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Agrivoltaics across the Water-Energy-Food-Nexus in Africa: Opportunities and Challenges for Rural Communities in Mali

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Abstract

Small-scale, rain-fed subsistence agriculture and pastoralism represent the major activity for Africa. For Mali, this represents about 80% of the population employed by the agricultural sector and contributes to about 42% of the Gross domestic product (GDP). The overreliance on rainfall, competing for the most valuable lands, the increasing scarcity of water, the lack of innovative technologies and infrastructure has made the agriculture sector vulnerable to climatic and non-climatic risks including an increase in the number of land conflicts. In addition, inadequate access to affordable energy has also limited social opportunities for the poor communities, especially in rural areas of Mali. Water Energy and Food (WEF) Nexus solutions such as agrivoltaics are increasingly being deployed to improve access to water for agricultural uses, improve yields and incomes, reduce drudgery especially for women, enhancing resilience and microclimate, improve land use efficiency and food security. This innovative approach has opened new prospects to improve the quality of life for people as well as their environment as a whole. Agrivoltaics is rapidly gaining popularity in many countries but not yet in African countries. This paper presents a feasibility analysis, recommendations and future directions of agrivoltaics in Mali and in Africa as a whole. Furthermore, applications of agrivoltaic systems are discussed in terms of their socio-economic and environmental effects, emphasizing also the necessity of integrative thinking in the process of strategic planning for achieving security in water, energy and food.

Keywords: Nexus solutions, Climate change, Sahel region, Sub-Saharan Africa, Innovation

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1. Introduction

The promotion of access to water, energy and food security has been a top priority for most African countries. Overcoming potential access gaps would rely on a diversified strategy (e.g. WEF Nexus) complementary to the continent's growing demand for resources. The WEF Nexus offers an innovative solution with the potential to reveal business models that could connect energy with water and food to respond to essential developmental needs. This goes further to improve access to resources, increase economic productive capacities and drive socio-economic welfare in Africa (RES4Africa Foundation and Enel Foundation, 2019). On the other hand, the interdependency of these resources in some cases has been translated into adverse impacts. Therefore, the implementation of such a solution necessitates integrative thinking and strategic planning.

According to many studies (e.g. Mahmoud, 2021 ed; FSIN and Global Network Against Food Crises, 2021), African countries still face complex challenges such as persistent food and water insecurity, widespread poverty and unemployment, lack of infrastructure and industrial capabilities, population growth, food loss and food waste, economic and political instability. This also includes a surge in demand over basic resources such as water, food and energy and the continuous migration of people (particularly youths) from rural to urban areas as the continent becomes the fastest-urbanizing in the world. Globally, over 759 million people, mostly located in rural Sub-Saharan Africa still do not have access to reliable and affordable electricity, 771 million people lack basic drinking water services, and around 750 million people experience severe food insecurity (IEA et al., 2021; UN-Water, 2021; United Nations, 2020). If business-as-usual continues, the number of people without access to these basic resources is even expected to increase by 2030.

Small-scale rain-fed subsistence agriculture and pastoralism remains the largest source of employment in Africa. According to the Food and Agriculture Organization of the United Nations (FAO), one of the main causes of food loss and food waste in this sector and particularly Africa is the unavailability of proper food storage such as cold chain facilities, especially for perishables during post-harvesting as well as in later stages of the value chain (FAO, 2016). Even when storage facilities are available, they are unreliable and inadequate due to electricity cuts as well as insufficient agro-processing skills among smallholder farming communities. The total loss of food in sub-Saharan Africa has been estimated at about $4 billion annually (FAO, 2020).

In the context of climate change, the hike in demand for these resources would be exacerbated by the potential effects of climate change to which Africa is particularly vulnerable. "Water scarcity is expected to become an ever-greater concern for many smallholder farmers as seasonal droughts, interspersed by heavy rainfall with high levels of run-off, increasingly undermine their natural resource base" (RES4Africa Foundation and Enel Foundation, 2019). In fact, extreme climate shocks would constrain the capacity of smallholder farmers to cultivate productively and raise livestock. These climate shocks threaten to push them deeper into poverty and make them less able and willing to invest in their production systems (RES4Africa Foundation and Enel Foundation, 2019).

Water management and allocation in a water-scarce environment are potentially conflict-laden tasks with a great impact on developing opportunities for the different sectors as well as on equity and sustainability. Sufficient water supply is essential for the agricultural sector. This has resulted in a push for more irrigated areas demanding the extraction of more water and energy for pumping water from groundwater and surface water. The energy system and sector, itself, in most parts of Africa faces several interrelated challenges such as low energy access, unstable energy security and an increasing environmental degradation. In 2019, only about 56% of the population of Africa had access to electricity (IEA, 2020). According to the same data, the situation is even worse in rural areas with only 37% as to 81% in urban areas having access to electricity (IEA, 2020). Therefore, ensuring access to water, energy and food in Africa is critical and promotes sustainable development.

In Mali, there has been an increasing scarcity of arable lands. Next to arable land being scarce, food loss and waste are additional problems negatively impacting food availability. Access to energy is also a major problem in Mali. Most households in rural areas satisfy their energy needs by using kerosene and batteries, which are expensive and unreliable (African Development Bank Group, 2015). Climate change is expected to exacerbate this situation with potentially severe effects on agriculture, forestry, health, energy, water and many others. Interestingly, in Mali, the agricultural sector and energy sector are among the sectors with the highest emission of greenhouse gasses. These gases are drivers of climate change.

Climate Watch (2020), in analyzing the historical emissions data per sector in Mali, observed an increasing trend in Greenhouse gases emissions with the agricultural and energy sectors being the highest emitters each year, starting from 2013 through 2018. Mali, in 2021, submitted to UNFCCC an updated issue of their 2016 *Nationally Determined Contributions* (*NDCs*). In this document, Mali strengthened her commitment to reduce emissions in the following sectors: by 31% for the energy sector, 25% for agriculture, 39% for land use and forestry and 31% for waste sectors by 2030 using *"business as usual"* as the baseline (NDCs: UNFCCC, 2020). For these targets to be achieved, the country must implement new and innovative approaches, particularly in sectors with high emissions. "Energy innovation contributes positively in reducing GHG emissions" (Álvarez-Herránz et al. 2017).

Long-term and sustainable solutions that improve living conditions and create an enabling environment for socio-economic growth in rural areas would instill market confidence and attract investment appetite for rural markets across Africa. In the absence of grid connected power, solar PV systems have attracted a lot of attention but with very few successful examples to show in the context of the Water, Energy and Food Nexus. While improvements take place every day, efforts are still needed to increase accessibility to energy and make Mali and Africa as a whole a stable and attractive market for investors to speed-up socio-economic development.

Agrivoltaics (AV) represents an integrated dual land-use system that opens the door for several synergies. The basis of agrivoltaics is to increase Land Equivalency Ratio (LER) through the combined use of a single area of land for simultaneous energy and crop production. In recent times, the integration of rainwater harvesting from the PV systems has made it serve a triple land-use purpose. The approach provides energy for productive uses at farm level such as pumping water, operating labor-saving small-scale machinery, raising poultry and producing fodder (chaff cutters), etc., as well as for value-adding processes (grinding, rice milling, drying, packaging, threshing, and ensuring effective cold storage facilities for storing perishable goods). Additionally, the shading provided by the PV modules has the potential to increase agricultural yield through reducing evapotranspiration and physical protection of crops. However, agrivoltaics are yet to be proven as a key innovative element to tackle climate change in Mali and the region.

This paper seeks to reflect on the complex reality facing smallholder farmers and rural communities dependent on rainfed agriculture as their main source of income and explore potentials of agrivoltaics to provide water, energy and food while enhancing rural development and human wellbeing. The paper discusses insights from agriculture, socio-economic and solar energy research conducted within the framework of the APV-MaGa project funded by the German Federal Ministry of Education and Research (BMBF). The research aims at revealing the challenges and opportunities of agrivoltaics systems as well as to gain a deeper understanding of synergies and interactions between the Water-Food-Energy-Nexus. The project is implemented at the farmland of Rural Polytechnic Institute for Training and Applied Research (IPR/IFRA) located in Katibougou, some 60 km from the country's capital Bamako.

2. Material and Methods

2.1 Study Area Description

Mali is located in West Africa and among the countries constituting the Sahel region of Africa. The Sahel region is considered one of the world's most vulnerable regions to climate change, as temperature increases are projected to be 1.5 times higher than in the rest of the world" (USAID, 2017). Mali is a relatively flat "tableland" and landlocked country that stretches from the Sahel zone in the south through the Niger basin to the Sahara, which occupies about 60 % of the country's surface. It is the eighth-largest country in Africa, with an area of over 1,240,000 square kilometers (471,118sq. miles) with a population density of 17 inhabitants per km^2. Fig. 1 shows the map of Mali with the neighboring countries. According to The World Bank Group (2022), Mali's population is estimated at about 20 million people, with about 49.9% of the population being female. According to 2020 data, 56% of the population in Mali lives in rural areas (Worldometer, 2022).

The mean annual temperature and precipitation for Mali is 28.84 °C and 322.56 mm respectively (World Bank group, 2021). There are three seasons in Mali which could be distinguished as follows: from November to February which is dry and mostly warm; from March to May, the temperature rises to very hot; from June to September/October, which is humid and brings partly very heavy rainfalls. Rainfall distribution shows huge seasonal differences and is often concentrated in the months of July and August. Rainfall variability and the risk of drought has been increasing in recent times as a result of climate change. Overall, there is water scarcity in Mali especially during the dry season, making it impossible to irrigate fields and severely limiting access to potable drinking water.

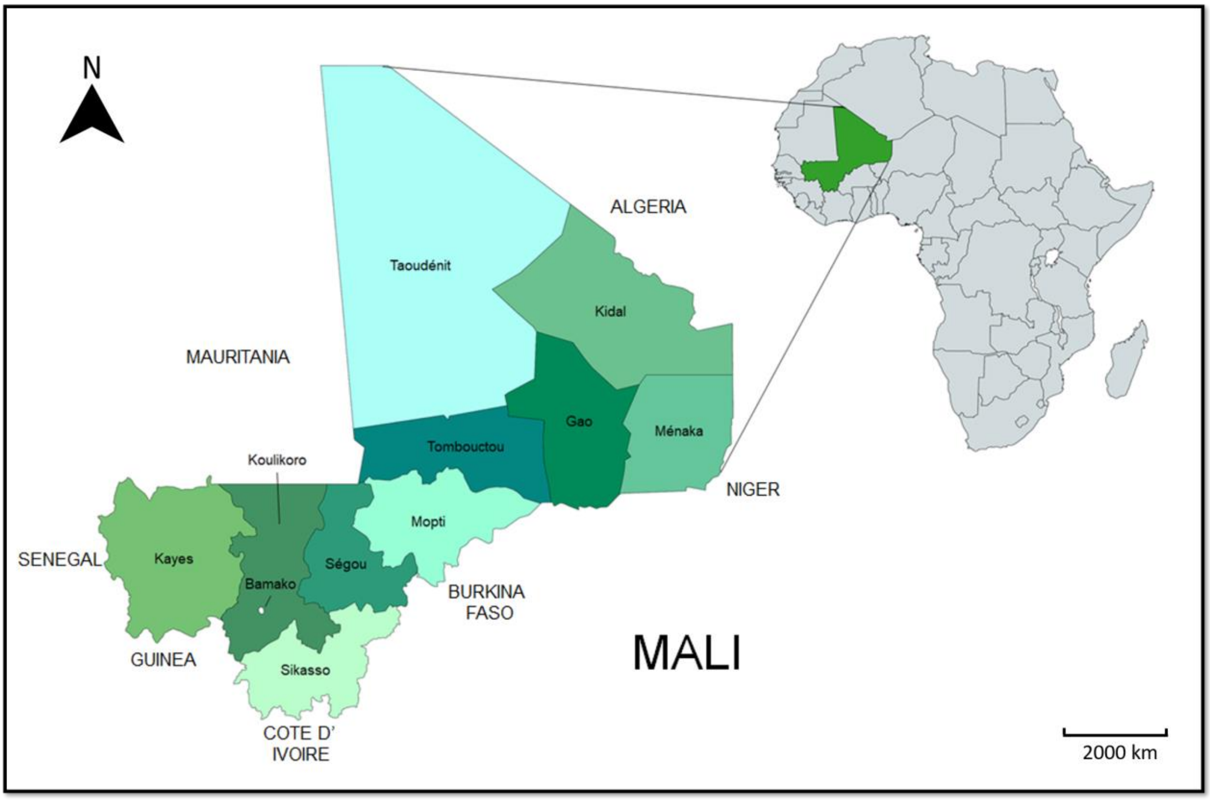

Fig 1: The Map of Mali, also showing the location in Africa. (Created by authors using mapchart.net)

The annual growth of the Malian economy depends heavily on agriculture production. Fig 2 shows the livelihood map of Mali presenting the distribution of the different agricultural activities and practices in the countries. Agricultural practice in Mali is still labor intensive with the lack of innovative technologies and infrastructure. People in water-scarce areas are increasingly dependent on groundwater, because of its buffer capacity which can easily be accessed mostly by the rich. On the other hand, with the intensification of human activities and land use change, there is an increased demand for groundwater. In addition, there is a higher risk of depletion of aquifers, especially in case of small and shallow aquifers, during periods of long droughts. Therefore, the strategic use of groundwater for water and food security in a changing climate is very important.

Resource-use conflicts between farmers occur in cases of changing land-use practices and access to water resources e.g. the cases in the Koutiala District with cotton production or Douentza district in Central Mali between cattle herders and arable farmers. The recent wave of large-scale land acquisitions for agricultural investments has also been characterized by conflicts and governance challenges (Djiré et al. 2012). Multiple pressures are exacerbating competition for valuable lands and increasing the number of land conflicts. These pressures also have a negative influence on the quality of land governance, creating fertile ground for corruption (Bujko, 2016), abuses of all kinds and tenure insecurity for the most disadvantaged groups.

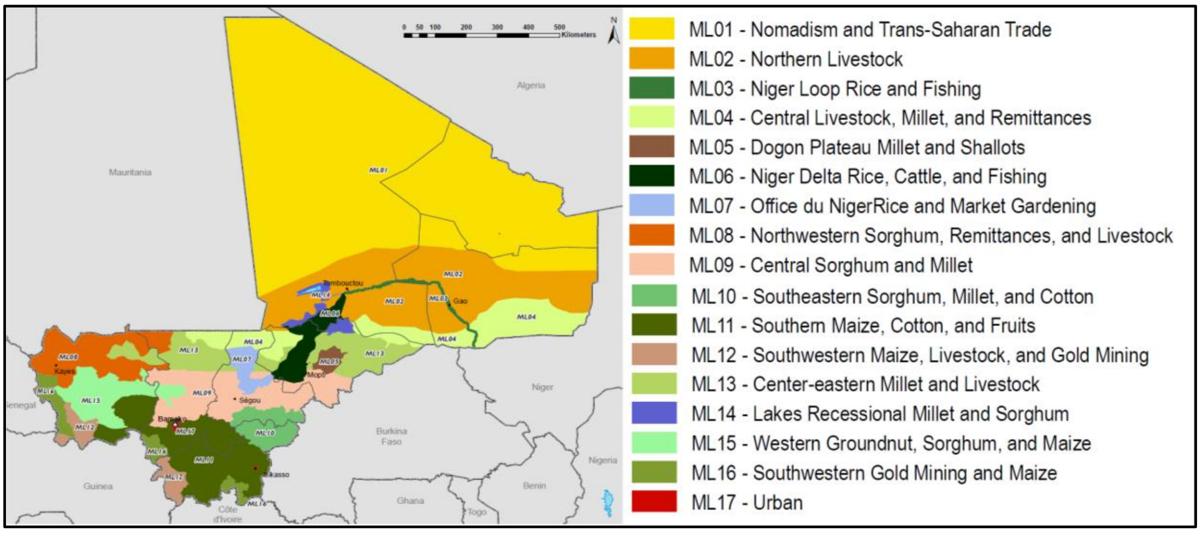

Fig 2: Mali Livelihood Zone Map (FEWS NET, 2015)

About 50% of the population have access to electricity with 78% of the people located in urban areas whereas 28% of the people are located in rural areas (IEA, 2020). The government of Mali has actively made the call for partnership to develop an estimated 800 MW energy from hydroelectric power and solar energy to address energy poverty in the country (U.S. Embassies abroad, 2021).

"Electricity production is dominated by hydraulic (55%) and thermal (44%) sources" (U.S. Embassies abroad, 2021). "There is an immediate and short-term demand on the residential and commercial network of the state-owned energy company Énergie du Mali (EDM) of at least 180 MW, on isolated networks of at least 60 MW, and by 17 large industrial companies of at least 200 MW" (U.S. Embassies abroad, 2021). Despite the presence of various hybrid systems (e.g. solar and diesel), the share of renewables excluding large hydropower remains low. Irregular energy supply is the main constraint for development in the country particularly the industrial sector. Inadequate access to affordable energy is also limiting social opportunities for the poor, women and youth. In particular, gender disparities in accessing energy are blocking the social development of communities, especially in rural areas.

Due to the abundance of sun and the possibility to provide access to electricity also in remote areas, solar energy presents a great potential for enabling the socio-economic development of large parts of Mali's population. The solar potential is estimated at 5-7 kWh/m2/day and a lighting duration of 7-10 hours/day, well distributed over Mali. So far, the PV technology has been utilized to supply the basic needs of the population such as water pumping, lighting, battery charging and refrigeration represented as follows: solar water pumping representing more than 65% of the total PV installed power, communication representing 20%, lighting representing 13%, refrigeration representing 1.6%, (LESO, 1994).

The overall energy strategy for Mali has been focused on the development of local resources such as hydropower and solar energy. This has been intended to keep oil importation as low as possible. Here, the main objectives of the national energy policy are: promotion and expansion of renewable energies, searching for financing mechanisms that are adapted to renewable energy technologies and ensuring a sustainable environment for these technologies. The adoption of the new Electricity Act also brought the end to monopoly by EDM and opened up competition under transparent regulation by an independent agency. Other important policies are the introduction of an import tax exemption for solar modules, wind turbine blades and pump turbines as well as the National Renewable Energy Action Plan that aims at installing 1.42 GW of renewable energy in Mali by 2030 (Spaes, 2020). Mali is also a member of regional organizations (such as ECOWAS, Senegal River Basin Development Organization) with energy policies that might have an influence in the management and distribution of energy in the country.

2.2. Methods

This study combines qualitative methods and the active participation in a field visit in Katibougou, Mali permitted to have an in depth discussion and interviews with local stakeholders such as community leaders, local university, EDM and the villagers to understand the complexity and nuances of the research focus. The main sources of data and information for the study were collected from literature works (e.g. published, peer and non-peer reviewed, and unpublished sources). The collection process has been in combination with the analyses of secondary data obtained from World Bank databases (e.g. The World Bank Group, 2021 and 2022) and others (e.g. Worldometer, 2022) on population and climate information for Mali. In addition, the consultation and involvement of local experts who double as project partners were valuable in strengthening the analysis.

3. Agrivoltaics across the Water-Energy-Food-Nexus

3.1 Agrivoltaic systems: application and current status

Agrivoltaic (AV) offers an innovative approach to simultaneously address water, energy and food security in Mali and Africa as a whole. The approach seeks to integrate the production of water, energy and food on the same unit of land in order to achieve higher efficiency in land-use, alleviating potential land-use conflicts between energy and agricultural production and thus, contributing to a more ecological and socio-economic sustainable development. The land use efficiency as defined by the land equivalent ratio (LER) in return has the potential to increase by up to 90% if compared to traditional single land use systems (Trommsdorff et al. 2021). The LER represents the ratio between the area of an AV installation and the sum of areas that would be necessary to generate the same agricultural and electrical output. Additional benefit of implementing agrivoltaics is that it could reach even further in African rural areas, considering the relevance of agriculture as a source of employment and income generation for the local population.

Agrivoltaic systems can be classified into two categories, namely open agrivoltaic systems and the closed agrivoltaic system. Fig. 3 details the distinction between the two systems. Open agrivoltaic systems include interspaced PV systems which are standard fixed or single axis tracking ground mounted systems with extended spacing between module rows, allowing for agricultural activity in-between or vertical with PV modules. Overhead PV systems are usually elevated (2-6 m) above ground level in order to ensure agricultural activity beneath the panels can continue unobstructed. Systems can either be fixed, single or dual axis tracking. The shading rates in this system range between 20-70% to ensure healthy crop growth (Weselek et al. 2019). Crops cultivated within this system include but are not limited to: orchards, vineyards, hay and fodder varieties and vegetables. PV greenhouses fall under the category of closed systems and the typical applications here are horticulture and aquaculture.

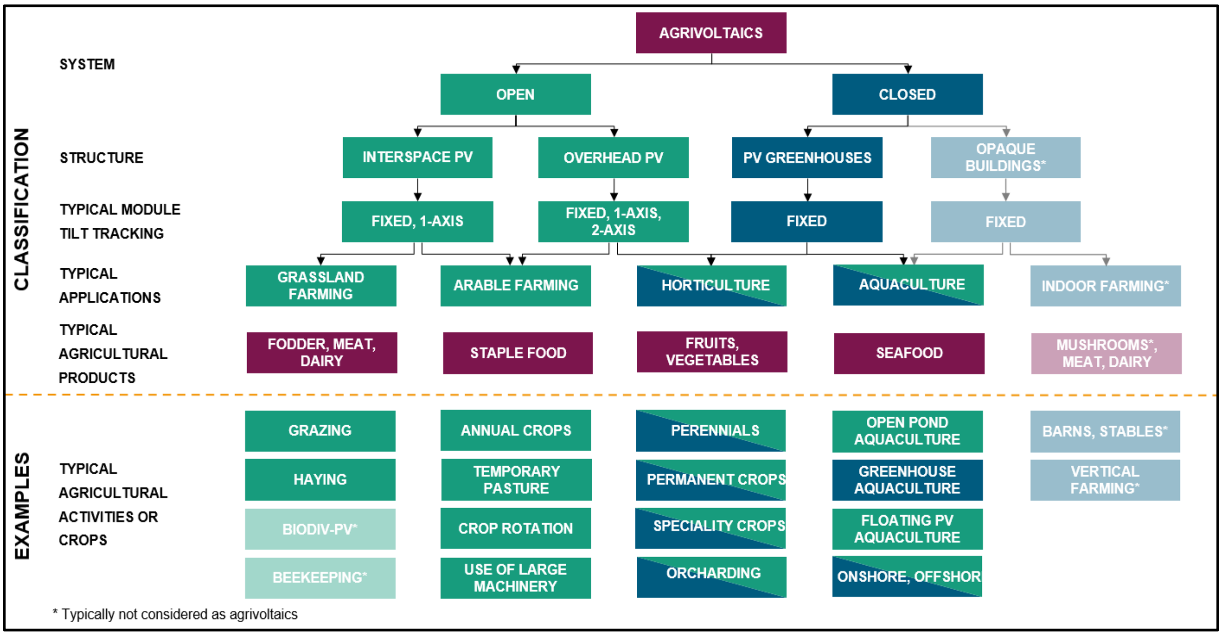

Fig 3: Classification of agrivoltaic systems and typical associated agricultural activity

Agrivoltaic systems show a large variety of applications with different technical characteristics. Nevertheless, the main objective of successful installation is not to hinder agricultural activity. This was recently highlighted in the German preliminary standard DIN SPEC 91434 (DIN, 2021). The key points mentioned in the guideline included:

- Agricultural production on the land should remain possible during the lifetime of the AV system.
- Land loss due to the installation of the AV system should not exceed 10-15%.
- The agricultural yield after the installation of the agrivoltaic system must amount to at least 66% of the reference yield. Whereas the reference yield is defined as a three-year average value of the same agricultural area before the installation.

In addition, systems layout that enable a comparatively low cost for installations and easy maintenance are of great importance since often the initial capital is usually not affordable for many rural communities in Africa.

3.2 Benefits of agrivoltaics across the Water-Energy-Food Nexus

A key contribution of agrivoltaics to the WEF Nexus is addressing aspects of a changing climate through the maintenance of agricultural activity while protecting crops from climatic elements and simultaneously generating electricity. The energy generated can be used in multiple ways, including water pumping for irrigation purposes on farms, provision of energy to accessories such as cold storage, supplying electricity to surrounding communities or potentially even to feed into the grid. Additionally, the PV module surfaces can be used to collect rainwater, providing an alternative water source.

In general, solar photovoltaic systems, through their flexibility in usage, offer a unique opportunity for the energy sector to provide "packages" of energy services to remote rural areas for rural health care, education, communication, agriculture, lighting and water supply (Hernandez et al. 2019). PV systems are cheaper when compared to conventional approaches such as installing power lines and transformers for various applications e.g. building lighting, water pumping for livestock farming and irrigation purposes etc. (Chel & Kaushik, 2011).

Therefore, energy generated from the agrivoltaic system would significantly contribute in reducing costs or replacing alternative, environmentally unfriendly sources of energy, such as diesel generators commonly used in rural communities.

Furthermore, depending on the location and climatic conditions, especially in arid regions and drylands, the shading effect provided by the PV panels could have multitude benefits including creating a microclimate suitable for the crops beneath, reduction of daytime temperature, direct sunlight and atmospheric demand for water and an increase in nighttime temperature, air humidity and soil moisture, compared to a traditional agricultural setting (Barron-Gafford et al. 2019, Marrou et al. 2013). The general assumption is that in dry, hot and sunny climatic regions such as Mali, most agricultural crops cultivated underneath agrivoltaic systems are expected to respond with higher yields as the partial shading protects them from excessive sun, heat and severe weather events. This partial shading effect also increases the resilience of the crops to changing climatic conditions, thus also having a positive effect on the crop quality.

Additionally, rainwater could be harvested directly from the solar panels and used for irrigation or for other purposes on the farm and their surroundings. This could potentially facilitate the installation of irrigation systems, hence improving sustainable water management (Amaducci et al. 2018). The direct transfer of rainwater to a storage system bypasses the natural mechanism in which rainwater falls directly on the ground and infiltrates the soil, eventually replenishing the groundwater sources (aquifers). This process has multiple benefits including the maintenance of the quality of rainwater (i.e. rainwater collected by the agrivoltaic system does not get salinized nor collect excess nutrients and contaminants present in soils) and reduction in over extraction of groundwater resources (Glendenning et al. 2012). As a downstream benefit, energy used for water purification, and for pumping of water from deep natural aquifers and distant sources is reduced.

According to Conway et al. (2015) due to the rigorous structure of government departments, agencies and policies regarding the water energy and food sectors, efforts to integrate these sectors are often restricted. Additionally, different scenarios and models represent a challenge to identify a joint impact on GHG reductions and the overall tackling of climate change (Conway et al., 2015). The special setting of the agrivoltaic system provides the unique opportunity to integrate these sectors while also having the potential to address diverse GHG emissions from these sectors.

4. Opportunities and challenges of agrivoltaic systems for rural communities

Agrivoltaic systems as innovative technology enabling electricity production and improving food production simultaneously thus have the potential of filling the missing gap on food security, access to water and to energy. In the following section the opportunities and challenges of agrivoltaics for rural communities in Mali are discussed.

4.1 Opportunities of agrivoltaic system for rural communities in Mali

Technically, the introduction of agrivoltaics in Mali might be highly beneficial. Mali receives some of the highest levels of annual radiation in Africa due to its latitude with an annual average of 2,200 kWh/m2. Fig. 4 shows the Global Horizontal Irradiation (GHI) for Mali. The installation of agrivoltaic systems comes with direct effects, indirect (i.e. second- and third-round) effects and spillover effects that materialize over the lifetime cycle of the system. Fig. 5 shows these effects as well as the aggregate country-specific factors that could come as a result of the installation of an agrivoltaic system. Closer reflection shows, that direct effects on energy generation, water management and agricultural yields are first-round effects only, although they occur throughout the entire lifetime cycle of the system (see Fig. 5) and might even increase over time because of e.g. learning curve effects (see, e.g., van der Zwaan and Rabl 2003; Nemet 2006; Elshurafa et al. 2018).

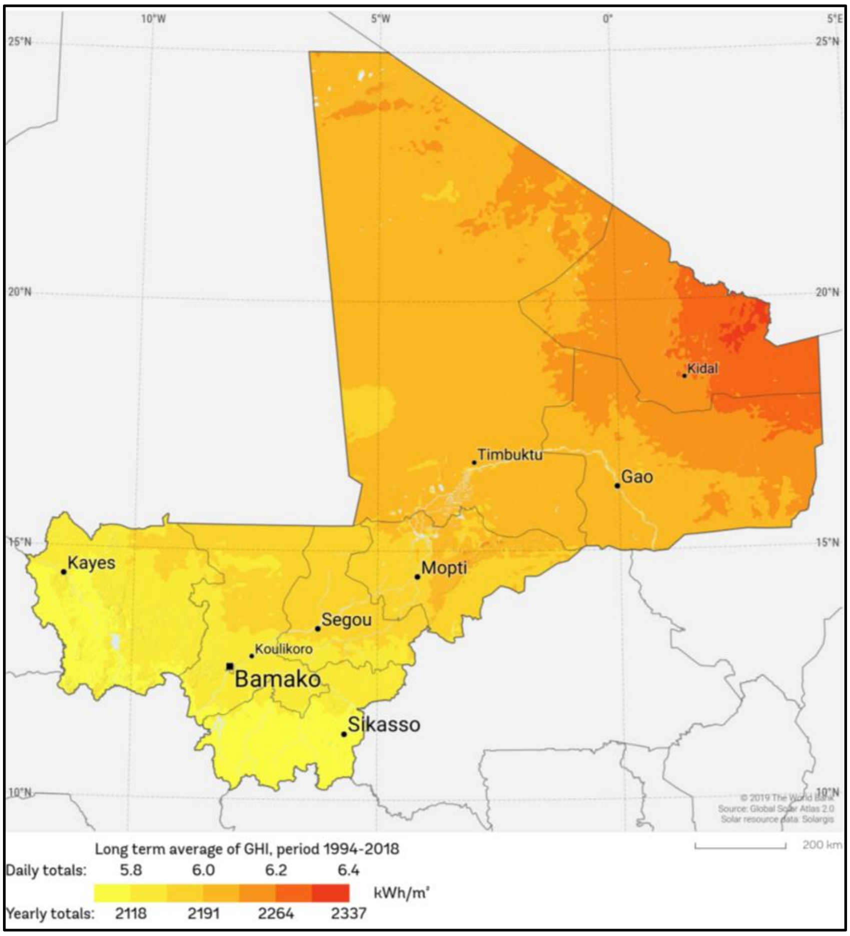

Fig 4: Global Horizontal Irradiation (GHI) for Mali (© 2019 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.)

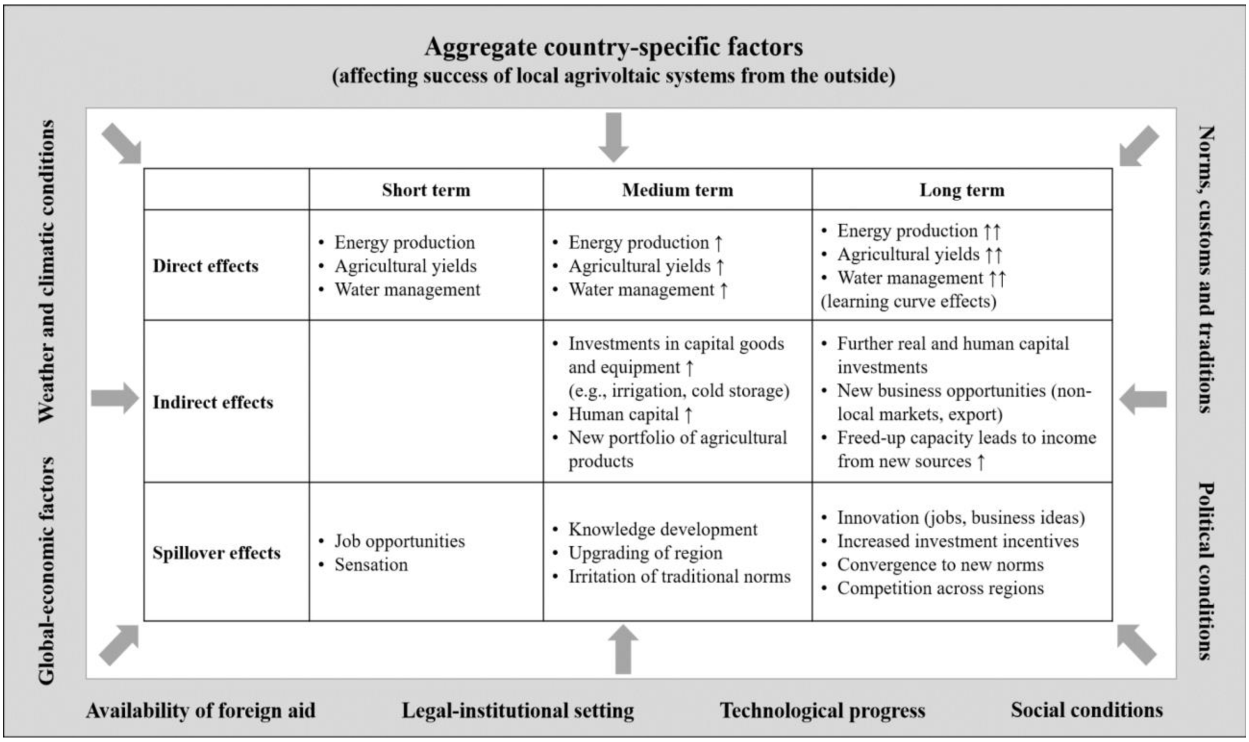

Fig 5. Aggregate country-specific factors

The economic impact of agrivoltaics ought to be seen as a dynamic process with an overlapping value-added at different stages. Turning to indirect effects, short-run income (net of investment costs) generated from, e.g., increased yields might allow owners and/or users of agrivoltaic systems to buy capital goods and equipment, such as irrigation systems or cold storage facilities, which can be utilized over several periods.

An optimized water management might increase crop yields but – more generally – also ensure the amount, quality and availability of water over the seasons. The integrated cold storages offer the possibility to sell agricultural products at a later point of time especially during periods of excess which usually lower the market price. Sometimes the local farmers are forced to abandon these products in the market when not sold because of lack of storage facilities. Cold storages allow for the storage of perishable products, thereby prolonging the shelf-life and allowing local farmers to establish a new product portfolio i.e conserving perishable products until to a more desirable period of need. In the long run, other new business opportunities might arise as a result of investments in the capital stock. For example, it might become possible to sell products in non-local markets or even export them to markets abroad.

Irrigation systems (and, in the longer run, possibly also agricultural equipment that are run using electricity) have important third-round effects as well, by reducing farmers' working hours on the fields. This frees-up work capacity that could be used to generate additional income besides income from agricultural work. Even if saved working hours are not directed into paid work, individual utility might rise through additional leisure time and a reduction of physically demanding fieldwork. Note that, depending on how fieldwork has been organized before and after the implementation of an agrivoltaics system, these benefits might have a substantial gender-specific component. The effects mentioned above might also interact; for instance, with additional resources that are available for investments into capital goods, less fieldwork and an improved portfolio of agricultural products because of cold storages, might allow a local community to acquire a refrigerated truck and have a driver serve distant markets with valuable products.

Agrivoltaic system does not only increase the adaptive capacity of smallholder farmers, but also has the potential of a greater gender empowerment, nutrition and youth employment. The adoption of such a technology could enable women farmers to break their dependence on seasonal rainfall, which typically limits them to a three to six month growing season. Furthermore, the availability of water for small productive activities, such as home gardens and high-value small off-season vegetable plots could have a positive impact on the nutrition and health of the rural communities. According to RES4Africa Foundation and Enel Foundation (2019), households in Africa, on average, have earned an additional $7-8 per week and consumed (including tomatoes, amaranth, okra, and carrots), on average, 1-2 kg of their products per week from home gardens. Such an outcome motivates farmers to engage in market-oriented agri-business activities, and this can ultimately have a transformative impact on local rural economies.

Previous projects and studies that have introduced electricity or multifunctional platforms (United Nations, 2012), into communities in Mali have demonstrated positive cash flows could be generated through the platforms. This does not only expand income from already established economic activity but also provide additional income opportunities. According to Sovacool et al. (2013), the increase in productivity and quality from agricultural processing contributes to higher prices and overall increased income of farmers, thus tackling rural poverty.

In addition, with such multifunctional platforms, women could save time on their (usual daily) agricultural practices and focus on other economic activities, e.g. trade and marketing, further food processing, as well as on education and leisure. The multifunctional platforms contribute to women empowerment through enabling freedom of choice on how to spend time and further businesses. Men also showed increased engagement in economic activity e.g. by providing mobile phone charging stations, opening up carpentry and night-time convenience stores (Sovacool et al., 2013).

Beyond direct and indirect effects related to the immediate production and sale of agricultural products, the construction agrivoltaic systems might spill over to other parts of the local economy and labor market. Due to their size alone, the systems create a sensation and may have a positive impact on a country’s image in terms of the commitment to act against climate change. In addition, job opportunities for the local population arise especially during the construction phase and potentially on a limited level in the security and maintenance area afterwards (Brunet et al., 2022). Looking at medium-term effects one important mechanism is improved labor division: a more diversified portfolio of products resulting from investments into capital goods and equipment requires diversified expertise beyond traditional agricultural techniques. Specializing on specific knowledge and skills goes along with skill-upgrading, i.e., the building up of one’s own human capital, which is one of the main avenues for escaping from poverty (Londoño and World Bank 1996; Attanasio et al. 2017; Olopade et al. 2019). In addition, local labor markets that provide a variety of skills may attract further investments from outside the region.

The agrivoltaic system set up in Katibougou may in fact serve as a widely observed indicator of a dynamically growing local economy and labor market. Ideally, the initial investment starts a virtuous circle of both human and real capital building up and positively reinforcing each other. This might finally spill to the larger region around Katibougou but also attract imitators (and, possibly, future competitors) elsewhere in Mali and beyond. Once several regions in Mali have established comparable business models based on agrivoltaics, the need for improving the insufficient grid infrastructure in the entire country might become so pressing that it would forces the national government to redirect public resources for such projects (Szabó et al. 2011; Randle-Boggis et al. 2021) thus benefiting the entire country. Agrivoltaics can also reduce the dependency on fossil fuels carbon footprint across all sectors especially when embedded into integrated strategies across WEF sectors.

4.2 Challenges of agrivoltaics for rural communities in Mali

Numerous challenges might arise during planning, construction and long-term operation of agrivoltaic systems. Various natural, economic and institutional factors may turn out unfavorable and challenging to the success of investing in agrivoltaic systems (see outer ring of Fig. 5). While some factors might be outside the scope of local actors, others could be kept under control if properly anticipated. The uncontrollable factors include turbulent weather conditions (especially during the early payback period), unforeseen shortages of building material and spare parts, difficult construction sites, political turmoil (which is a very relevant challenge in Mali), unsettled or insecure land property rights, local and global demand shifts, changing preferences of donors etc. While larger investors who operate several sites may be able to hedge these risks, private investments by small communities or even a single individual may suffer severely whenever one of these risks materializes. Potential risks and challenges are further elaborated in the subsequent sub-section.

4.2.1 Technical challenges

Many technical challenges could exist at different stages in the implementation of AV systems in Mali, ranging from the procurement phase to the operation and management of the system. Part of the challenge includes the lack of skilled labor for the construction and maintenance of solar PV projects, a lack of quality control during the procurement and construction, warranties management and little local capacity for maintenance as well as after-sales service. The difficulties in deploying AV technology in Mali could be found in the supply chain which is usually challenging in most African countries for different reasons such as logistics, high transportation cost, security etc. While PV technology does not require heavy infrastructure as other renewable non-modular technologies, efficient logistics need to be addressed with knowledgeable onsite managers. Additionally, the lack of adequate safety guidelines and on-site quality standards (e.g. from machinery tests to quality assurance practices) might not only limit the quality of the system built but also endanger human life.

Maintenance and following-up the operationalization of the AV system could be also very challenging taking into consideration the local infrastructure and available capacities. This increases the vulnerability of the stakeholders. Backlash could also arise from the reliance of multiple energy services on solely one energy source. The performance of the solar technology installed requires regular checkups, with special attention to soil loss due to the climatic condition as well as the effect of temperature and irradiance to electrical components, from inverters to cables. Electrical and communication faults diagnosed through the lifetime of the AV system should be resolved fast enough to prevent a major problem and loss of energy yield. A fast response time to tackle the fault is questioned, especially in rural areas with difficult accessibility. It is therefore important to build local capacity to respond to any issue that occurs during the operation of the AV system.

4.2.2 Social and socio-economic challenges

Considering community engagement, external financing of projects through charitable organizations potentially leads to less identification and hence a lack of perceived ownership with and of the AV system (Diarra & Akuffo, 2002). The lack of perceived responsibility for the functioning of the system might then result in less care-taking and maintenance efforts. In addition, among others, lacking motivation, low levels of payment for maintenance services, trained members leaving the community without adequate transfer of knowledge, conflicts arising from (traditionally assigned) gender roles regarding higher social status achievements by women, seem to be impacting maintenance efforts negatively (Nygaard, 2010; Sovacool et al., 2013). Moreover, the system output of the AV system might be overestimated by users, e.g. through insufficient understanding of the lower efficiency due to high temperatures and hence lower overall performance of AV systems. In addition, commercial dealers might disregard detailed technical explanations to customers on appropriate system operation and provide only poor after sale services (Diarra & Akuffo, 2002).

Another challenge is the time sequencing of energy-consuming activities as a collective action dilemma (Nygaard, 2010). Conflicts potentially arise through different interests regarding amount, time and significance of activities depending on electricity generated by the AV system. Nygaard (2010) critics even proposed only focusing on one energy-consuming activity and private individual- instead of community-ownership to avoid conflicts of interests among community members (e.g. women's groups). Overall, poverty, particularly in rural areas of Mali, is a further burden on development opportunities through AV systems. Generating additional income is thus limited due to the lack of financial resources of potential uptakers of product and other services (Sovacool et al., 2013). More detailed information on potential social and behavior-related challenges that might arise when planning, constructing and introducing an AV system into communities could be found in Nuru et al., (2022) and Gazull et al. (2019).

Agrivoltaic systems are relatively complex in various dimensions, thus constituting another potential risk factor in the African context. Technologically, implementing agrivoltaic systems follows the leapfrogging approach whereby developing countries leapfrog to the most advanced energy technologies (Goldemberg 1998; Gallagher 2006; Amankwah-Amoah 2014). According to Van Benthem (2015), economic growth in less-developed countries is not less energy-intensive than past growth in industrialized countries, highlighting the enormous potential (and need) of leapfrogging. However, being latecomers in the industrialization process, less developed countries often are limited in their capacity to implement change and adopt advanced technologies (Goldemberg 2011).

Beyond the technological realm, substantial societal challenges may arise. Here, there are two partly intertwined aspects which includes (1) how to govern the new technology and (2) what are the repercussions to traditional models of living in the neighborhood or village where the agrivoltaic system has been installed. With regards to the first question, situations in communities might lead to a Hardin-type of 'tragedy of the commons' (Hardin, 1968), when by in a small village, a private good or production facility is treated as common property. There is therefore the need to establish a governance to ensure that the common resource is efficiently used. The common outcome of bad governance is that the resources are overused and not properly maintained.

According to Ostrom (1990), commons are frequently used efficiently; however, only under certain conditions and usually after introducing a careful monitoring system. Normally, it takes some time to establish the respective rules or institutions that help to achieve this outcome. Against this backdrop, leapfrogging technologies might constitute a problem because these technologies might interfere with traditional ways of dealing with local affairs and thus creating an acceptance problem (for a general discussion of acceptance problems, see e.g. Brewer et al. 2015; Hanger et al. 2016; Vuichard et al. 2020). For instance, the traditional use of the seniority principle in decision-making might be problematic, particularly when the most senior people in the administration of a village lack an understanding of modern technologies. This might result in either poor decisions or internal conflict. One could also envisage that the introduction of new technology might challenge existing gender norms because traditional working fields for specific gender might not be relevant. It is therefore important to closely monitor how the introduction of new technology might interfere with local norms and traditions.

4.2.3 Policy and regulatory challenges

Despite the great commitment to energy policy, there are mainly structural problems in the energy sector. According to Power Africa (2018), there are three main bottlenecks facing Mali's energy sector: Utility's unreliability, unstable grid network and an insecure, unstable governance. The uncertainty within the management of the energy sector is also reinforced by its many participants (Diarra & Akuffo, 2002). The involvement of many ministries, departments and other actors also requires many legal texts and regulations which are sometimes difficult to implement and poorly communicated between these institutions. In addition, to create a sustainable competitive business environment that is attractive to private investors and operators would require the reform processes and institutions to be further strengthened.

5. Conclusion

The WEF Nexus approach for energy security allows for the adoption of the most suitable renewable energy solutions or technologies to deliver needs-based services for local beneficiaries and consumers. This variety in technologies or solutions allows for the adaptation of the energy investment components to the needs of local communities. Agrivoltaics offer sustainable solutions to leverage synergies between water, energy and food sectors to enhance resource optimization, foster economic development, and benefit communities. Additionally, agrivoltaic improve access to water and energy in remote areas generating positive impacts across entire economic value-chains. The integration of energy supply, water supply, agri-food supply and services, particularly for rural communities secure access to stable and modern energy services, reduces the risk of investors by diversifying their consumer base, strengthening the business case for investment which helps to reinforce the commercial viability of the integrated business model through an agrivoltaic system.

With growing demand and changing environmental conditions, the agricultural sector has always been adapting to meet the dynamic needs of the society. Innovative solutions such agrivoltaic have been demonstrated in other parts of the world as potential technology in addressing these emerging challenges as well mitigate risks brought on by a changing climate. In the case of increasing temperature, the modules offer additional benefits to plant growth which has been demonstrated to increase crop yield.

Agrivoltaics, especially in case of larger systems – could be realized more cost effectively on average due to economies of scale, which contributes to keeping renewable electricity affordable especially for rural communities in Africa. In addition, the ability to cultivate on the same piece of land and to provide services using energy generated creates job opportunities and enhances the local livelihood.

Solar energy has been forecast as the main energy pillar in the future. With the occurrence of climate change and the increasing scarcity in water in the region would demand new approaches in the agricultural sector, particularly to still keep the sector economically and ecologically resilient. Also, to alleviate land use competition, agrivoltaic technology offers the opportunity for large-scale expansion in photovoltaic systems while still keeping fertile agricultural land usable for food production. Therefore, the triple land use of food, water and energy production through the agrivoltaic technology considerably increases the land use efficiency. Soils that are usually exposed to increasing and more frequent severe weather events such as high temperature, drought or heavy rainfall are now protected or regulated under such a system. However, the technical and economic viability of the integrated triple land use system still needs to be proven in rural communities in Mali.

The agricultural sector remains the main source of employment in Africa, particularly in rural communities. The long-term economic growth and the eradication of poverty in Africa will depend on the ability to industrialize the sector, increase productivity, innovate and advance development of rural areas. Here again, agriculture and their related industries would not succeed without secure energy sources and the availability of sufficient water resources. Agrivoltaics can then act as an enabler that increased food security, improved access and management of water resources for both human and agricultural uses and create new business opportunities that would enhance the livelihood of the local communities. WEF approaches such as agrivoltaics allows for cost-competitive, indigenous and sustainable solutions that could be applied in a decentralized manner, thus easy to implement in many rural communities.

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Statements & Declarations

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The authors have no relevant financial or non-financial interests to disclose

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ambe Emmanuel Cheo, Nora Adelhardt, Jessica Berneiser and Federico Alberto Sanchez

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