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Opportunities and Challenges for Scaling Agrivoltaics in Rural and Urban Africa

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Abstract. Crop Area Integrated Photovoltaics (CAIPV) systems yield electricity and crops on the same area of land. Most CAIPV research and commercial activity over the last decade has taken place in temperate countries of the Global North; activity in Africa has been comparatively very limited. Depending on several factors, the shade from the PV arrays may cause crop yields to decrease, increase, or remain close to control. It is expected that yields of many crops would increase on sunny arid sites in Africa. This paper seeks to quantify and compare CAIPV's two yield components (electricity and food) under different scenarios in the African context, with a close look at potential CAIPV integration into PV mini-grids. Metrics of PV energy generation and demand are contrasted with crop yield and demand, and it is shown that the PV surface area required to meet electricity needs of most Africans is dwarfed by the corresponding land area needed for crops to meet nutritional needs. As PV area corresponds to crop area in CAIPV, it becomes clear that per capita food yields of projects will only make a miniscule contribution to local nutrition if distributed equally amongst all users of a mini-grid. Corollary agricultural benefits of mini-grids such as food refrigeration and electrified crop processing are noted to be attributed solely to the PV electricity, and have no relation to the shade provided by the PV arrays. Nevertheless, it is shown that significant quantities of food and jobs may be created if CAIPV systems can increase their surface area by securing large energy offtakers, whether in the form of off-grid industrial clients, via on-grid feed-in tariff schemes, or even future possibilities of large-scale PV-to-fuel intercontinental export operations. In all cases, policy support is urged in building the educational, legal, and financial frameworks to facilitate such scaling.

INTRODUCTION

Modern large *conventional ground-mounted photovoltaic* (CGMPV) projects seek high levels of power density per hectare to help achieve a minimized levelized cost of energy. As PV technology continues to evolve, CGMPV's average power density continues to increase (1). Recently bucking this trend are attempts to derive parallel agricultural revenue streams from the same field, typically requiring a reduction in PV project power density. Dupraz et al. (2011) coined the term *agrivoltaics* to specifically refer to the cultivation of food crops under and between PV arrays (2). However, there has been a growing tendency to conflate this original definition of agrivoltaics with other on-farm PV applications such as sheep grazing (3) and honey production (4). To avoid confusion with these alternate formats, we propose the term *crop area integrated photovoltaics* (CAIPV) to refer to all scenarios in which the partial shading of PV arrays falls upon crops- whether in fields, orchards, vineyards, or even greenhouses and other protective coverings, using earth or hydroponic substrates. Non-food crops such as cotton and aloe vera could be considered CAIPV if the crops are indeed co-located within the PV array areas, but grass for grazing would be excluded from CAIPV. We will employ "agrivoltaics" as an umbrella term to encompass CAIPV as well as the broader applications mentioned above.

Most pioneer CAIPV construction and research over the past decade has taken place in temperate countries of the Global North such as France and Japan. There has been comparatively very little widely disseminated CAIPV activity to date in Africa; we have been able to identify only a few existing operational small commercial CAIPV projects in

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South Africa, Madagascar, and Réunion. Africa's first research-driven CAIPV pilot projects are now in advanced planning, under construction, or recently completed in Kenya, Uganda, Tanzania, Mali, and the Gambia (5) (6).

One may consider CAIPV a novel form of agroforestry. In agroforestry, shade-tolerant shorter plants grow below and beside taller plants; in CAIPV, shade-tolerant shorter plants grow below and beside PV arrays. Just as some understory plants may deliver disappointing yields in agroforestry plots with excessive tree cover, the same can easily happen in CAIPV with too dense of a PV canopy. While some experiments have indeed yielded unsatisfactory crop yields over the last decade in CAIPV, many encouraging projects have also been carried out that have shown that the technology is capable of maintaining or increasing crop yields and/or quality, or reducing water requirements, especially in sunny arid regions (7).

Rather than focus on specific crop compatibility or system optimization, this paper takes a critical look at the potential scale of socioeconomic impact of CAIPV integration in rural African off-grid communities, followed by more urban locations. It can be considered that CAIPV provides two primary sets of benefits: electrical and agricultural, which at very first glance, may seem like a promising offering for any sunny dry regions of rural Africa. The agricultural component of CAIPV refers strictly to the agronomic yield of the crops cultivated under and beside the PV arrays, and does not include corollary agrifood system benefits derived from the electrical component: the PV energy which can be used to power such loads as refrigeration and crop processing. This paper recognizes that while PV-powered mini-grids (CAIPV or not) typically deliver -via the electrical component- life-changing benefits to the majority of the local community, that very low local electrical demand and limitations in grid feeding opportunities in rural off-grid areas may limit total system area, and thus limit the potential of CAIPV's agricultural component to proportionally affect the lives of large quantities of locals.

This paper draws upon a scoping review in the research areas of CAIPV/ agrivoltaics, energy and electricity, and sustainable development. An analysis of local (off-grid) versus national per capita electricity use is examined, as well as per capita food production and consumption.

OFF-GRID CAIPV IN RURAL AFRICA

CAIPV Peak Power per Hectare Potential

Planning to deliver solar energy to unelectrified rural areas requires an understanding of PV generation capacity per area as well as average local per capita energy/ electricity use, and in the case of CAIPV, similar per capita figures for agricultural production and crop consumption are also useful to take into account. A recent 2021 PV Magazine article has noted that while CGMPV systems (in Germany) nowadays typically feature a peak power density of about 1.000 kW_p per hectare, a recent CAIPV project came in at 800 kW_p/ ha (8). The Fraunhofer Institute has suggested CAIPV project ranges of 500 to 800 kW_p/ ha (9). This article uses as a base 800 kW_p/ ha for further calculations for CAIPV in Africa. The high irradiation and low agricultural mechanization prevalent in many parts of the continent may permit higher peak power densities in some instances, just as certain crops and formats may result in lower densities. Depending on the local insolation profile, annual electricity generation will vary; see Table 1.

Per Capita Energy & Electricity Use Compared with CAIPV Generation

The concept of *per capita energy use- national* (**PC-En-N**) refers to the cumulative energy consumption (total primary energy supply) of a country, divided by the population count. All of a nation's residential, commercial, industrial, and often transport energy use is typically included in the figure. Though typically stated in tons of oil equivalent, it can alternatively be expressed in watt-hours – a more relevant metric as formerly fossil-fueled energy applications are becoming increasingly electrified. Global PC-En-N figures range from under 1 MWh in the poorest countries to over 100 MWh in the most energy-intensive countries (10).

PC-En-N stats may seem high when compared to *per capita energy use- household* (PC-En-H) which is typically limited to electricity and fossil fuels consumed inside an average home, sometimes including the energy used in the operation (but not the manufacturing) of the family vehicle(s.) PC-En-H accounts for 15 to 25 per cent of PC-En-N in developed countries and a higher share in developing countries, in which non-commercial fuels are furthermore often not reflected in official statistics (11). In between these two values, one can consider *per capita energy use-local* (PC-En-L) to refer to the energy consumed within a designated city or town.

To get an idea of strictly electrical use, one can substitute electricity for energy in the above metrics to get the respective: {PC-Elec-N; PC-Elec-H; PC-Elec-L.} PC-Elec-L is especially relevant for the dimensioning of remote mini-grids without any links to the main public grid; PC-En-L must also be considered if the mini-grid planning involves a parallel electrification campaign of loads such as cooking, heating, and transport that have previously locally been served by bio- or fossil fuels.

Average PC-Elec-N figures for SSA are amongst the lowest in the world, with 16 countries below 100 kWh; rural numbers are markedly lower (12). In Sub-Saharan Africa (SSA), the average rural electricity access rate is approximately 25%. Electrification in rural Africa is typically achieved by either grid extensions, or isolated local generation solutions such as the establishment of (increasingly PV-powered) mini-grids, solar home systems or other pico-solar devices which focus heavily on lighting and mobile phone charging. While solar home systems are modular and sized according to each household's needs, dimensioning a mini-grid requires a careful estimation of PC-Elec-L. Mini-grids typically count on "anchor loads" in the form of small businesses and industry, apart from residential use (13). The market study on "Productive Use Leveraging Solar Energy" in SSA -carried out by the World Bank- suggests a threshold of 200 kWh PC-Elec-L for mini-grid systems to allow for agrifood activities such as irrigation, grain milling, and cold storage (14). Many mini-grids in Africa have been sized considering PC-Elec-L figures below 100 (15). Sufficient electricity for "general lighting + fan + television" can require a PC-Elec-L of 44, and simple task lighting and phone charging just 8 (16).

Rural electrification schemes typically seek to improve the lives of every family in a given community via access to activities such as studying at night and telecommunications. Local food systems can enjoy a boost of resiliency by utilizing the solar energy to power refrigeration and crop processing, providing such appliances are present. Without in-depth analysis, one might assume that the agricultural component of a CAIPV project could have as far-reaching an effect as the electricity component; unfortunately, this turns out to be far from the case. Low per capita electricity use corresponds with a low requirement for photovoltaic surface, and thus, a small area of land beneath the PV. To get a clearer idea of how much crop cultivation area can be made available to each local resident, *PC-CAIPV-m²* shall refer to the available soil space within the area of a CAIPV project available to each local inhabitant of a mini-grid. This is derived by dividing PC-Elec-L by the projected annual PV generation per square meter of a given location.

TABLE 1. PC-CAIPV-m^2 for various PC-Elec levels (800 kW_p/ ha); selected insolation profiles

Location	Abidjan	Maputo	Niamey	Khartoum	Windhoek
PVOUT Estimate(17)	**1340**	**1530**	**1720**	**1830**	**1980**
GWh/ ha/ yr.	**1,072**	**1,224**	**1,376**	**1,464**	**1,584**
kWh/ m^2/ yr.	**107,2**	**122,4**	**137,6**	**146,4**	**158,4**
PC-Elec-L= 50	0,46	0,41	0,36	0,34	0,32
PC-Elec-L= 100	0,93	0,82	0,73	0,68	0,63
PC-Elec-L= 200	1,86	1,63	1,45	1,37	1,26
PC-Elec-L= 500	4,66	4,08	3,63	3,42	3,16
PC-Elec-L= 1.000	9,33	8,17	7,27	6,83	6,31
PC-En-G= 23.000*	214,6	187,9	167,1	157,1	145,2

Table 1 shows that considering PC-Elec-L numbers for typical non-industrial solar mini-grids in Africa, PC-CAIPV-m^2 numbers are below one square meter per local inhabitant and do not exceed 10m^2 even in the case of PC-Elec-L at 1000. For comparison's sake, 23 MWh is shown as "PC-En-G", which represents the global average per capita energy use for 2018 (18). Even at such a level, PC-CAIPV-m^2 remains below 0,02 ha at most African insolation levels.

CAIPV Land for Local Nutrition

For each corresponding group {global, national, local,} *PC-cropland-m²* shall refer to the per capita demand for crop land. Though determining is challenging due to wide variations in diets and agroecological resources, Wackernagel et al estimated *PC-cropland-m²-G* at 2.500 m^2 (19). Grid Arendal shows that most countries surpass this figure (20). It is therefore clear that people's energy needs are met with areas of PV that are much less than the amount of land used for nutrition.

While micronutrient-rich/ calorie-poor colorful fruits and vegetables are important for optimal health, staple caloric food yields are humans' vital source of energy. Dinesh and Pearce (2016) identified cassava as a CAIPV-compatible crop (21). Extrapolating from Niger's Africa-leading average cassava yield (23,5 T/ ha) we can consider a favorable case scenario of 2,35 kilos per m^2 per year for this staple crop (22). At 1.600 calories per kilo, this translates to 3.760 calories per m^2 per year (23). Meeting the per capita calorie requirements at 2.200 per day would require 213,6 m^2 of high-yielding cassava alone, without considering the variety of other foods required for healthy lifestyles. 213,6 m^2 of CAIPV in the Niamey region could yield nearly 30 MWh of electricity annually.

CAIPV Mini-Grid Integration

Case studies of mini-grids for rural electrification show that most projects have fallen in the range of 10-100 kW_p of PV (only 125 ~ 1250 m^2 of soil area, considering 800 kW_p/ ha) for villages of a few thousand people (13). In mini-grid projects, often, solar arrays are used as a shade element for a small structure or steel container (the footprint of a 40' ISO container is approximately 30 m^2) that houses critical electrical equipment such as batteries and inverters; this shade keeps them cool and more efficient. Moreover, as cold storage units are often employed as anchor loads for mini-grid projects, it may make more sense to site them under the PV arrays to benefit from the shade for reasons above. If after higher-priority electromechanical gear shading is covered, significant PV array areas remain, small CAIPV plots could certainly be established on available earth. As established above, this will not provide a major source of nutrition for the local community, and thus should not be marketed as such. Nevertheless, whatever under-module shade area is available could be harnessed to grow some saleable crops and thus support a quantity of employment positions proportionate to the available CAIPV-m². If extensive shading is identified as a desired commodity that could potentially aid local agriculture, lower cost resilient agroforestry systems could be considered, via informed design and operation. Shade nets may be implemented, under the caveat that they are often manufactured from polymers that may have a short lifespan and not be properly recycled.

While <100 kW_p mini-grids have been the norm for some time, the convergence of lowered prices in both PV and energy storage, the electrification of more currently fossil- or biomass-fueled energy loads, as well as improved engineering, signal a ramp-up in both average size and total volume of mini-grids in Africa for the future (13). Also, if a mini-grid is built to power a considerable industrial exploitation for mines, manufacturing, large crop processing facilities, or other significant electricity consumer, PC-Elec-L will of course increase, leading to a proportionate increase in PC-CAIPV-m². While PC-CAIPV-m² will alas remain far below PC-cropland-m² in such scenarios, proportionate increases in local food and/or agricultural jobs can be expected as this value rises.

GRID-CONNECTED CAIPV IN AFRICA

Limited power grid infrastructure prevents the development of utility-scale PV in most rural parts of the continent (23, 15). Though mini-grids and SHS may be achieved at a lower cost than grid extensions, their power ceiling eliminates any possibility of selling excess energy to a wider market, thus limiting the potential of local CAIPV scaling and job creation. The characteristic of being grid-connected has been, so far, highly associated with CAIPV; all identifiable commercial projects in Europe and North America have been grid-connected.

While grid extensions may be welcome in rural communities for both the arrival of electricity and the potential for larger utility-scale CAIPV projects to sell electricity (if regulations allow) to dense nodes of industrial and/or urban consumption, the potentially negative cultural, visual, and ecological impacts of large-scale rural PV must also be considered. As the following short section on smaller-scale urban CAIPV will show, the current legal situation in most of Africa points towards utility scale GMPV as the highest-impact platform for the agricultural component of CAIPV for at least the short term.

Grid-connected CAIPV in Urban/ Periurban Africa

Africa is Earth's last majority-rural continent, but it is urbanizing at the fastest rate in the world (25). The estimation of when the number of Africa's city dwellers would surpass that of the countryside has varied in recent years from 2035 (24) to 2030 (26). While rural areas often show worse levels of poverty and hunger, cities in SSA do still face tremendous challenges to raise levels of quality of life for their inhabitants.

While most farming activity takes place in rural areas, Dixon acknowledges the key role of urban and periurban agriculture as one of Africa's 15 farming systems. Urban and periurban agriculture is widespread in Africa, taking advantage of nearby markets, and sources of fertilizer and water and power that are often more reliable that their rural counterparts. Alas, many city farming sites are often precarious, and water and nutrient inputs of low quality. Nevertheless, it is embedded in urban culture, with 40% of urban households involved to some extent in agriculture in Africa. Crops grown in urban and periurban agriculture vary widely across the continent (24).

Urban areas in Africa typically offer much higher levels of electrification than rural regions, yet grid-connected residential and commercial PV use remains low (27). Net metering opportunities remain limited throughout most of the continent, though some legislation is reported to have commenced in Morocco, Nigeria, Ghana, and Kenya (28). Though net metering legal frameworks would undoubtedly help urban PV uptake in general, CAIPV would still face similar barriers to those encountered in mini-grid environments: power ceilings limited to local (or in the urban case, household or business) electricity use. Only in the case of energy sale contracts such as feed-in tariffs (FIT) will CAIPV project sizes be able to scale to the level in which teams of agricultural workers could be ensured steady work, and larger volumes of food produced. CAIPV projects above a few hundred kW_p in peri-urban areas could employ dozens of agricultural workers per site; further job creation in food processing, sales, and distribution could follow suit. Inhabitants of dense inner-city settlements with very limited access to land and reduced employment prospects could be candidates for such posts.

Small scale FIT legislation could allow the installation of bank-owned micro-CAIPV projects in backyards throughout urban Africa. Though homeowners might only consume the PV energy from one or a few kW_p of PV, a backyard of 200 m^2 (for example) could host $16kW_p$ of CAIPV, providing ample shade for a family's micro cash crop cultivation; banks could compensate the homeowners with a land lease fee.

CONCLUSION

Future Outlook for African CAIPV

We suggest those policy makers managing the new influx of PV on the continent consider requiring or promoting CAIPV where appropriate on large GMPV projects, as part of broader strategies to improve agricultural yields, food accessibility, and employment opportunities. Of course, this may require non-traditional interdepartmental collaboration, as state energy, agriculture, educational, and employment agencies may not have close contact with one another. Incentivized or not, it is hoped that the added revenue stream from crops could help push the needle in favor of CAIPV projects as default format for GMPV on many African project sites, especially if equipment can manage to stay close to resembling inexpensive CGMPV (avoidance of excessive array height and spacing, and use of specialty modules,) and if socioeconomic and technical conditions are right. In regions with adequate agroecological resources for abundant crop cultivation, non-CAIPV agrivoltaics (grazing turf management) seems less appropriate than true CAIPV, considering the higher potential caloric yield per acre of crops as opposed to ruminant products (29).

In regions where CAIPV feasibility may be limited due to soil quality or water/ fertilizer availability, but the integration of native grasses and forbs (optionally complemented with ruminant grazing) is possible, this should be required for GMPV projects, as it has been shown to improve the functioning of ecosystem services such as biodiversity, pollination, carbon sequestration, and soil and water retention capacities. In the driest sunniest desert regions, if vegetation cannot grow whatsoever, bifacial PV arrays that harness ground albedo for extra energy production might be the best option. Unique studies should be carried out for each site.

Even if a potential GMPV project site hosts ideal conditions for crop integration, CAIPV's complex interdisciplinary nature and immature track record may dissuade local developers from attempting such a project. Designing either agroforestry or CAIPV projects requires a keen understanding of the interplay of several crucial factors, which can lead to an infinite set of possible project formats and outcomes. We have been unable to identify any comprehensive CAIPV design manuals or training courses available online. Considering agroforestry's wide reach in Africa, existing studies of crop cultivation under the shade of trees in different regions of the continent should also be further consulted and compared through a CAIPV lens, and of course, existing CAIPV research under similar environmental parameters should be consulted.

Even if a project has been appropriately designed and constructed for CAIPV, it may be easier to operate the built project as an animal grazing operation (or abandon agriculture altogether), as compared to a proper CAIPV farm with agricultural workers, crop cultivation, and harvest, sales, and logistics management. It is therefore suggested policy makers consider implementation of comprehensive transdisciplinary CAIPV training programs and follow-up requirements for FIT eligibility.

Though such factors as the unprecedented challenge of managing large amounts of intermittent solar energy on power grids has traditionally limited state-run utilities' enthusiasm for PV uptake in many parts of Africa, such hurdles are apparently being overcome, as evidenced by the recent and projected major ramp-up in PV throughout the continent. Of the 54 African countries surveyed in AFSIA's 2021 African Solar Outlook, 40 countries had installed PV capacities of below 50 MW_p; 27 countries host less than 5 MW_p of PV (30). Nevertheless, the continent is on the cusp of a PV revolution: 30 countries report PV pipelines and projects in development exceeding 100 MW_p. Many countries are poised to leapfrog from single to double or triple digit MW_p figures, with DRC, Ethiopia, and Botswana looking to catapult from nearly zero PV to the gigawatt club.

Longer term, it is projected that PV installations will continue to increase worldwide and eventually become the dominant energy (not just electricity) source for humanity. Business cases are improving for converting PV energy into liquid or gas fuels such as hydrogen, methanol, and methane that can be used for heavy transport and industrial purposes, and can be traded continentally via pipeline, train, or trucks on roadways, or globally via tanker ships. In any case, infrastructure investments will be required. Moreover, PV-derived "green ammonia," produced via the Haber-Bosch process, shows strong potential as a long-term solution for both fertilizer production and fuel (31).

The considerable solar resources in many parts of Africa coupled with projected increased global demand for such low-carbon liquid/ gas energy sources may foster energy export industries of PV-derived synthetic fuels, which would greatly expand the PV land footprint. If carried out in areas that meet key environmental parameters, a large portion of the hundreds of gigawatts could be built in the form of CAIPV, especially if mandated by local/ national authorities. Ecological, cultural, visual and caveats on GMPV should of course be heeded.

CAIPV faces the same hurdles that non-agri-PV faces in Africa, the most critical being finding offtakers to commit to long-term contracts to buy the energy. It is urged that pro-CAIPV grid-feeding legislation be enacted throughout the continent, but only accompanied with robust multi-stakeholder education frameworks.

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