capacity, which would make it the largest hydro facility in the world [56], IRENA [56], estimates that around 92% of technically feasible potential has not yet been developed. Given that large hydro projects often have outputs far more than the country’s electricity demand, it is necessary to develop these as regional projects. The construction and successful operation of the major hydro dams in Sub-Saharan Africa usually requires cross-border co-operation between countries that may be suffering from political instability and even civil disorder. In such circumstances, achieving the necessary water access agreements across national boundaries may prove challenging. However, it can be assumed that the creation of regional power pools will boost cross-border transmission in Sub-Saharan Africa. The expansion of hydropower capacity is expected to further progress by reaching 93 GW in 2040, with several major projects (such as Inga III and the Grand Renaissance Dam) coming online incrementally over the projection period [48]. In this respect, the water footprint, human displacements as a result of large-scale hydro electricity generation, and the social costs have to be taken into account since many parts of Africa are already experiencing water shortage, with about one-third of Africa’s productive area already classified as dry-land [51,74]. Thus, stakeholders have to consider the impact of hydropower development on local populations, their impacts on water use and rights, as well as issues concerning the biodiversity impacts of large-scale hydropower developments. Most refurbishment projects focus on the electro-mechanical equipment, but can involve repairs or redesigns of intakes, penstocks, and tail races. For large hydropower plants, economic lifetimes are at least 40 years, with 80 year lifetimes as the upper limit. Meanwhile, for small-scale hydropower plants, the typical lifetime can be 40 years or less. In this case refurbishment of hydro projects fall into two categories, namely, life extension and upgrades [53,54]. The costs of life extension and upgrades for old hydro plants have been estimated. Moreover, life extensions cost around 60% of electro-mechanical costs and upgrades anywhere up to 90% depending on their extent [53,54]. Considering hydropower has a particular cost advantage compared to other renewable sources that have not yet been amortized, an additional 500 €/kW CAPEX should be considered for old hydropower plants (> 50 years). Considering solar PV and wind energy are cheaper alternatives compared to hydropower, it may be not necessary to build large hydro dams to utilize all the available capacity in Sub-Saharan Africa.

Further review of the energy mix shows contradictions of the results of this research to the IEA [48] Africa Energy Outlook, which reports that the total renewable share will grow to 44% in Sub-Saharan Africa. The findings of this research is that 100% RE is already low cost based on 2030 financial assumption. According to IEA’s findings, the power generation capacity in 2040 will include a dominating hydropower capacity mainly based on large-scale hydro power generation providing a 26% supply share. IEA [48] projects that the coal demand in Sub-Saharan Africa is expected to grow for power generation and coal-to-liquid production. However, the immense societal and environmental burden of coal consists of the impacts of lethal chemicals and heavy metal emissions that cause severe health problems and respective high health costs aside from mortality related to air pollutants discharged through coal combustion that is nevertheless not captured. Epstein et al. [27] and the International Monetary Fund [50] have already pointed out that these high costs represent subsidies which places coal electricity in an uncompetitive position to solar PV and wind energy due to its very high societal cost. The most direct risks and hazards are presented by coal sludge, coal slurry, and coal waste impoundments; the total contributions of nitrogen deposition due to eutrophication of fresh and coastal sea water; and the extensive appraisal of impacts owing to an increasingly unstable climate [64].

This study considers the hourly system balance between generation,
demand, grid transmission, charging and discharging storage units. The storage units get charged when power generation surpasses demand, thus PV use results in reliance on battery storage, notably during night hours. This makes solar PV a key attribute of battery use. However, solar PV complements well with wind power generation, especially during night hours to cut down on battery reliance. Additional generation from flexible biomass and hydro dam plants, as well as backup discharge from large-scale storage facilitates grid utilisation and thus significantly reducing storage needs. In the integrated scenario, installed capacities for PV and wind energy increase by 40.9% and 54.9% contrasted to the area-wide scenario, correspondingly, because of the higher demand for electricity, the low cost of PV and wind energy, and enhanced system flexibility. Based on the demand projections for 2030 by IRENA [56], forecasts have a slight dissimilarity from our results. IRENA predicts that RE generation for the whole of Africa (including North Africa) will surpass 1000 TWh, attaining 50% of the total power generation. Around one-third of total power generation will come from hydropower plants with the remainder coming from solar PV, CSP, wind energy, and geothermal. The results of this study clearly indicate that a much higher RE generation could be achieved, mainly driven by low cost solar PV and wind energy.

5.7. Sustainable biomass use

The use of biomass as a replacement for fossil fuels will have a greater impact on a global scale regarding carbon emissions because biomass is considered to be carbon neutral. Biomass is the main source of energy for well over 2 billion people living in developing countries. More than 90% of Africans rely on biomass for fuel, compared to about 20% in Europe [79]. Today, traditional biomass use meets around 60% of Africa’s energy demand for heat [39]. Considerable future increases in biomass demand are expected due to the expected growth of world population, improvements in human diets, and increases related to biomass used for energy provision [59]. High, inefficient, and unregulated use of solid biomass energy is a fundamental limitation to attaining sustainability in the energy sector [81]. The growing urban population in Sub-Saharan Africa will result in higher demands for wood fuel, food, and timber, thus a potential increase in biomass use (Tilman et al., 2011). By 2050, as the world population reaches 9.1 billion, per-capita GDP almost triples, and aggregate historical trends in agricultural productivity gains continue [78]. The available land for food production has to be taken into account when biomass is used for electricity generation, especially in Sub-Saharan Africa, where the population has been increasing dramatically. Global food demand is growing rapidly, much of the world’s current cropland has yielded well below its potential, and today’s global trajectory of agricultural expansion has serious long-term implications for the environment [59]. Biomass can provide diverse sustainable alternatives to fossil fuels, plus new incomes and increased energy security for rural communities. However, for these benefits to be realized, its use must be carefully planned, implemented, and monitored for environmental and social sustainability [79]. Producing biomass feedstocks on highly productive agricultural land could result in food shortages and price hikes or simply displace food production, leading indirectly to more forest clearance. However, at a global level, there are many opportunities to develop plantations on marginal agricultural land and degraded landscapes [80]. The biomass figures taken from DBFZ et al. [24] take into account sustainability regarding land use and crops for food productions.

The role of bioenergy for the future energy mix in Sub-Saharan Africa is strongly debated. The biomass resources available for electricity production for all the scenarios under consideration in this study amount to 355 TWh/a, which is inadequate when compared to 866 TWh/a needed to cover the total electricity demand for both the region-wide and area-wide scenarios or to 1224 TWh/a required for the integrated scenario. However, renewable energy technologies could still play a vital role in cooking and water heating. Globally, 100% renewable energy would need bioenergy from an additional 250 million ha of crops (which represent 5% of global agricultural land) and tree plantations by 2050 plus 4.5 billion m³ of wood from multiple sources [78]. However, a global or a regional electricity demand can be covered by an optimal renewable mix [56, 20, 82, 32, 9]. As seen in the Greenpeace [39] Advanced Energy [R]evolution scenario, renewables can provide 68% of Africa’s total heat demand in 2030 and 91% in 2050. The future models will include additional demand sectors for heating, cooking, and mobility. Further review of the energy mix shows a complete contradiction to IEA [48] Africa Energy Outlook, which reports that bioenergy (biomass) use for cooking dominates the primary energy demand with 80% of household consumption. Based on IEA [48] projections, biomass use will reach 5699 TWh (40% of primary demand) and continue to dictate the energy mix in 2030. The measure at which wood fuel is renewable energy depends on how much is produced or consumed (IEA, 2014). Current biomass assessments and models do not take these land use efficiency measures into account [4]. IRENA [56], estimates that 70% of thermal energy demand will come from coal, oil, and natural gas. However, this comes with a high proportion of residue use (30% is a mixture of biomass and waste products).

Forests are the main sources of firewood and charcoal in Sub-Saharan Africa. Projected population growth in regions reliant on traditional wood energy, as well as demand for wood for new biomass production technologies, could expand or intensify the harvesting of forest wood [79]. Deforestation continues to be a major source of greenhouse gas emissions, biodiversity loss and habitat destruction in Africa [60]. Globally, deforestation and forest degradation drive climate change, resulting in about 20% of global anthropogenic CO2 emissions. Forests in Sub-Saharan Africa are currently largely in the hands of humans, and without intervention, it seems likely that rapid deforestation will continue while reforestation in protected areas is not enough to counterbalance deforestation elsewhere [10]. Around the world, unregulated biomass production is directly related to significant pressure on ecosystems including deforestation, fertilizer use, and pesticide application, with detrimental environmental effects such as groundwater depletion, ecosystem degradation, or biodiversity loss [59]. The ever increasing population in Sub-Saharan Africa requires more wood fuel, and this contributes to a higher proportion of deforestation. In Sub-Saharan Africa, insufficient forest protection policy has led to encroachment on protected forests, which has led to deforestation [60]. Further, developing countries have ambitious biomass targets, but lack supporting legislation [79]. Most Sub-Saharan Africa countries have electricity access targets and policies in place, but fewer have objectives and approaches related to clean cooking [48].

Traditional biomass use is characterized by low efficiency as well as adverse impacts on human health and living conditions from the high concentrations of particulate matter and carbon monoxide, among other pollutants (IPCC, 2012). In Sub-Saharan Africa, almost three quarters of those people using traditional biomass do not have access to energy efficient cooking stoves. The result is wasteful fuel use and serious health effects from wood smoke, which along with coal smoke kills almost 2 million people a year [79]. In this context, non-combustion-based RE power generation technologies have the potential to reduce local and regional air pollution significantly and lower associated health impacts compared to fossil-based energy production. Thus, additional generation from other sources is needed. The results show that wind energy and solar PV are more cost competitive in Sub-Saharan Africa compared to biomass. A closer look at the area-wide scenario reveals that the LCOE for the solid biomass, waste-to-energy, and biogas power plants are 60.6 €/MWh, 86.0 €/MWh and 78.2 €/MWh, respectively, compared to solar PV and wind energy LCOE, which are 26.1 €/MWh and 36.1 €/MWh. Therefore, solar PV and wind are more cost competitive in comparison to biomass when it comes to electricity production. As a consequence, the biomass usage in the model is still low, at 34.3% of the available sustainable resource
potential, with solid biomass, waste, and biogas producing 58.5 TWhth, or about 4% of the total generation by renewables. The synthetic natural gas and the heat generated by the system as a by-product of biogas and biomass CHP plants, waste-to-energy incinerators, gas turbines, electrolyzers and methanation units has the potential to replace some biomass used for heat purposes. Based on IEA [48], the growth in gas use is insignificant and is focused on cooking and water heating in gas-rich countries, mainly Nigeria, Mozambique, and Tanzania. As illustrated in the energy flow diagrams (Fig. 9, Supplementary material Figs. 7 and 8), the usable heat increases from 74 TWhth per annum for the area-wide scenario up to 106 TWhth for the region-wide scenario. The higher efficiency as a result of interconnectivity plays a key role in the low amount of heat generated in area-wide scenario.

The area efficiency regarding energy yield from biomass in comparison to solar PV indicates reasons for the cost differences. According to Geyer et al. [37], regardless of the crop type and growing conditions, the sunlight conversion efficiency of plants is below 1%. According to Green et al. [41], the solar irradiation to electricity efficiency of PV modules is in the range of 20%, which is also accessible in the markets. Biomass land-use for energy purposes requires 10–40 times more land than the PV based options in same locations.

5.8. Heat and synthetic fuels demand

According to the Greenpeace [39] Advanced Energy [R]evolution scenario, higher efficiency gains can be achieved in the heating sector compared to the electricity sector. About 1000 TWh can be saved as a result of the introduction of high energy standards and highly efficient technologies, e.g. for industrial and commercial process heat, cooking and air conditioning. The waste heat from biomass and gas power plants is evenly distributed over the year. Cooling demand is mainly included in electricity demand numbers and therefore does not generate an additional demand. For the integrated scenario the amount of usable heat is slightly smaller than for the area-wide scenario, at 122 TWhth, due to increased efficiency in gas turbines, which covers the heat losses in methanation and electrolysis. Synthetic fuels can also have an alternative use in mobility. Based on the Greenpeace [39] Advanced Energy [R]evolution scenario, the generation of synthetic fuels will fully substitute fossil fuels in Africa by the end of 2050. Greenpeace [39] estimates that 560 TWh will be utilized for hydrogen generation and 790 TWh for synthetic liquid fuel generation intended for the transport sector. Fasih et al. [33,32] conclude that renewable electricity based synthetic fuels are a real option for decarbonizing the energy system for the period of the year 2030 and beyond. The findings for the Sub-Saharan Africa 100% renewable resource-based energy system clearly show the potential of the region for RE generation and for a global climate change mitigation strategy. The results of a fairly low LCOE for the year 2030 (in all the considered scenarios) added to the already existing RE policies and low carbon development plans can boost the development of a renewable power system in Sub-Saharan Africa in the coming decades.

5.9. Competitiveness of 100% RE

Renewable energy technologies are cost competitive compared to the high cost alternatives; for instance, the low carbon based energy systems and non-renewable options, such as nuclear energy, natural gas and coal carbon capture and storage (CCS), as highlighted by Agora Energiewende [2]. The LCOE of the alternatives are as follows [2]: 112 €/MWh for new nuclear (assumed for 2023 in the UK and Czech Republic), 112 €/MWh for gas CCS (assumed for 2019 in the UK) and 126 €/MWh for coal CCS (assumed for 2019 in the UK). According to Ram et al. [69], coal CCS CAPEX are around 3891 €/kW in 2030, while the LCOE is around 105 €/MWh. For gas CCS, the CAPEX range from 1934 €/kW to 2118 €/kW in 2030, the respective LCOE ranges from 94 €/MWh to 130 €/MWh. According to Breyer et al. [15], the CAPEX assumed for nuclear range from 6200 €/kW in 2015–6000 €/kW in 2020. Representatives from South Africa’s largest utility and policy, where the only nuclear energy programme in SSA is operated, mentioned in early 2018 that nuclear would be not at the top of the agenda and that South Africa simply could not afford nuclear [30]. A report published by the European Commission [29] concludes that CCS technology is not likely to be commercially available before the year 2030. The findings for Europe are assumed to be also valid for Sub-Saharan Africa in the mid-term. Research from climate change modeling, such as Griffin et al. [40] conclude that not having CCS and nuclear energy would be too high in cost and therefore not possible. However, in Luderer et al. [62] and its Supplementary Material, it is stated that the 2050 CAPEX assumptions for solar PV and wind energy in Griffin et al. [40] are 1200–1400 USD/kW and 1000 USD/kW, respectively, which is fine for wind energy but fully wrong for solar PV since we already have today CAPEX which is 10–20% lower and the learning curve is continuing [13,34,77]. More realistic CAPEX assumptions would be 300–400 €/kW in 2050 according to Vartiainen et al. [77]. Such limited solar PV industrial insights are a key reason why in many energy scenarios a misleading conclusion is drawn, that fossil-CCS and/or nuclear fission would be without any alternative.

The 100% renewable resource-based energy system options for Sub-Saharan Africa presented in this work seem to be considerably lower in cost (about 48–57%) than the other alternatives, which have still further disadvantages. Globally, the end use combustion of carbon fuels is the principal source of potential CO2 emissions, accounting for about 90% of total estimated emissions, on average [44]. Climate change mitigation is one of the key driving forces behind a growing demand for RE technologies. The price of emissions could influence electricity prices, so as to reduce fossil fuel consumption and to promote cleaner technologies with benefits related to air quality and climate change [35]. Castellano et al. [20] conclude that, if Sub-Saharan Africa aggressively promotes renewables, it could obtain a 27% reduction in CO2 emissions; this would result in a 35% higher installed capacity base and 31% higher capital spending, or an additional 153 billion USD. The uncertain future value of CO2 emission abatement will not affect the renewable energy drive in Sub-Saharan Africa. Bazilian et al. [5] foresee a decrease, in relative terms, of carbon-intensive resources in Africa in the coming two decades, even without an explicit focus on climate change mitigation. In addition to reducing GHG emissions, renewable energy technologies can also offer benefits with respect to air pollution, health, and overall welfare compared to fossil fuels. These benefits are related to reduced risks of nuclear melt-down and terrorism, unsolved nuclear waste disposal, remaining CO2 emissions of power plants with CCS technology, a diminishing conventional energy resource base, and high health cost due to heavy metal emissions of coal-fired power plants. Further nuclear energy produces both operational and decommissioning wastes. The radioactive waste possesses a threat to the environment and is unsafe for humans. The Chernobyl and Fukushima nuclear melt-downs have shown the disastrous effects of nuclear radiation on humans. Nuclear energy also calls for massive subsidies required for development and operation, and loan guarantees. Dittram [26] also emphasizes the mentioned limitations on nuclear fission, but also points out that the financial as well as human research and development resources spent towards nuclear fusion are both no help towards solving the energy problems in the world and, even worse, these resources are not available for research of pathways towards a low cost energy future.

Policies to promote renewable energy have been established in many African countries over the past decades, but the legal and regulatory frameworks remain inconsistent. Vested interests in the current fossil-based power sector and unwillingness to adjust existing business models are some of the barriers to renewable energy development in the region. However, diverse opportunities to explore renewable energy in SSA will involve establishment of regional cooperation and renewable energy transmission corridors. In addition, decentralized...
approaches to connect off-grid areas provides a better opportunity to harness the renewable energy resources in the region [68]. A 100% RE-based system is achievable and a real policy option in SSA. Policy action that will restrict new investments in conventional power technologies and enhance RE development is exigent from a long-term perspective.

The findings for the Sub-Saharan Africa 100% renewable resource-based energy system illustrate the capability of the region for RE generation and a global climate change mitigation scheme. The result of a rather low LCOE for the year 2030 (in all the considered scenarios), added to existing RE policies and low-carbon development programs, can boost the development of a renewable power system in Sub-Saharan Africa in the future years.

6. Conclusion

This research work establishes that a 100% renewable resource-based energy system is a technically and economically practical solution for Sub-Saharan Africa. RE technologies can generate sufficient power to provide for all electricity demand in Sub-Saharan Africa for the year 2030 at a low overall cost of 47–58 €/MWhel, and this depends on the intensity of geographic integration and energy sector coupling. The power required to cover PtG technology, and SWRO desalination demand can be produced by RE resources, providing the region with 100% renewable synthetic natural gas and clean water delivery. However, the synthetic gas price is perhaps high compared to current levels, and government regulation and subsidies are still needed to ensure the commercial viability of this synthetic fuel.

In the recent past, the crucial issue of dependency on biomass energy has widely contributed to deforestation in various countries in Sub-Saharan Africa. This problem can be dealt with by shifting to a least cost energy mix with additional generation from solar PV and wind energy. The HVDC interconnection of the sub-regions and the integration of gas and desalination sectors significantly influences the mix of renewable technologies and thus the storage requirements for the energy system. This results in a reduction of the required generation and storage capacities, thus reducing the total LCOE. Meanwhile, PV self-consumption causes a moderate increase in total electricity costs of about 3–4%, which may be outweighed by other positive effects.

Indigenous SNG generation as seen from the integrated scenario increases demand side flexibility and can also be used for long-term storage as a by-product service as a consequence of reducing reliance on battery storage. The system further can curtail heat losses through SNG production, and this results in flexibility and system cost reduction.

A fully integrated renewable energy system has to be simulated and deeply studied to understand the findings for Sub-Saharan Africa better. However, this research work indicates that a 100% renewable resource-based energy system is a real low cost option for the near future.

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Appendix A. Supporting information

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References
