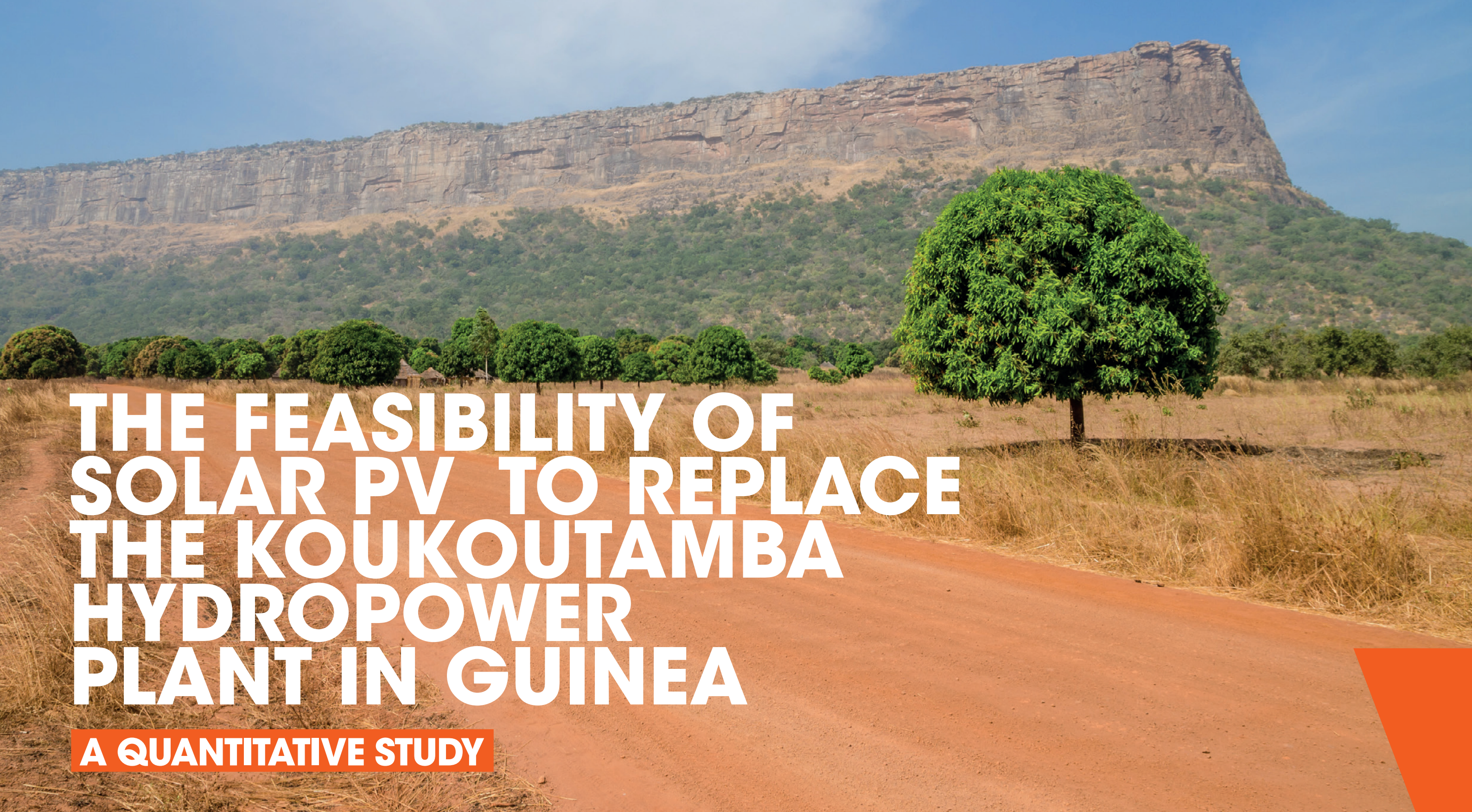

THE FEASIBILITY OF SOLAR PV TO REPLACE THE KOUKOUTAMBA HYDROPOWER PLANT IN GUINEA

A QUANTITATIVE STUDY

VRIJE UNIVERSITEIT BRUSSEL

THE FEASIBILITY OF SOLAR PV TO REPLACE THE KOUKOUTAMBA HYDROPOWER PLANT IN GUINEA

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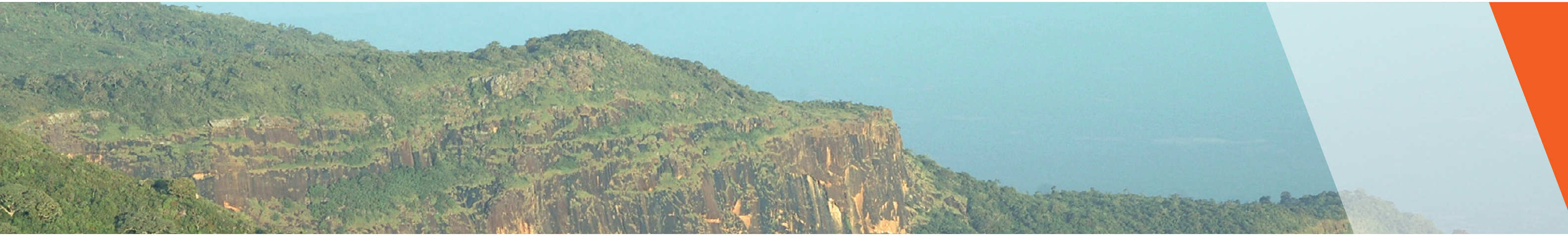


CONTENT

INTRODUCTION

The West African nation of Guinea is known as the “water tower” of the region, with many of West Africa’s most important rivers originating in its highlands—such as the transboundary Senegal, Niger and Gambia rivers. Accordingly, Guinea’s specific topography means that its potential for hydropower generation [1] is among West Africa’s highest. In this context, it comes as no surprise that Guinea’s on-grid electricity generation has historically been mostly hydropower-based [2].

Guinea currently has several large-scale hydropower plants in operation, the largest of which is the nearly-finished 515-MW Souapiti plant on the Konkouré River. This river has already undergone substantial damming in the past, with Guinea’s three other hydropower plants with more than 20 MW capacity all located in the Konkouré basin (cf. Figure 1).

In its updated Nationally Determined Contribution (NDC), Guinea indicated its intentions to develop various other hydropower sites by 2030 and derive 80% of its electricity from hydropower by the same year, i.e. maintain a consistently high contribution of hydropower into the future [2]. One of the hydropower projects slated for development is the 294 MW Koukoutamba hydropower plant, to be located on the Bafing River (the upper section and largest tributary of the Senegal River; cf. Figure 1).

The annual production from Koukoutamba’s 294 MW has been projected at 888 GWh/year according to estimates [3], which would translate to a long-term average capacity factor (CF) of 34.5%. The electricity generated by Koukoutamba would be shared between Guinea and the other member countries of the *Organisation pour la Mise en Valeur du Fleuve Sénégal* (OMVS) [4], with a 73.5 MW share in capacity for Guinea. This would correspond to an average annual electricity generation of 222 GWh from Koukoutamba for Guinea.

Koukoutamba has been promoted as a solution to address persistently low electricity access rates in Guinea [5]. However, some observers have raised questions about the dam's cost-effectiveness and whether its power will be affordable to the Guinean public, while noting that much of the dam's power is destined for export to neighbouring countries. Meanwhile, concerns have been raised about the potential displacement of several thousand inhabitants of the region, as well as the potential flooding of a national park housing the critically endangered western chimpanzee [6]. These relate to broader concerns surrounding new large hydropower projects in general, in terms of their impact on river ecology, valley flooding, and potential emissions of methane from decaying biomass in reservoir lakes that would contribute to global warming [7].

In this context, it has also been suggested that solar photovoltaic (PV) power could present a more sustainable investment and serve as alternative to Koukoutamba. Solar PV technology would avoid many of the negative ecological impacts of hydropower and has undergone highly favourable cost trajectories in recent years [8].

The latter point is underscored by the fact that solar PV's average levelized costs of electricity (LCOE), which represents the price at which the electricity generated by a project should be sold for that project to break even at the end of its lifetime, are now in many cases lower than the expected LCOE from hydropower projects (see Figure 2). The decline in LCOE for new projects in the period 2010-2020 has been more drastic for solar PV than for any other form of renewable electricity generation.

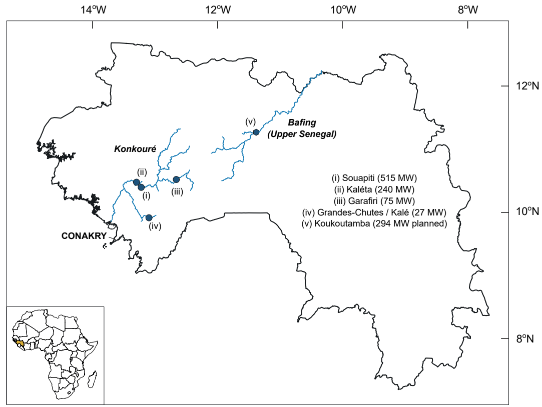


Figure 1: Map of Guinea with the locations of all existing hydropower plants of more than 20 MW installed capacity (all in the Konkouré river basin), as well as the planned Koukoutamba hydropower plant on the Bafing (Upper Senegal) river. River shapefiles for the Koukouré and Bafing were obtained from [5]; only the river sections with yearly average discharge of above 10 m^3/s are shown. Inset: map of the African continent with Guinea indicated in yellow, for reference.

This study assesses the options for foregoing the construction of Koukoutamba in favour of investing in solar PV in its stead. This is done from the perspective of costs (levelized costs as well as upfront investment), overall levels of electricity generation to be matched, the challenges posed by the temporal variability of solar PV resources, and geospatial planning aspects. The following sections deal with these respective topics.

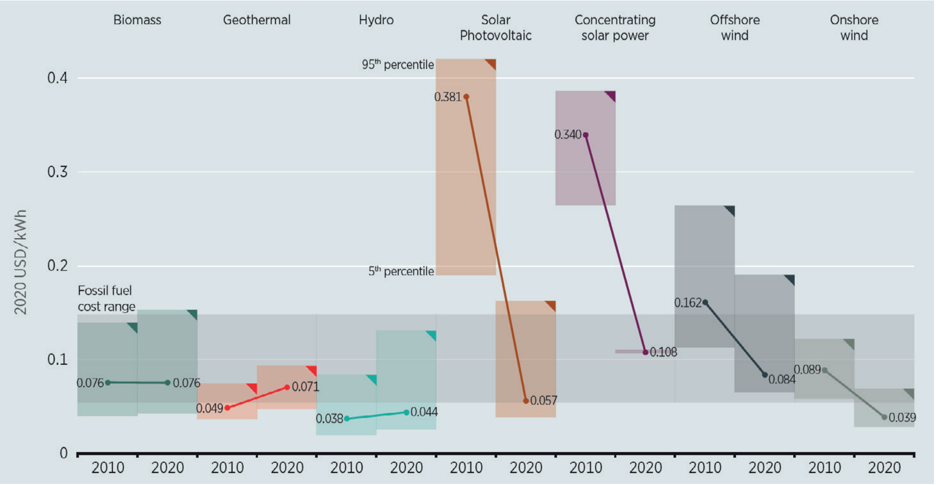


Figure 2: Global LCOEs for newly commissioned, utility-scale renewable electricity generation projects. Thick lines are the global weighted-average LCOE value derived from the individual plants commissioned in each year. The project-level LCOE was calculated with a discount rate of 7.5% for OECD countries and China in 2010, declining to 5% in 2020; and 10% in 2010 for the rest of the world, declining to 7.5% in 2020. Taken from [8].

ASSESSMENT OF KOUKOUTAMBA'S COSTS IN COMPARISON TO SOLAR PV

This section assesses the expected costs of electricity generation from Koukoutamba and compares them to those of potential solar PV plants in Guinea. Specifically, we calculate the levelized cost of electricity (LCOE) as follows:

$$LCOE = \frac{\sum_y \frac{(C + O_y)}{(1+r)^y}}{\sum_y \frac{E_y}{(1+r)^y}},$$

where y represents the year of the asset's lifetime ($0 \leq y \leq Y$, with Y the plant's lifetime), C are the capital expenses (CAPEX) related to construction of the asset, O_y are the operational and maintenance costs (OPEX) in each year y, E_y is the total electricity generated by the plant in each year y, and r is the discount rate.

To calculate the LCOE for Koukoutamba, we use project-specific data on overnight costs and projected electricity generation, and generic data on other parameters. The overnight costs of Koukoutamba are taken to be 812 million USD [9]. For electricity generation, we employ a range of estimates of Koukoutamba's capacity factor (CF) from the African Hydropower Atlas of the International Renewable Energy Agency (IRENA) [10], [11], corresponding to normal (CF = 29.9%), wet-year (40.3%) and dry-year (20.1%) scenarios, respectively. We compare these against the official estimate of 34.5% [3] (see Introduction section), which falls within this range. It is to be noted that estimates of the CF differ across scientific literature; one study has estimated the CF of Koukoutamba to be potentially as low as 14% [12]. Notwithstanding such uncertainty, in light of the above, it appears that there is general consensus that the average CF of Koukoutamba is likely to be substantially below 50%. We assume, given the technological maturity of hydropower, that all CAPEX and OPEX parameters pertaining to Koukoutamba are static in time.

Conversely, for solar PV, we assume substantial declines in CAPEX and OPEX across the coming decade according to recent projections by IRENA [13]; thus, we provide a range of LCOEs for solar PV, based on the year of construction start of potential solar PV plants (between the present-day and 2030), to compare against Koukoutamba. We note that the 2030 values are likely to be the most pertinent values for comparison with Koukoutamba, given the expected construction time of the latter.

All cost assumptions for Koukoutamba and generic solar PV are shown in Table 1.

Parameter	Koukoutamba	Source	Generic solar PV	Source
Specific CAPEX	2761.90 USD/kW	[9]	1378 USD/kW (2020) 984 USD/kW (2025) 886 USD/kW (2030)	[13]
Specific OPEX	71.74 USD/kW/yr (fixed) 0.003 USD/kWh (variable)	[14]	10% of CAPEX	[13]
Capacity factor	29.9% (normal) 20.1% (dry) 40.1% (wet) 34.5% (official estimate)	[5], [10], [11]	18.7% (including assumed 8% losses, consisting of 4% outage and 4% inverter and cable losses [15])	[16], [17]
Discount rate	7.5%	[8]	7.5%	[8]
Project lifetime	50 years	[7]	25 years	[13]

Table 1: Cost parameters used for the calculation of the LCOE of Koukoutamba and generic solar PV in Guinea

Using these assumptions, we find that the LCOE of Koukoutamba is likely to lie in a range of 80—156 USD/MWh (cf. Figure 3) with a central estimate (based on hydrologically normal years) of 106 USD/MWh. Using the official capacity factor estimate, we obtain an LCOE of 92 USD/MWh. This is higher than any LCOE estimated here for solar PV: under 2020 cost assumptions, the LCOE lies at 78 USD/MWh, 27% lower than the normal-year estimate for Koukoutamba. For solar PV projects started in 2025 and 2030, this LCOE would be projected to decline to 55 USD/MWh (48% lower) and 45 USD/MWh (58% lower), respectively.

It is worth noting that large hydropower projects have a tendency for construction cost overruns [18]. In Box 1, we explore the potential implications on the LCOE of Koukoutamba's hydropower if such cost overruns were to happen.

In light of the above, we conclude that, on a costs-per-MWh basis, solar PV will indeed be a cost-effective source to serve as alternative to Koukoutamba. Next, we explore to what extent the integration of solar PV in Guinea's electricity mix would be feasible, whether this would be able to replace the electricity generation foregone because of potential non-construction of Koukoutamba, and how much this would cost.

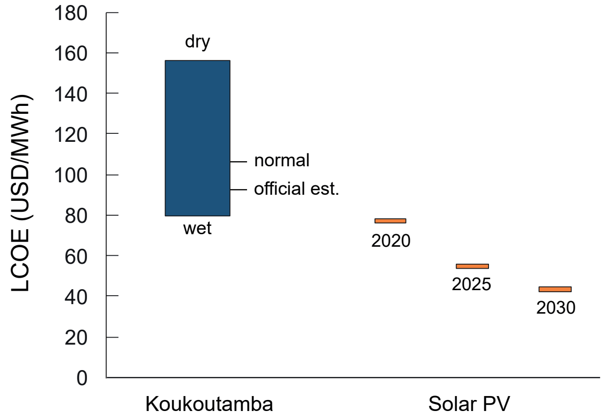


Figure 3: Estimates of the LCOE of Koukoutamba (with high/low ranges indicating assumptions on dry/wet river conditions) versus the LCOE of generic solar PV installed in Guinea in the period 2020—2030.

BOX 1: THE IMPACT OF HYDROPOWER COST OVERRUNS

Historically, large hydropower plants have had a tendency for investment cost (CAPEX) overruns [20]–[22]. Any such cost overruns to Koukoutamba would impact its economic competitiveness vis-à-vis solar PV even more as compared to the results shown in Figure 3. For instance, if Koukoutamba suffered from a 20% cost overrun, its LCOE (based on the official capacity factor estimate) would increase by 14% (to 106 USD/MWh). At a 35% cost overrun, the LCOE increase would be 25% (to 115 USD/MWh), and with a 50% cost overrun, the LCOE would increase by 35% (to 125 USD/MWh). The cost overruns in such scenarios would thus further decrease the cost competitiveness of Koukoutamba as compared to solar PV.

EXPLORING THE POTENTIAL FOR SOLAR PV TO REPLACE KOUKOUTAMBA

The principal challenge to replacing hydropower from a reservoir-based plant like Koukoutamba with solar PV lies in the need to account for the temporal variability of solar. Solar PV is classified as a source of variable renewable electricity (VRE) due to the variability it exhibits on diurnal and seasonal timescales. While the seasonality in solar PV generation in low-latitudinal countries like Guinea is relatively limited (with somewhat lower generation during the wet season as compared to the dry season), the diurnal cycle of solar PV generation would require dispatchable sources of power and/or storage solutions in the event of substantial penetration of solar PV in the electricity mix, to ensure proper system adequacy during evening, night and morning hours throughout the year.

Reservoir hydropower is an often-invoked example of a power source that can be dispatched flexibly to support VRE [12], [19]. Given that Guinea's on-grid power generation is currently nearly fully based on reservoir hydropower, Guinea's existing hydropower fleet (notably Souapiti, Kaléta, Garafiri and Grandes-Chutes/Kalé; cf. Figure 1) could provide an opportunity to support a certain amount of solar PV on diurnal and seasonal timescales, determined by their storage size and the seasonality of river inflow to their respective storages.

The potential for this type of hydro-supported VRE integration has been mapped out in previous scientific literature. In particular, ref. [12] calculated the overall amount of solar PV that existing hydropower plants in Guinea (and other West African countries) could flexibly support from hourly to seasonal timescales, taking into account the constraints in flexibility linked to downstream minimum environmental flow requirements as well as safe upper and lower limits for reservoir lake levels. Such requirements put clear upper limits on the amount of solar PV generation whose variability can be matched by flexible dispatch from each individual hydropower plant. We summarise the most important findings from that study pertaining to Guinea in Table 2.

Hydropower plant	Capacity (MW)	Yearly hydropower generation (GWh)	Potential supported solar PV (GWh)	Required solar PV capacity (MW)
Souapiti	515	1204	239	146
Kaléta	240	946 [10]	187*	114
Garafiri	75	112	20	12
Grandes-Chutes (Kalé)	27	100	1	1
Total	**857**	**2362**	**447**	**273**

*Table 2: Summary of hydropower generation and potential for solar PV support through flexible hydropower dispatch from existing dams (> 20 MW) in Guinea. Data summarised from ref. [12], unless otherwise noted. Hydropower generation figures refer to medians over multi-year periods spanning both wet and dry years from the "Reference" scenario of ref. [12]. * Since Kaléta does not have its own reservoir but makes use of Souapiti's, being situated just downstream of the latter (cf. Figure 1), it is assumed that the potential solar PV supported by Kaléta has the same proportion to yearly hydropower generation as for Souapiti.*

We conclude that Guinea's four existing hydropower plants of more than 20 MW could likely support the uptake in the electricity system of 273 MW of installed capacity of solar PV, which would produce 447 GWh/year on average. This represents 50% of the total expected yield of Koukoutamba (888 GWh/year, based on the official CF estimate of 34.5%; cf. Table 1), and even 86% based on dry-year assumptions (518 GWh/year). It also represents more than double the amount of Koukoutamba's yield allocated to Guinea (222 GWh/year, based on the 73.5 MW allocation of installed capacity for Guinea; see Introduction). Thus, Guinea's existing hydropower would support the uptake of sufficient solar PV to more than replace the electricity foregone for Guinea through the potential non-construction of Koukoutamba (by a factor of about 2.3).

Based on the financial parameters shown in Table 1, the total upfront investment costs of a given amount of solar PV capacity can be calculated (for the years 2020, 2025 and 2030) and compared against the investment costs of Koukoutamba; results are shown in Figure 4. In Figure 4a, we show the total investment costs of Koukoutamba against those of 273 MW of solar PV capacity, the total amount supportable by existing Guinean hydropower plants. The investment costs for the required solar PV turn out to be 54% (for 2020) to 70% (for 2030) cheaper than the investment costs for Koukoutamba. In Figure 4b, we show Guinea's assumed share of 25% of the investment costs for Koukoutamba (since it is an OMVS project and 75% of Koukoutamba's electricity production would be destined for export) against the investment costs for 131 MW of solar PV capacity, the amount that would produce 222 GWh/year and thus match the estimated yield of Koukoutamba for Guinea. The costs of this generation-matched solar PV turn out to lie 8% (based on 2020 CAPEX for solar PV) to 41% (based on 2030 CAPEX) below the costs of Guinea's proportional share in Koukoutamba.

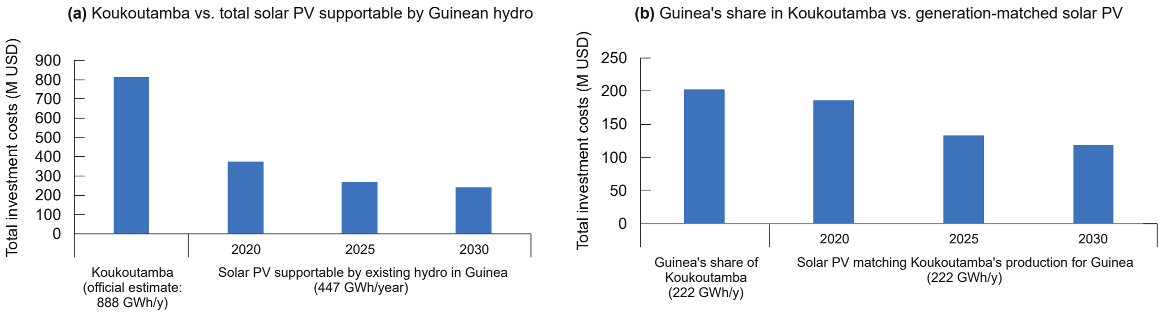


Figure 4: (a) Investment costs of Koukoutamba versus investment costs for the amount of installed solar PV capacity whose uptake in the electricity system Guinea's existing hydropower could support, and which would yield more than double the amount of electricity compared to what Koukoutamba would produce for Guinea. (b) Investment costs of Guinea's share of Koukoutamba's capacity (one-fourth of overall investment costs) versus the amount of solar PV capacity that would, on average, yield the same annual electricity generation as what Koukoutamba would yield for Guinea, according to official estimates.

We conclude that existing Guinean hydropower could support the uptake of solar PV generation up to roughly half of Koukoutamba's expected annual total power generation (based on the official estimate), and this would require less than half the total investment costs of Koukoutamba. We also conclude that Guinea's share in Koukoutamba's costs would be higher than the investment costs needed to construct the solar PV plants required to match Koukoutamba's electricity benefits for Guinea.

From Figure 4b, we infer that foregoing Koukoutamba and replacing all of its projected annual electricity generation (i.e. not only Guinea's share, but also that of other OMVS countries) by solar PV, would also result in lower investment costs overall. If the total investment costs for Koukoutamba were reallocated towards solar PV, this would suffice to finance solar PV capacities of 590 MW (based on 2020 CAPEX) up to 916 MW (based on 2030 CAPEX).

However, it is not guaranteed that all of this solar PV across the OMVS countries could easily be supported by existing hydro in the same way that Guinea's existing hydropower could support solar PV plants in Guinea, since Guinea's hydropower potential surpasses that of its neighbours [12]. Therefore, in order to replace the potentially foregone hydropower from Koukoutamba with solar PV while mitigating the impact of the latter's temporal variability, the other OMVS countries could be better advised to call upon other dispatchable capacity and to expand storage options other than hydropower reservoirs, especially through batteries [14], [23].

SPATIAL DEPLOYMENT OPTIONS OF SOLAR PV

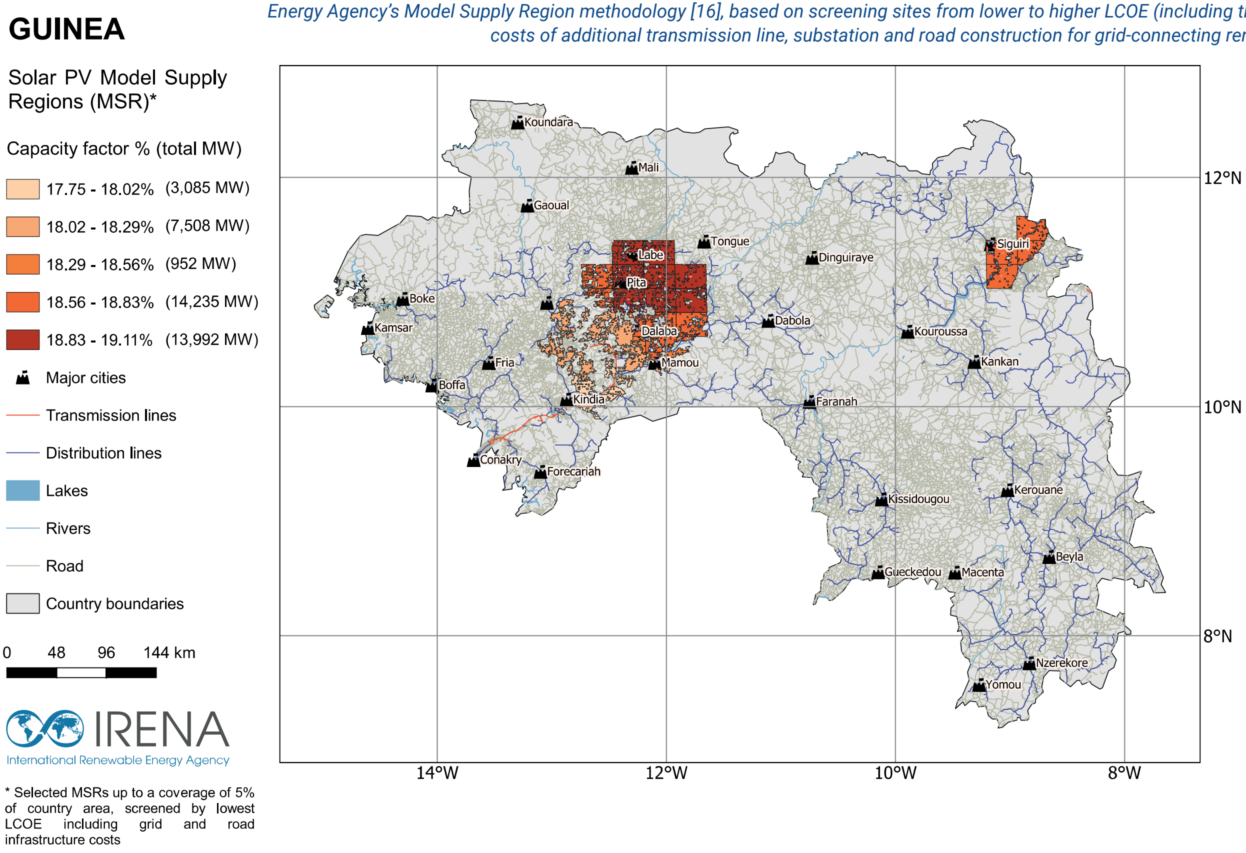
If Guinea were to opt for developing solar PV instead of Koukoutamba, the question of where this solar PV could be spatially deployed must be answered. Generally, in terms of available potential, the possible locations for solar PV plants are not as constrained as those for hydropower. These locations may, however, differ in costs for solar PV deployment. Potential differences in costs between different locations are most readily explained by two factors:

(i) The strength of the resource: the higher the CF (yield per unit of installed capacity), the lower the LCOE;
(ii) The distance of the resource from existing grid infrastructures: the longer this distance, the higher the costs for additional transmission lines, roads and substations required to evacuate the produced electricity. (Note that this cost category, which applies to both hydropower and solar PV, was not included in the calculations for Figure 3.)

In practice, there is likely to be a balance to be struck between exploiting excellent far-from-grid resources and less excellent (but still good) near-grid resources. Comprehensive methodologies to assess such compromises and identify lowest-cost sites have been developed in recent years [15], [24]; on the basis of these, IRENA has developed georeferenced maps for every African country showing the lowest-LCOE locations for solar PV in each country (up to a maximum coverage of 5% of each country's territory) [16].

The results for solar PV for Guinea are shown in Figure 5. This shows that the most attractive locations for deploying solar PV parks in Guinea, taking into account the compromise between resource strength and grid distance invoked above, and excluding protected or otherwise a priori unsuitable areas, are primarily in (i) the Fouta Djallon mountains, around cities such as Dalaba, Pita and Labé (e.g. close to the headwaters of the Gambia and Senegal rivers) and (ii) close to the Malian border, around Siguiri (along the Upper Niger river). Many locations in category (i) are seen to be rather close to the planned location of Koukoutamba (cf. Figure 1). Hence, it is conceivable that replacing Koukoutamba with solar PV would not require major changes in terms of geospatial planning for grid expansion.

Figure 5: The 5% most attractive land area for developing utility-scale solar PV parks in Guinea according to the International Renewable Energy Agency's Model Supply Region methodology [16], based on screening sites from lower to higher LCOE (including the levelized costs of additional transmission line, substation and road construction for grid-connecting remote sites).



Datasets sources
Major cities: Natural Earth, available at https://www.naturalearthdata.com/downloads/10m-cultural-vectors/10m-populated-places/
Lakes: World Wild Life, available at https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database
Rivers: Natural Earth, available at https://www.naturalearthdata.com/downloads/
Roads: Meijer, J.R., Huijbregts, M.A.J., Schotten, C.G.J. and Schipper, A.M. (2018): Global patterns of current and future road infrastructure. Environmental Research Letters, 13-064006. Data is available at www.globio.info
Transmission and distribution lines: Arderne, C., Zorn, C., Nicolas, C., Koks, E.E., 2020. Predictive mapping of the global power system using open data. Sci Data 7, 19. https://doi.org/10.1038/s41597-019-0347-4
Country boundaries: Global Administrative Unit Layers (GAUL)

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A final comparison that could be made, concerns the area potentially covered by the solar PV capacity required to match Koukoutamba's electricity generation for Guinea. It has been reported that the flood zone of Koukoutamba would cover 264 km^2 [25]. Based on the typical spatial footprint of 33 MW/km^2 for solar PV panels [26], we can estimate the area that the 136 MW of solar PV capacity (matching the amount of 222 GWh/year for Guinea) would take up amounts to about 4 km^2.

For actual projects, the area taken up by solar PV plants may have to be corrected upwards, considering a typical "land use discount factor" which reflects the portion of the area needed in practice to set up other necessary infrastructure around the plant (substations, roads, etc.), which could thus not actually host photovoltaic panels. Even assuming a very conservative land use discount factor for solar PV of as high as 90% [15]—leading to a 10x higher value of the area needed—this would still only amount to 40 km2, almost seven times lower than the area reportedly to be inundated by the Koukoutamba reservoir. In addition to taking less available land, solar PV could be installed with a significantly lower social footprint, because it would not require significant displacement of communities and having to pay for their relocation.

Even if we consider a solar PV capacity of four times 136 MW, which would match Koukoutamba's overall power generation and not only Guinea's share, the spatial impact of solar PV—while substantial—would thus still be lower than that of Koukoutamba.

CONTEXT OF THE WEST AFRICAN POWER POOL

It is likely that one of the policy reasons behind a continued push for hydropower development in Guinea lies in the fact that Guinea's hydropower potential surpasses that of its neighbouring countries. This could allow Guinea to become a regional power exporter in the framework of the West African Power Pool (WAPP).

If future hydropower development in Guinea would be foregone in favour of solar PV, this would impact the strategic positioning of Guinea in the WAPP. It is likely that, instead of exporting baseload power to neighbouring countries, power trade involving Guinea would instead be focused rather on Guinea's existing hydropower plants providing flexibility. In particular, it has been shown that an ambitious deployment of VRE in other West African countries—solar PV in all, and wind power in the Sahelian countries—alongside a continued drive towards greater regional integration of power grids, would allow further spatiotemporal complementarities between existing hydropower and future solar and wind power to be harnessed. This would avoid the need for further exploitation of West Africa's hydropower potential, while accentuating the flexible role of existing hydropower plants. This potential role for hydropower would mainly consist of backing up solar PV during night time (aided during the dry season by wind power from the Sahel) and of backing up both solar PV and wind power during the wet season, during which both of these exhibit marked drops in yield [12], [27].

However, it is already clear that existing hydropower in West Africa will not suffice as the only backup for solar PV and wind power [12], and should rather be seen as an initial lever to support the integration of a first push towards more VRE before other storage solutions would become indispensable. To achieve continuously high shares of VRE in West African countries' electricity mixes against the backdrop of a consistently rising demand, battery storage in particular is estimated to increase strongly in importance towards mid-century [23].

POLICY IMPLICATIONS

If Guinea were to forego the construction of Koukoutamba in favour of solar PV on utility scale, this would likely require the attraction of additional private sector investment to provide the needed upfront expenses for solar PV plants, especially given that investment in solar PV tends to involve relatively more private sector finance than investment in hydropower [28]. There are various levers to increase a country's attractiveness for private investment in power generating infrastructure, such as various de-risking measures to lower the perceived risk by investors when setting up project companies. These include e.g. clear policy from governments in terms of objectives for renewable electricity to be installed; potential tax rebates on imports of solar power plant equipment; clear policy in terms of land allocation and transmission infrastructure buildout; guarantees for financial risk mitigation through e.g. multilateral development banks leveraging private sector participation, and various others [29].

Guinea already has a dedicated public-private partnership unit within the Ministry of Energy [30], [31]. However, among the many projects in which the Guinean government appears to be looking for investors, solar PV is still markedly absent [31]. A policy shift in which a more proactive approach towards diversifying power generation towards a higher share of solar PV is central, would therefore appear essential to allow replacing projects such as Koukoutamba with solar PV.

CONCLUSIONS

This study investigated the potential for utility-scale solar PV in Guinea to potentially replace the hydropower generation that would be foregone if the Koukoutamba hydropower plant were not built. The results highlight that solar PV would likely be a more attractive investment than Koukoutamba from an upfront investment point of view, and could result in a lower levelized cost of electricity. It has also been seen that Guinea's existing hydropower plants could allow substantial amounts of solar PV to be integrated in the electricity mix without the temporal variability of solar PV posing substantial problems to the adequacy of this mix. The amount of solar PV supportable by existing hydropower in Guinea could surpass the electricity that Koukoutamba is slated to generate for Guinea, and the investment costs for the required solar PV capacity are favourable in comparison to what Koukoutamba would cost. It has additionally been seen that many of the most attractive sites for solar PV generation in Guinea are located relatively close to Koukoutamba's site, meaning that major changes in geospatial planning for grid expansion would be unlikely to be necessary if the policy choice of replacing Koukoutamba with solar PV were to be made. Lastly, although the spatial requirements for installing solar PV capacity are not to be underestimated, solar PV would still likely have a lower spatial footprint than Koukoutamba's reservoir.

It is to be noted that the other member countries of the OMVS do not have sufficient existing hydropower capacity for similar principles to be applicable if they were to forego their projected share of Koukoutamba's electricity output. For these countries, replacing this output with solar PV and/or wind power would likely require a strong push for using other dispatchable technologies and other storage solutions, in particular battery storage. Batteries have been cited as a prime lever for increasing the share of VRE (both solar PV and wind power) in power systems across West Africa according to recent scientific studies and—just like solar PV—their cost are rapidly reducing.

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