Identification of advantageous electricity generation options in Sub-Saharan Africa integrating existing resources

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Abstract

Pioneering approaches are needed to accelerate universal access to electricity while simultaneously transitioning to reliable, sustainable and affordable energy systems. In Sub-Saharan Africa (SSA) the challenges lie in attracting the private sector to complement public investments. Here, we present an integrated "low-hanging fruit" approach aimed at boosting private investment and speeding up the deployment of renewable energy systems in SSA. We analyse the potential of existing energy infrastructure, where a significant up-front investment has already been made, to be exploited for electricity generation. We develop a comprehensive methodology to identify and select suitable locations in SSA and estimate their potential for exploitation. These locations have been further analysed in terms of power capacity potential, electricity output, investments needed and population to be benefited. This strategy to attract additional finance can easily be reproduced, engaging private investors while simultaneously helping to achieve the UN Sustainable Development Goals on energy.

Most countries in Sub-Saharan Africa (SSA) are still struggling to escape from "energy poverty"; nearly 70% of the population does not have access to electricity (approximately 621 million people) [1]. If the conventional strategies are maintained, energy poverty will continue to rise and diverge among regions. In SSA, large hydropower and nuclear plants have frequently been considered but only a few were implemented, and projects of 3.5-4.8 GW have been stalled for a decade [2, 3]. The associated cost is so high that neither the public sector nor the private sector alone could fully finance such large-scale endeavours. As a result, power markets in SSA have been stagnant in recent years, with the growth displayed up to 2008 largely stalled [4]. Therefore, new approaches are needed to rapidly increase energy access by transitioning towards modern and decarbonised energy systems.

Many countries in SSA fail to reach past energy access goals for a number of barriers [5, 6]. More than 30 countries in SSA suffer from systematic generation shortages [7] and the grid infrastructure urgently needs refurbishment [8]. Many regional energy plans emphasise investments in grid extension as the major means of energy provision [9–11]. However, in most rural areas the absence of the grid, the geographically sparse population, and low per capita consumption, make grid extension a very expensive option. Electricity consumption in such communities is likely to remain low for the foreseeable future [12], which makes it unlikely that the cost of grid extension could be recouped. It is unrealistic to expect these countries to make more than modest increases in access via grid extension until the capacity constraint is eased. An additional barrier in most SSA countries is weak implementing capacity. This entails new or amended legislation, institutional strengthening, planning, and establishing technical standards and regulatory procedures.

SSA provides one of the classic examples of technology trumping traditional infrastructure [13]. The introduction of mobile phones has allowed millions of Africans to receive the social and economic benefits of telephone networks without the sunk cost of massive land-line infrastructure. The conventional approach to electrification, installing large power plants and extending the grid to new consumers, is neither appropriate nor pragmatic for the majority of non-electrified communities in SSA. The new ambitious SDG-7 targets could be more easily achieved following an analogous pathway for energy access, effectively "leap-frogging" traditional model of grid-based energy development. Moving to an affordable, reliable, sustainable and full-coverage energy system, will need unprecedented mobilisation across many sectors: a complex global interplay of research and development, public and private investments in renewable power generation [14]. The research community has been promoting alternative approaches that utilise distributed generation to increase energy access [15–18] and international development organisations have published numerous studies examining paths toward universal sustainable energy access [1, 19–21].

There are two correlated prerequisites that must be satisfied if these approaches are to gain much needed momentum: finding more competitive electrification options in place of grid extension and finding strategic ways to attract additional finance. To satisfy the first precondition, we propose that SSA leapfrogs conventional centralised fossil-based electrification by prioritising indigenous RE technologies [15, 22]. On a geographical basis, the economics of distributed options versus grid extension show that in most of SSA, distributed RE-based generation outperform both diesel-based distributed systems and grid extension. Energy projects, particularly renewable technologies, face capital constraints. High upfront costs often prevent investors from implementing such projects. However, there are numerous "low-hanging fruits" that could represent initial, important steps to accelerate private investment in sustainable energy.

Here we analyse existing energy infrastructure in SSA, where a significant up-front investment has already been made, but renewable capacity additions or fuel provision could substantially increase access. Specifically, we propose three transformation options: first, electrifying existing dams; second, adding PV systems to existing diesel-powered mini-grids; third, taking advantage of existing coal-fired power plants and sugar industries to exploit biomass resources in a more efficient manner (bagasse co-firing). Increasing the share of renewable energies in the electricity generation portfolios can lower the risks associated to the electricity systems [16, 23]. However, in the SSA context the country-specific risk can surpass the various benefits. Therefore there is need for additional mitigation measures [24]. The present study focuses on the risk components that can be mitigated by investors. Identification of the least-cost projects among the various options will help the private sector to get a competitive edge through learning-by-doing, and in this way to lower the operational, management and investment risks [25]. These lower-cost, lower-risk options can be implemented more quickly than similarly sized energy facilities built from scratch.

The low-hanging fruits approach

In energy analyses, the term "low-hanging fruit" is used primarily to refer to energy efficiency projects [26]. In a pioneering study on energy efficiency by McKinsey-EIA [27], a merit order of energy efficiency options was composed. The low-hanging fruits represent the most straightforward investment opportunities, because they are readily achievable and do not require a lot of additional efforts. Picking the low-hanging fruit is an investment strategy that companies can adopt to boost implementation of projects and gain valuable experience with minimal cost. Following this concept, low-hanging fruit in this analysis takes a twofold meaning. On one hand it refers to projects that have favourable investment characteristics: part of the investment is already made and the remaining investment has a high payback, because it will start producing net income earlier and quicker than projects starting from scratch. On the other hand, the proposed concept also builds on already existing human capacities: technicians and managers are already operating and maintaining the infrastructure. Tapping into such existing local expertise is a key advantage: specialists and their contribution to training additional personnel can be a decisive factor in securing investment.

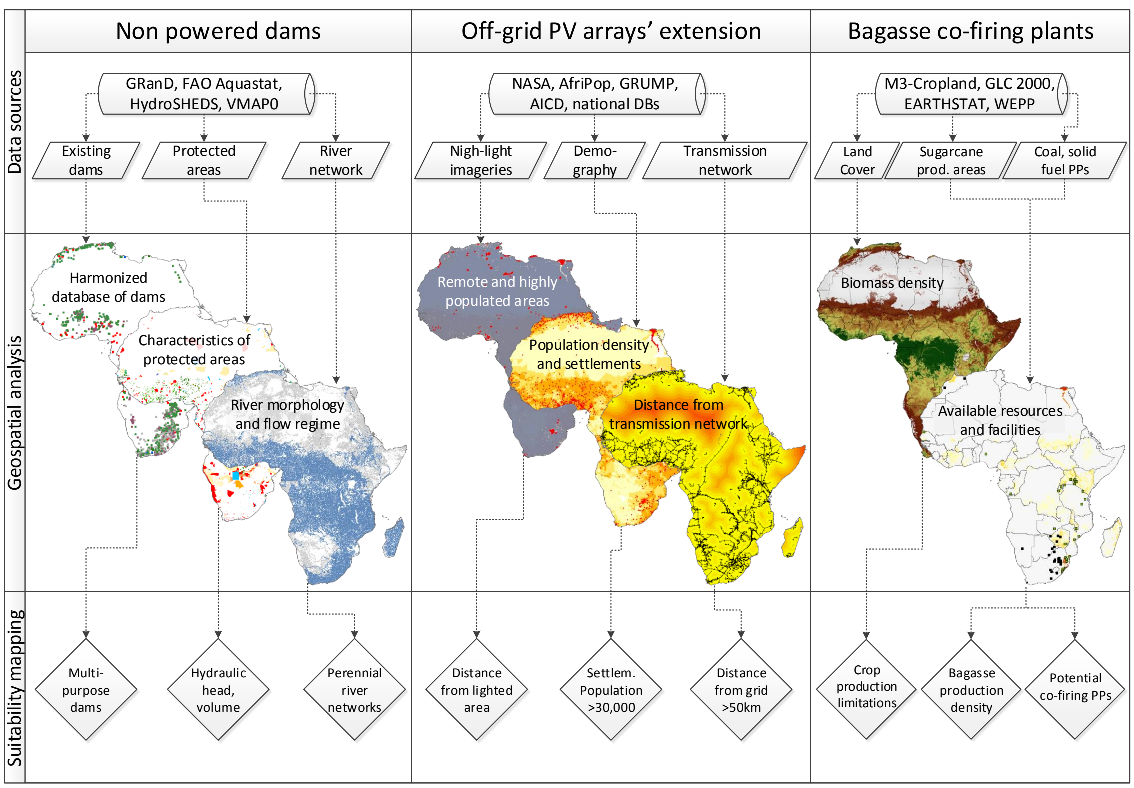


Figure 1: Workflow to identify low-hanging fruits for RE development in SSA. GRanD: Global Reservoir and Dam Database; FAO Aquastat: Global water information system of Food and Agriculture Organization of the UN; HydroSHEDS: Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales; VMAP0: Worldwide coverage of geo-spatial data, AfriPop: High spatial resolution, contemporary data on human population distributions, Africa; GRUMP: Global Rural-Urban Mapping Project; AICD: Africa Infrastructure Country Diagnostic; DBs: Databases; GLC 2000: Global Land Cover 2000 JRC project; WEPP: Platts World Electric Power Plants Database; PPs: Power plants.

We aimed to develop a comprehensive methodology to identify, select and estimate the potential contribution of low-hanging renewable energy fruits in SSA. Figure 1 illustrates the process followed for each resource. Firstly, the available data were collected, harmonised and verified. The data was processed spatially and various GIS layers were developed. By analysing and superimposing each layer, the suitable locations for exploitation were identified. These locations were further analysed to estimate power capacity potential, expected electricity output, and the population that could benefit by accessing the resource.

Transforming African dams

SSA has a large number of dams that are not currently producing electricity. These Non-Powered Dams (NPDs) were constructed for one or more non-energy purposes (e.g. irrigation, flood control). A subset of these dams, which meet certain conditions, are attractive low-hanging fruit because they can easily be retrofitted to produce electricity. Such a practice would quickly increase electricity production across SSA in a similar way to the one recently implemented in the USA and India, where between 1997 and 2008 about 500 MW have been developed on existing facilities [28]. In 2018 the utilisation of existing infrastructure in the Missouri river is expected to start its operation and the planned Red Rock station will have an estimated power capacity of 36.4 MW. The conversion of six more NPDs along the Ohio River will add a combined 350 MW of new hydropower capacity [29]. The possibility to convert NPDs to pumped hydropower schemes has also been examined in recent studies [30].

(a) (b) (c)

Figure 2: Aerial images of three classes of Non-powered dams (NPDs). (a) Not suitable for transformation, (b) Suitable for mini-scale (<1 MW) hydropower station, (c) Suitable for larger (>1 MW) hydropower station. Source of aerial photos: Google Maps.

With this strategy, most of the monetary costs and environmental impacts of the facility have already been incurred. Dam construction is associated with up to 70% of the total cost of a hydropower station. Thus, installing electrical generation at NPDs can cost as little as \$500/kW, compared to \$1050-8000/kW for "greenfield" facilities [31]. Additional advantages arise because of NPDs' existing road network that facilitates access, retrofitting works and maintenance. NPDs are generally connected to the grid in order to operate their own machinery (e.g. operation of pumps, sluice gates). These characteristics are expected to reduce the cost of feeding the produced hydroelectric electricity to the grid. Irrigation NPDs' proximity to rural, agriculture communities supports the development of hydropower-based independent mini-grids. The presented approach involves lower technological and business risk and faster implementation time, as the dam, the most complex element of the facility, is already in place.

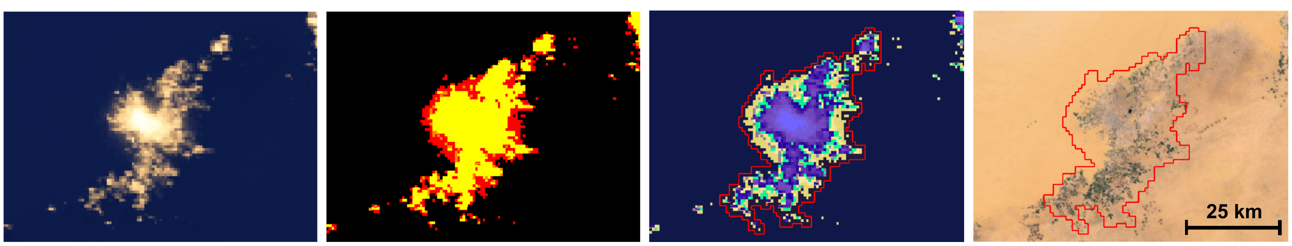
The minimal additional environmental impact implies faster licensing and implementation, which is particularly important for the investors in the SSA context.

Hundreds of African NPDs were identified and analysed (Figure 2, section "Methods"). From them, 91 NPD sites were selected. Of these, 52 have a potential to generate >1 MW and 39 have a mini-hydro (<1 MW) potential (Figure 4, Supplem. Note 2). The aggregated power capacity is at least 250 MW and could benefit approximately 3.5 million people (Table 2).

Integrating PV into decentralised rural mini-grids

We identified the low-hanging fruit option for solar technologies in SSA as the integration of PV systems into existing distributed mini-grids. PV module prices have declined dramatically and, under some circumstances, PV is now cost-competitive with incumbent technologies [32]. This cost competitiveness is reflected by the background colours in Figure 4, which highlight the regions where off-grid PV, mini hydro, and diesel options are projected to be more competitive than grid extension (see Supplementary Methods). Combining PV with the existing diesel mini-grids can result in half the electricity cost of "greenfield" PV mini-grids [15]. This is achievable by reducing the number of batteries required (which usually constitute 40% of the total system cost) and taking advantage of the existing distribution grid and metering equipment.

The methodology we implemented to localise existing diesel generators uses high-resolution satellite images of the amount of light emissions observed from the Earth's surface from night lights [33], combined with spatially explicit datasets (Figure 3; detailed presentation in Methods section and Supplementary Note 1).



(a) (b) (c) (d)

Figure 3: Analysis of night light satellite images. (a) Lighted area as a subset of the NASA image compiling data captured by a sensor aboard the NASA-NOAA Suomi NPP satellite. Spatial resolution: 750 m. (b) Processed signal in three classes re-sampled to 1 km resolution. Yellow: lighted area 75-100%, orange: lighted area 50-75%, red: lighted area <50%. (c) Delineated zone based on adjacent pixels with light signal within 1 km. Pixel colours derive from pseudo-colour composite of light signal. The red polygon encompasses a remote settlement potentially using diesel generators. (d) Verification of settlement localisation using aerial imagery. The modelled zone marked by red line represents a town rather than other light sources (e.g. gas flaring). Population is estimated by overlapping population data with the red polygon. The presented settlement has 125,000 inhabitants.

This methodology suggests 79 settlements in which PV arrays of 150-500 kWp could supplement the existing distributed mini-grids (Figure 4). In these settlements, the capital investments to add PV to existing diesel-based mini-grids would cost 35-50% less than installing new PV systems. Moreover, PV would increase the quality of energy services, reduce dependence on imported diesel fuel, and reduce environmental impacts associated with diesel transport and combustion for more than 10 million people (Table 2).

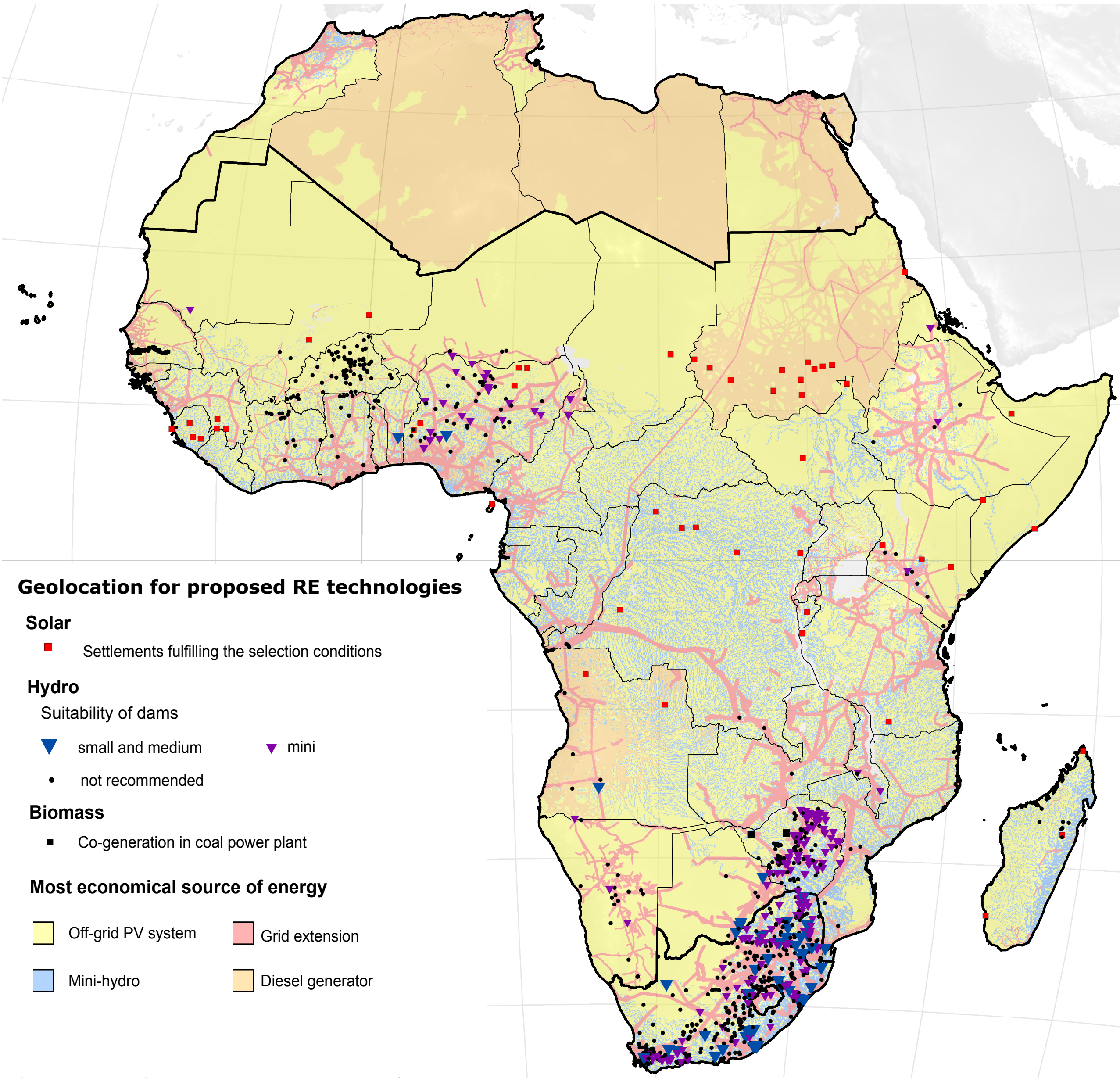


Figure 4: Identified low-hanging fruits of renewable energy in Africa. Supplementary Tables 1 and 2 provide detailed information and hyperlinks to the selected sites.

Bioenergy

Biomass is a widely used energy resource throughout sub-Saharan Africa. However, the majority is burned in small-scale inefficient devices for residential cooking and heating needs [34]. There is a large potential to increase both the quality and quantity of energy services derived from biomass [35], but many of these options are not low-hanging-fruit because the technologies are not mature and the existing institutional arrangements are inadequate to support rapid low-cost deployment in the region. Nevertheless, a few readily deployable biomass electrification options do exist. One example is bagasse (sugarcane waste), which is already used widely in many sugar-producing nations [28, 36]. Bagasse can be used in dedicated biomass-fired power plants, which are typically located at sugar refineries and provide the facility with both heat and power. Bagasse can also be co-fired in nearby thermal power plants. Mauritius represents an interesting example of bagasse co-firing. Sugar refineries provide close to half of the island nation's electricity supply, with roughly half of this derived from bagasse used during the cropping season. The balance is derived from coal, which is burnt during the off-season [37]. In Mauritius, dual-fuel boilers are utilised, but it is equally feasible to co-fire bagasse in boilers originally designed for coal, with minimal retrofitting, particularly in grate-fired boilers, as are utilised in Mauritius [38, 39]. In addition, co-firing with bagasse can actually improve coal reactivity and increase combustion performance compared with coal burned alone [40].

To incorporate bagasse electrification into the spatial analysis, the most advantageous regions for sugarcane production in Sub-Saharan Africa were identified (section "Methods"). However, given the sitting of existing coal plants, there is currently limited opportunity for co-firing with bagasse. Additionally, we identified 5 locations (see Supplementary Note 3) where bagasse power plants [36]. However, only a few of the identified power plants are located a reasonable distance from sugarcane production implying/assuming the bioenergy technologies are still not ready for a scale-up as a low-hanging fruit option.

Scaling up private investment to meet the challenge

Significant investments, from both the public and private sectors are needed to reach SDG-7 goals [21]. By one estimate $17 billion of annual investments are needed to achieve universal access to electricity in SSA, a six-fold increase compared to the level of investment in 2010, which was about $2 billion [19]. In a separate analysis, the African Development Bank estimates that $42 billion per year will be needed to meet Africa's energy demand by 2040; this includes a tenfold increase in private investment over the current levels [20].

Table 1: Actual/required annual investment to reach universal electricity access goals by UN [41], World Bank [42], and IEA [43].

values in $billion	**UN (2012)**	**World Bank (2010)**	**IEA (2009)**
Actual investment	9	7	9.1
Required investment	45	34	35
Finance gap	36	27	26

The multilateral development banks (MDBs) and the IMF state that to fill the gap in investments (Table 1), additional capital inflows must come from two sources: public domestic finance and private investment, which is the largest potential source of additional funding [42]. Sufficient funds will not be mobilised without adequate institutional capacity, which remains limited in countries throughout the region. Crucially, demand-side energy efficiency, when coupled with innovative off-grid energy supply solutions, can transform energy access markets by increasing the affordability of energy services [6]. The energy efficiency and RE goals have already mobilised huge private sector contribution at a global level: $388 billion has been mobilised globally [41]. The required mobilisation will not be met by only setting up the necessary financial schemes. It also requires overcoming the inadequate institutional capacity, which remains a barrier in most of the SSA countries. Possible mitigation measures are presented in the conclusions and outlook section. The discussion below focuses on finance for the supply side, where the private sector should be crucially engaged from the start to cover the finance gap necessary for universal access to electricity ($26-36 billion).

Table 2: Projects' distribution: resulted power, consumers and investment (€million).

	Non-Powered Dams			Solar PV and Bagasse*		
Country	**Power [MW]**	**Number of consumers**	**Estimated investment**	**Power [MW]**	**Number of consumers**	**Estimated investment**
Angola	1.1	44,000	1.7	15.0	230,000	12.0 – 22.5
Benin	2.0	80,000	3.0	/	/	/
Botswana	4.1	164,000	6.2	/	/	/
Burundi	/	/	/	5.0	73,000	4.0 – 7.4
Cameroon	0.4	16,000	0.6	/	/	/
Chad	/	/	/	9.7	150,000	7.7 – 14.5
DR Congo	/	/	/	91.5	1,300,000	73.2 – 137.3
Eq Guinea	/	/	/	6.9	90,000	5.5 – 10.4
Ethiopia	0.2	8,000	0.3	/	/	/
Guinea	/	/	/	16.1	235,000	12.9 – 24.1
Kenya	0.2	8,000	0.3	14.0	210,000	11.2 – 21.0
Lesotho	0.7	28,000	1.100	/	/	/
Madagascar	/	/	/	37.7	550,000	30.1 – 56.5
Malawi	0.3	12,000	0.5	19.6	305,000	15.6 – 29.3
Mauritania	0.2	8,000	0.3	/	/	/
Mozambique	0.5	20,000	0.8	/	/	/
Namibia	0.3	12,000	0.5	/	/	/
Nigeria	2.9	116,000	4.4	44.8	650,000	35.9 – 67.2
Sierra Leone	/	/	/	148.9	2,100,000	119.1 – 223.4
Somalia	/	/	/	80.5	1,400,000	64.4 – 120.7
South Africa	223.0	3,000,000	334.5	/	/	/
South Sudan	/	/	/	11.0	170,000	8.8 – 16.5
Sudan	/	/	/	146.3	2,400,000	117.1 – 219.5
Swaziland	0.9	36,000	1.4	/	/	/
Tanzania	/	/	/	31.8	550,000	25.4 – 47.7
Zimbabwe	6.7	268,000	10.1	200*	900,000*	40.0 – 150.0
Sum	243.5	3,820,000	365.7	878.8	11,313,000	582.9 – 1,168.0

Conclusions and outlook

The UN has set the ambitious goal of reaching universal access to electricity in less than 15 years [41]. Indigenous renewable energy sources can play an important role in reaching unelectrified populations in SSA, where conventional fossil fuel grid extension methods have failed. However, the SDG-7 goals will not be achieved with business-as-usual approaches, which are financially unattractive and lack sufficient motivation for the private sector to invest.

This analysis describes a new approach for the private sector to accelerate investment decisions that have higher impact on human and economic development for the funds invested. If the proposed PV addition option are realised, the estimated investment required to meet SE4All's projected off-grid installation targets could be reduced by 40% ($3 billion), while providing access to over 10 million people (Table 2) [43]. Similarly, the proposed NPD retrofits could save $1.2 billion (60% of the overall investment cost), and the bioenergy option, though limited, could reduce fossil fuel expenditures by $100 million, assuming efficiencies achieved in Mauritius. This considerable cost saving would lower barriers to investment by reducing the upfront costs and ensuring positive cash-flow with a much shorter time than greenfield investments, reducing the risk that investors abandon projects at an early stage. Projects' implementation would be cheaper and much shorter. Therefore they would start paying back earlier eventually leading to much lower risks and scaling up the investors' appetite for financing projects.

Table 2 illustrates the estimated number of beneficiaries per country, showing that if all the identified proposed projects were implemented, 15.4 million people in SSA would benefit. Although this represents only a 2-3% of the unelectrified population, this approach identifies projects that can provide genuine momentum to scale-up renewable energy investments for the private sector. Investors attempting lower cost, lower risk options may be motivated to scale-up their operations in SSA, increasing their participation in distributed and multipliable investments, and stimulating the growth renewable energy options. After decades of standstill, Sub-Saharan Africa can accelerate access to electricity by scaling-up the low-hanging technologies based on indigenous energy resources. Sustainable, affordable and independent source of energy could preserve the communities' present living environment.

To take advantage of existing infrastructure, dam infrastructure is suitable for PV installation if oriented appropriately [44, 45], which further increases the power potential of NPD sites. The combination of PV and hydropower could achieve a smoother, more stable output. The present research, which was limited to small towns of 30,000-50,000 inhabitants, could also be expanded to consider rural settlements with lower population densities.

Despite the relative small power output envisaged by the "first-run" of picking the low-hanging fruits (1.1 GW), diesel and bioenergy technologies offer a clear potential for quickly scaling-up their market. Indeed, at least 1.8 GW diesel generators are already operational in SSA. Moreover, the estimated 250 MW hydro additions are not negligible as they account for 7% of the existing mini/small scale hydropower capacity in Africa [46].

Although the role of bioenergy in this analysis was limited and solely focused on opportunities that leverage existing infrastructure, similar opportunities to bagasse occur in other agricultural industries or dedicated bioenergy pathways like short rotation woody crops. SSA countries will continue to derive a large fraction of their primary energy from biomass. While the vast majority is currently utilized in small, simple devices for residential and small-scale commercial applications, several assessments have noted that the region has a vast potential to expand and modernise the ways in which bioenergy is utilised, including substantial electricity production [28, 47].

This study utilised the latest available datasets and satellite images. The solar PV integration analysis was based on the most recent night time light dataset, the existing transmission network in 2013, and the consumption figures from the latest Global Tracking Framework [21]. The projects identified provide a baseline on which further research could be conducted, given that updated information becomes available. The latter may include updated night light satellite imagery of higher-quality as well as updated electrical network datasets. Naturally, amended datasets and information would alter the number and/or location of potential projects and identify new low-hanging fruit opportunities.

Similarly, increased availability of reliable electricity consumption data could support case-by-case analysis and more accurate estimation of the potential contribution of identified projects. Per capita consumption patterns are related to systems' power capacity design and are expected to increase in the future as a result of global efforts as SE4All [21]. More accurate information of load consumption curves would also allow near-optimal design and sizing of the identified low-hanging fruit mini-grids and facilitate planning, investment and implementation.

The few low-hanging biomass options, such as bagasse-based co-generation and co-firing biomass in thermal power plants, have limited potential to upgrade or expand. This is due to geographic disparities between existing thermal generation capacity, which is concentrated in Southern Africa, and sugarcane production, which is spread throughout the region [48]. Nevertheless, there are ample biomass resources available throughout the region and bioenergy has substantial potential for future development in SSA. Additional research is required to identify existing expertise that can be leveraged and pinpoint the most promising feedstocks and pathways from a range of options including livestock and municipal solid waste, agricultural residues, and dedicated energy crops [49, chapter 11].

Methods

Analysis of non-powered African dams. The methodology identifies the most suitable NPDs for energy production based on estimations of hydraulic-head, volume, seasonality of flow, and environmental constraints. In order to estimate the hydropower potential in each dam it is required to know the available hydraulic head (H) and the seasonal-monthly water discharge information that define the design flow (Q). This information can support estimations on expected power (energy yield) through the following Equation 1:

$$P = n \times \rho \times g \times H \times Q \tag{1}$$

P: power, n: dimensionless efficiency coefficient, ρ: water density
g: gravitational acceleration, H: hydraulic head, Q: design water flow.

This approach, when applied over a large area and for a large number of dams, will inevitably include assumptions and approximations that result in a degree of uncertainty. Therefore, such analysis can be regarded as appropriate only for reconnaissance-level studies [31]. In the context of SSA, the lack of consistent hydrologic data further increases the uncertainty [50]. In order to overcome this limitation we developed an empirical approach to roughly estimate their potential power capacity.

Initially we excluded dams placed in protected areas. Moreover, dams with particularly small storage capacity and very low head (<5 m) have also been excluded, due to their low potential, which is not expected to justify the investment. In order to estimate the available hydraulic head we used information on the dam height contained in the datasets. Depending on the geographic setting, some NPDs would have the turbine installed in the body of the dam, while others might need the turbine installed in the vicinity, using a diversion canal to transfer water from the dam. Taking this into account, we estimated the hydraulic head, also considering information on water levels and the possible placing of the electro-mechanical equipment.

The reservoirs' water capacity and surface area provided indications on the design water flow. Assuming different utilization periods of the dam's capacity for the different climate areas and uses, resulted to estimations of the design flow and eventually, using Equation 1, of power. In order to streamline the analysis, power estimations were juxtaposed with capacity information of existing hydropower dams.

Due to the uncertainties involved, these estimations can only provide general indications on the available power. We have, thus, classified the suitable NPDs to different size categories, micro/mini/small/large (Figure 2) and avoided providing hard numbers. Hydropower size categorisation varies among countries [46], therefore we adopted a definition that aligns with the majority of SSA countries' definition: large-scale (>10 MW), small-scale (between 1 and 10 MW), mini-scale (between 0.1 and 1 MW), micro-scale (less than 0.1 MW).

Night light and population data. In Sub-Saharan Africa, obtaining reliable data on existing diesel-based mini-grids is a challenging task. Systematic data of the location and capacity of such installations is simply unavailable. Existing datasets lack specific geo-locations and cover only systems with a capacity of more than 1 MW.

The present analysis addressed this limitation by combining three independent spatial datasets: In the first step, lighted areas far from known transmission networks have been delineated based on the light signals of NASA Earth Observatory 'Earth at Night' imageries in the resolution of 750 m [33]; where an image pixel showed a light signal, that pixel was assigned to the group of cells forming a binary map of lighted/dark areas. In the second step, population data from two data sources have been involved. The first demographic dataset is the vector-based "global rural-urban areas dataset" GRUMP [51] including populated places on medium- or large-sized settlement scale. Where the GRUPM data including 30k+ settlements was matching with the remote lighted areas the model considered them as a subset of potential locations (about 140 sites). The second approach applied the raster-based AfriPop data providing population density distribution in Africa in the resolution of ≃1 km^2 at the equator [52]. After the necessary harmonisation of reference systems and re-sampling operations, the total number of population covered by adjacent lighted cells was calculated and considered as a potential location (about 111 sites). In order to minimise the uncertainty rooting in the scarce demographic information, the model considered the intersection of the two subsets of delineated areas (79 sites) as derived from the two independent datasets on demography.

Proximity to the existing grid infrastructure was analysed based on the existing transmission network in Africa that was collected and harmonised for the study. The distance between the identified lighted settlements to the existing grid was then calculated to allow comparison among the various options. The principal data source is the GIS database of the "Africa infrastructure country diagnostic" [53] that was updated with available national grid data. The thematic layers of the grid infrastructure are illustrated in Supplementary Methods.

Data processing and multi-criteria evaluation. Based on the described datasets we developed a methodology to distinguish existing diesel-based mini-grids from hydropower mini-grids and gas flaring sites. In that sense rural areas with electricity were detected from light emissions, using GIS tools to process the afore mentioned spatially explicit datasets. Accordingly, a four-step analysis was developed to process the images, shown in Figure 3. Thus, lighted settlements located far away from the existing transmission network were selected based on the following spatial, multi-criteria evaluation: Firstly, a strong night light based on NASA imagery was identified. The distance from the transmission network was more than 50 km, while the zone around lighted areas was set to a radius of 10 km to also include peri-urban areas.

The delineated areas with night light signal were then overlaid with the mentioned demographic datasets [51, 52] in order to identify the subset of populated areas fulfilling the pre-set conditions on size of target population.

The criterion for the settlement population has been defined at 30,000 according to the vector-based GRUMP data for the year 2000 [51] and at 50,000 for the raster-based population density data (to include the semi-urban areas) for the year 2010 with the projection to 2015 [52]. The multi-criteria evaluation approaches involving the combined thresholds on population ($> 30,000$ and $> 50,000$), the distance from the transmission network (50 km) and the delineation of night light signals resulted in 79 locations (Figure 3) as settlements with electrified by diesel genset.

Calculation of consumers and investment. We assumed a 100 kWh/year electricity consumption per capita that is in the middle of values used by the SDG Tracking [21] (365 and 1200 kWh per annum per household). The medium value was selected to obtain a conservative estimate of the number of beneficiaries. The only exception was South Africa for which we used a 300 kWh/year/capita value, since in this country the average consumption is higher than the other SSA countries.

For the NPDs in the calculation of the consumers we assumed 4000 hours/year operation and €1500/kW investment cost (40% of the total investment cost for micro-hydro power plants). Further information on the system cost for mini hydropower along with the assessment of the available mini-hydro resources in Africa is provided in the "Methods" section.

The calculation of the number of beneficiaries for the PV project was based on the population figures of the identified settlements. We assumed that the population in the lit settlement already had access to electricity through connection existing mini-grids and that the integration of PV into the mini-grid will improve the quality of the provided service and reduce the fuel costs. We have used the irradiation figures from PVGIS [54] for the investment cost calculation for each country. The lower and upper threshold for the PV 800-1500 €/kWp module price.

The costs calculation for bagasse co-firing was based on the REN21 report data [55]. This provides estimations for the co-firing costs ranging between 200-800 $/kW (180-700 €/kW). According to [56], a new coal plant costs ≃3000 $/kW. Accordingly, the additional required investment in Zimbabwe (Table 2) was estimated based on min (10%) and max (30%) range of the new plant cost.

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Additional information

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