Chapter

Economic Development of Rural Communities in Sub-Saharan Africa through Decentralized Energy-Water-Food Systems

Johannes Winklmaier, Sissi Adeli Bazan Santos
and Tobias Trenkle

Abstract

Access to electricity is essential for humanity to develop. Nowadays, 600 million people in sub-Saharan Africa (SSA) have no access to energy services, most of them living in rural areas. However, this region has an outstanding solar potential that could unlock cheap power generation through solar power systems. This raises the question of how rural communities in Africa could avail the benefits of renewable energy systems to gain access to electricity and develop sustainable and productive activities around while facing low purchase power, high interest rates, and high investment costs. The concept of decentralized energy-water-food system proposes a solution: it enables renewable energy access with biomass and solar energy for the private power of the local community, provides secure water supply and year-round irrigation, and increases their livelihood through the profitability of farming and generation of jobs. The concept is applied to a case study in rural Ghana and the least-cost design is obtained. An economic feasibility analysis is carried out on the evaluation of profitability and the total financial value generated for the main stakeholders. The results portrait the economic advantages of the proposed concept design—a hybrid solar-biogas system—to deliver affordable electricity, water, and food supply.

Keywords: rural electrification, economic model, hybrid energy system, sustainable development, least-cost optimization, agricultural productivity, water-food-energy nexus

1. Introduction

In 2017, internal migration was estimated at 1 billion people in developing countries. Rural to urban migration is at the core of this displacement [1]. Rural migration is “one of the main coping and survival mechanisms that is available to those affected by environmental degradation and climate change” [2], an important component of rural livelihoods’ strategies to couple with poverty, food insecurity, lack of employment and income-generating opportunities, and inequality, among the root causes [3]. In sub-Saharan Africa (SSA) rural migration counts at least for

75% of all internal movements [4]. Not without reason, migration is particularly important in this rural-dominated society. Most of rural communities driven to migration in SSA have still traditional rain-fed farming as the main source for income and food security, and their livelihood is characterized by inadequate infrastructure—including the reliable provision of mobility and services such as electricity and water access [3, 5]. These factors, added to exposure to climatic change on farming, push rural dwellers to escape low-productive and climate-vulnerable agriculture, searching the opportunity to raise their level of income. Indeed, according to the last report of rural migrants' profiles of the FAO, around 60% of rural household members in SSA earn less than 1 USD per day and increase their earning to 2 USD per day per rural migrant from the change of main economic activity and access to basic infrastructure [5]. The search for better income-generating activities to cover basic human needs as food, water, and energy supply is hence a crucial motivation.

Decentralized energy-water-food systems (EWFS) propose a sustainable mechanism to improve living conditions in rural communities with the supply of electricity, water, and food using renewable resources and catalyze community welfare by investing in infrastructure for agricultural productivity. This concept was presented in [6, 7], which introduced the theory of techno-economic linear modeling and least-cost design of EWFS. Based on two case studies on rural Zimbabwe and Ghana, both contributions showed the positive effects of sector coupling models on the total system costs.

1.1 Contribution

On the basis of this preliminary work, this chapter formalizes the concept model framework of decentralized energy-water-food systems and presents an analysis of their economic feasibility based on least-cost optimization and scenario analysis, the latter based on the variability of interest rate and energy system design. The aim is to analyze the capability of EWFS to provide economic-feasible solutions for rural electrification in contrast with existing state-of-the-art solutions and assess its financial attractiveness for major stakeholders.

The next section addresses the root motivation of this work, the role of electricity access for sustainable economic development, and presents the challenges met by the public and private sector in providing it to the rural communities. Section 3 deals with the EWFS' concept and the modeling of its least-cost design. Lastly, Section 4 evaluates the economic feasibility of EWFS based on the variability of the weighted average costs of capital and on the change in system design. The scenario development will show that fully fledged EWFS is the most superior system design to achieve long-term economic sustainable development by enabling the access to electricity and water and increasing agricultural productivity with the lowest annual system costs.

2. The energy access paradigm on rural economic development in sub-Saharan Africa

"Access to affordable, reliable, and sustainable energy for all" is the seventh United Nations Sustainable Development Goal and a key enabler of economic growth and human development [8]. The clear correlation of higher poverty level with lower electricity access is estimated to catalyze the private and public investment of 6 billion USD per year over the 2017–2030 period towards electrification in SSA [9, 10]. While progress is being made, there are still around 600 million people in sub-Saharan Africa without access to electricity, over 80% of them living in rural areas [9]. Meanwhile, rapid population growth is estimated to offset the electrification efforts in the period up to 2030: more people in SSA would lack access to electricity than today; 90% of them would be living in rural areas [9].

Targeting electrification in rural areas is a resulting policy strategy to outperform the forecasts and enable the economic development that electricity access could potentially provide to these areas. One dominant strategy is the expansion of national power grid, which has accounted for 97% of new electricity connections since the year 2000; however, it is focused until now in urban areas [9]. Solar-based off-grid systems are the second strategy as SSA receives some of the highest levels of solar irradiation worldwide, with outstanding values of up to 2500 kWh/m^2 annually [5]. These systems, ranging to a power capacity of 5 MWel, offer a cost-effective solution due to the rapidly declining costs of solar photovoltaic systems (PV) and the improvement of their efficiency in energy conversion [11, 12]. However, there are still obstacles in both strategies for the allocation of investment by the public and private sector. Low and dispersed population, low per capita electrical demand, high costs, and efficiency losses of high-voltage transmission lines and distribution networks make rural areas an expensive strategy in the centralized electrification process and rarely economically attractive for electric utilities [13]. In addition, developing countries deal with the lack of sufficient generation capacity, poorly maintained network infrastructure, and the limited ability of rural households to afford the connection charges [10]. Shifting the paradigm towards off-grid solar-based solutions has not yet made a significant contribution on tackling energy poverty in rural areas either [14]. Solar home systems and other solutions tailored to the low payment capacity of the rural population offer the most basic private power, usually for lighting. This access does not enable economic development [15]. As shown in **Figure 1**, 1000 kWh per person are need for a medium human development, which is not achieved by the provision of light alone. Conversely, off-grid renewable solutions tailored for agriculture and other productive uses, which could potentially create jobs and increase the income level of the community, require a high upfront investment. This, coupled with interest rates of 15% and higher, depicts an unattractive high-risk investment for the private sector and an unattainable barrier for rural households, which are constrained by their low purchase power [17].

These challenges require electrification strategies of holistic nature, one that "plans to meet the targets for household electrification taking into account other

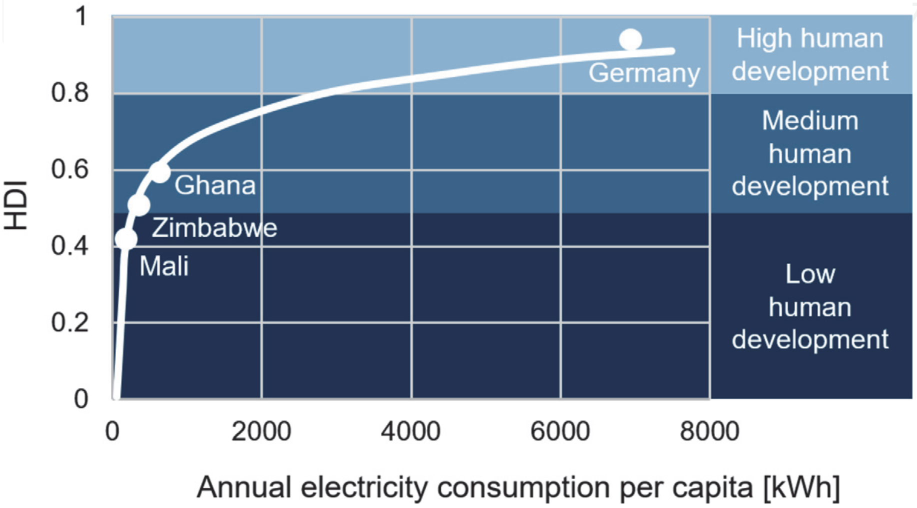

Figure 1.
Macro-level correlation between electricity and human development [16].

development goals and opportunities to use energy access to stimulate economic activity" [9]. In the absence thereof, rural electrification may not bring the economic development it promises.

3. Decentralized energy-water-food systems

Decentralized energy-water-food systems are the proposed solution for rural farmers in SSA to provide the necessary amount of electricity that fosters a higher level of human development. It addresses the low purchase power of the local community, gives renewable-based power access as pillar for human development, and increases the income of local community through agricultural productivity. It is based on the water-energy-food nexus, a conceptual framework for integrated resource management, which took particular prominence in 2011 as a wake-up call reacting to the forecast of a worldwide increasing resource demand, climate change, and the awareness of the unsustainable stress on scarce resources (energy, water, and food) [18]. As a result, it supports the coordination and management of the three sectors and the decision-making process under the consideration of synergies and trade-offs between the three resources when dealing with human development challenges [19]. This system thinking has from henceforth had an impact on the new policy frameworks, business assessment methods, and modeling tools, specially addressing challenges in the urban context and the multi-sectoral use of energy [20]. However, the application of this approach in the context of rural development of farming communities is limited. Due to the transformational effect of the nexus thinking [21], it deserves the formalization of a concept framework that is suited for rural farming communities and for sustainable economic development.

The model scheme for a decentralized energy-water-food system with their major inputs and outputs is depicted in **Figure 2**. Key system characteristics are:

1. Hybrid power system
2. Electric water pumps
3. Yield optimizing and sustainable agriculture
4. Biogas generation through agricultural waste

The combination of the photovoltaic battery and biogas system provides electricity to meet the private demands of a community. Because the deployment of diesel generators in off-grid villages is widespread [22], it is considered in this concept as well (1). Private power is provided free of charge in a first step and priced to cover potential system losses if needed. The hybrid power system generates enough power to operate electric groundwater pumps (2), powered mainly with cheap solar energy enabled by the strong global irradiation in SSA and by the flexible load management of water pumps. These pumps supply the community with domestic water demand. In this concept, up to 50 liters per day and capita are provided free of charge to meet the drinking and sanitation water right standards [23]. The pumps supply also all-year irrigation under the consideration of arable land and groundwater use constraints. Community farmers are able to grow crops independent of the rainfall pattern. This allows multiple harvests per year for selling to the domestic or external market participants (3). The resulting higher agricultural productivity leads also to an increase in biomass waste, which is fermented

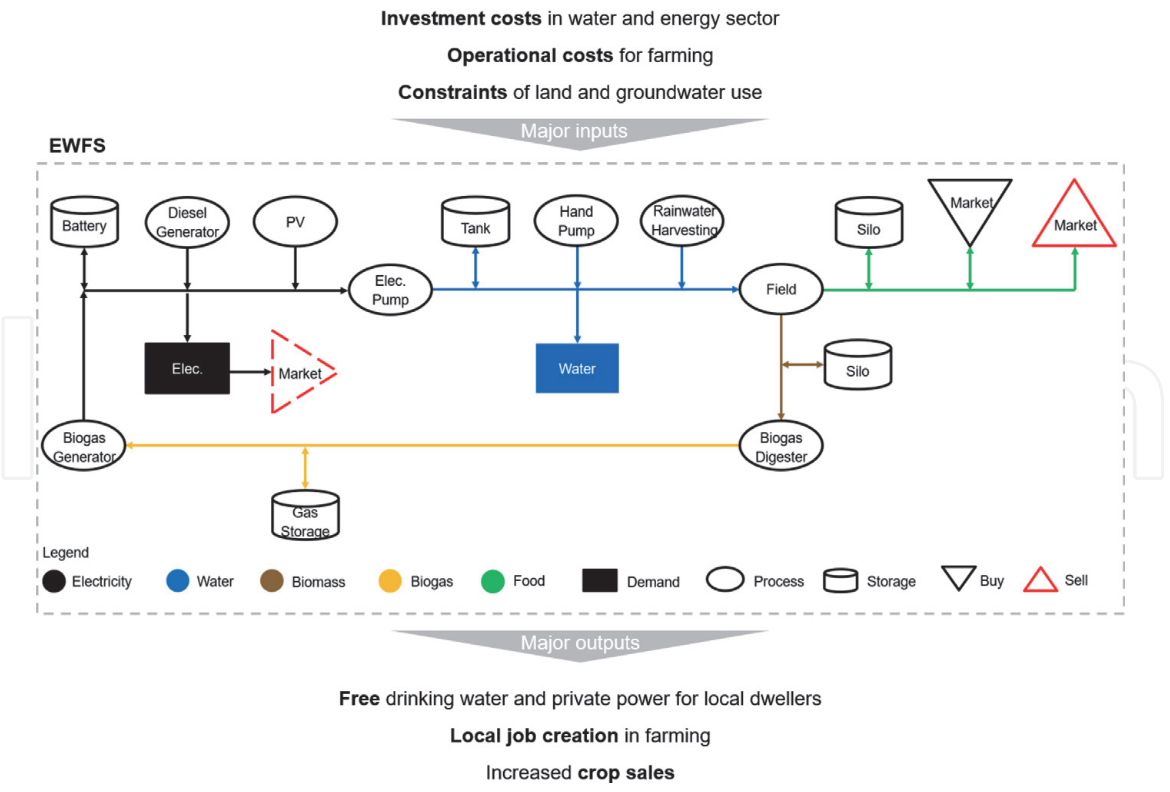

Figure 2.
Business model scheme of decentralized energy-water-food systems. Major inputs and outputs as well as system boundaries, technological components, and commodity flows are depicted. Modified from [6, 7].

into biogas and later converted into electricity (4). As a by-product, the biogas digestion process produces fertilizer that is used for agricultural purposes.

As a result, the rural community not only has gained access to electricity and domestic water supply but also secures the year-round supply of water for productive uses and food. In the medium to long term, the improved agriculture has the potential to create fair-paid jobs, increase the community's purchasing power, lead to a higher standard of living, and provide economic opportunities [12]. This concept also suggests that the high, so far unaffordable, investment costs for infrastructure development can be repaid by the local population through their revenues in agriculture as crops yield increase by up to 300% with regular irrigation [24]. After paying the system investment and operational costs, profits are distributed to the local community. Besides this socioeconomic benefits, preliminary studies of this concept in [6, 7] showed that due to the high resource potential of solar and biomass, the cheapest power generation is based to over 90% on renewable energies.

3.1 Least-cost design of decentralized energy-water-food systems

Decentralized EWFS have potential to deliver social, environmental, and economic returns. The sector coupling causes an unavoidable complexity in designing EWFS, specially when the lowest cost and technical feasibility are to be guaranteed. Optimization models facilitate the engineering effort to provide basic dimensions for the system implementation. These models are the state of the art for rural electrification as they enable stakeholders to understand, evaluate, and ultimately make decisions about the system setup [25, 26]. To date, there are only a limited number of models accessible to researchers that address all three resources of an EWF system together, and most tools cannot be customized to the specific environmental and economic characteristics of the respective project location [27]. The

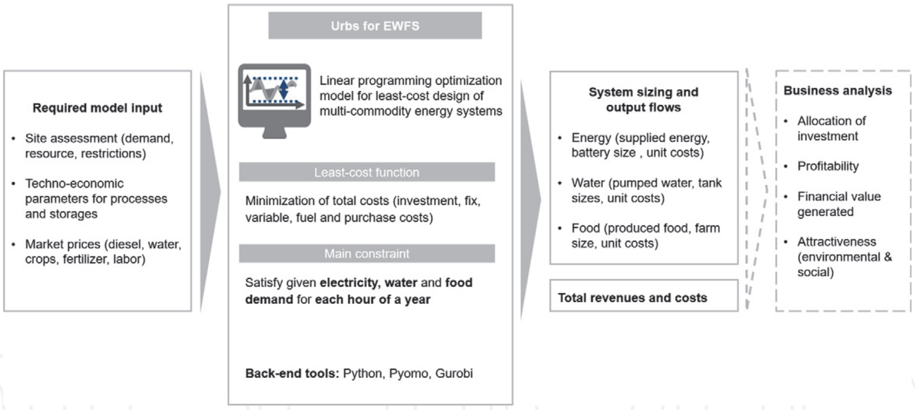

Figure 3.
Work flow to obtain least-cost design of decentralized energy-water-food systems with programming tool urbs. A business analysis is derived from the output results.

contribution [6, 7] addressed the adaption of *urbs*, an economic model, which was originally designed by the Chair of Renewable and Sustainable Energy Systems of the Technical University of Munich (ENS) for distributed energy systems. *Urbs* has a well-documented mathematical description; it is open-source and can be used for cross-sectoral models in any spatial and temporal resolution [28]. Hence, it is used to conduct the economic feasibility analysis aimed in this work.

urbs is a linear optimization tool programmed in Python and identifies the optimal system configuration based on the minimization of the total system costs resulting from the techno-economic modeling of each process and storage technologies in the system. **Figure 3** gives an overview of the *urbs* model for decentralized EWFS.

It requires three kinds of input data. Site data is defined by the demand, solar and rainfall time series, techno-economic parameters of the processes and storages as depicted in the EWFS model schema (**Figure 2**), and lastly the market prices of the commodities that can be bought or sold between the system boundaries. This data is read by *urbs*, which already has an implemented script adapted to model EWFS with a linear approach [7], and the total system costs are optimized. The output data includes the installed capacities related to the three sectors, the commodity flows, total revenues, and costs. A pre-feasibility analysis can be conducted on the basis of these results to evaluate the business attractiveness and ensure a sustainable project operation.

4. Economic feasibility of decentralized energy-water-food systems: case study Kpori

The northern region of Ghana is selected as case study. Although Ghana has a relatively high national electrification rate of 82.5% (2016), there is a drastic regional contrast between urban and rural areas within the country [29]. While the urban Greater Accra area has the highest regional electrification rate of 85%, the three northernmost, sparsely populated regions have an average electrification rate of only 30% [30]. These rural areas are the most expensive regions to be connected to the main grid and therefore particularly suitable for off-grid energy solutions. Since rural northern Ghana is characterized by high solar radiation and high agricultural activity, the use of solar photovoltaics and the coupling of the energy sector to the water and food sectors promise great productivity potential.

Kpori is a village of about 300 inhabitants in the West Gonja District in the north of Ghana. It is an off-grid village with no access to the national energy network, water infrastructure, or telecommunications network. Although agriculture is their main economic activity and livelihood, farming in Kpori is 100% rainfall dependent. At the same time, domestic water supply relies on rainwater harvesting and hand pumps. As a result of a significant drop in rainfall and an increase in temperature over the last century, the already climatically stressed region is dependent on drought-resistant plants such as maize and sorghum. According to on-ground questionnaire, Kpori's inhabitants have an annual income per capita below the lower poverty line of 208 USD/year [31].

4.1 Model input

As depicted in **Figure 3**, *urbs* already includes the EWFS model and optimization script. The input data needed about Kpori are the following:

- Demand time series: Residential electricity, domestic water, food
- Supply time series: Solar irradiation, rainfall
- Technical parameters: Efficiency, capacity, and lifetime of machinery and storage units
- Economic parameters: Weighted average cost of capital (WACC), investment cost, fixed cost, variable cost, purchase cost, and fuel cost of machinery and storage units

The community demand for residential electricity and domestic water is determined by the approx. 300 Kpori inhabitants distributed over 70 households with an average household size of 4.4 [32]. The hourly private power demand is obtained by a Monte Carlo simulation based on the hourly utilization probability of residential appliances and their rated power. This data was obtained from an on-site survey on the nearest electrified farming community. The results of **Figure 4** show a typical load profile of a farming community with a total annual consumption of 42.5 MWh or 138 kWh per inhabitant.

Domestic water demand is set to 50 liters per day and person based on the drinking and sanitation water right standards [23]. Daily food demand is modeled as 658 g of maize grain per inhabitant, which covers the minimum dietary calorie intake of 2400 kcal [33]. In Kpori, up to 263 tons of maize grain can be produced annually on the domestic farmland due to the maximum capacity of arable land of

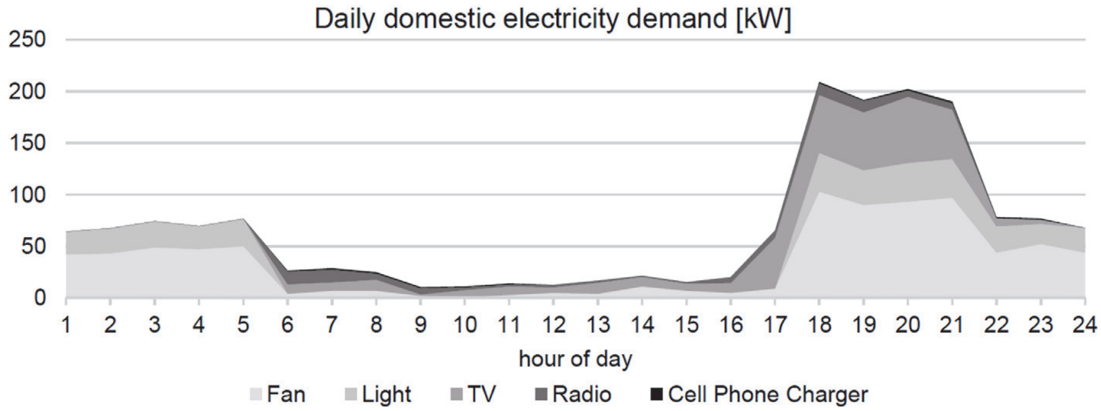

Figure 4.
Time series electricity demand for a Kpori house obtained with Monte Carlo simulation.

15 ha. Mismatches in food supply and demand can be balanced by selling or purchasing maize grain on external markets for 200 USD per ton. Additionally, maize stover and chicken manure is fermented into biogas. The capacity of the biogas digestion process is limited to 367.5 kg/day due to the amount of manure available from approx. 3000 chickens in a nearby town. The solar and rainfall time series are obtained by data from geographical information systems (GIS) or online data bases.

The technical and economic parameters for all technologies depicted in **Figure 2** are listed in the Appendix. Lastly, the weighted average cost of capital is assumed to be at the market rate of 15% according to the study [17].

4.1.1 Scenario development

The proposed scenario development, summarized in **Table 1**, evaluates the economic feasibility of a EWFS for sustainable project operation and as an attractive investment for its stakeholders. The base scenario (S1) analyzes these factors for a complete EWFS, as designed in **Figure 2**, with a cost of capital at the average market rate of 15%, the integration of all power generation technologies (diesel generators, solar photovoltaics, and biogas generators), and the coupling of the three sectors: energy, water, and food. Secondly, the system's sensitivity to changes in the cost of capital is tested through a parameter variation for discrete values between WACC 0% and WACC 30% (S2). The WACC variation serves as an appropriate starting point to evaluate the economic attractiveness of a decentralized EWFS in SSA. Indeed, there are highly investment-intensive installations related to an EWFS, and the WACC is therefore of great relevance. The third analysis tests the changes of power-generating technologies in the system design. It compares the fully fledged EWFS, in which electricity is generated from diesel, solar, and biogas, with a system without biogas and a system based exclusively on diesel.

4.2 Optimization results

The techno-economic results for all scenarios are listed in the Appendix.

4.3 Results of base scenario S1

Starting with a look on the economics of the base scenario depicted in **Figure 5**, the total system costs (52,562 USD) slightly exceed total revenues (52,560 USD) by 2 USD—the profitability break-even point is almost reached. In this scenario, the maximum field capacity of 15 ha is utilized, covering the entire domestic food demand (70 tons) and selling the remaining 193 tons to external market participants. Maize grain is sold to the domestic community at the market price of 200 USD per ton and accounts for one quarter of total revenues. On the cost site, the biggest contributor is labor costs related to agriculture, which accounts for 37% of the total costs. The second biggest contributor is investment costs, 30% of total

Scenario title	WACC (%)	Technologies	Sectors
S1: Base scenario	15	DG + PV + BG	E + W + F
S2: WACC variation	0–30	DG + PV + BG	E + W + F
S3: Technology variation	0, 15, 30	DG,DG + PV	E + W + F

Table 1.
Modeled scenarios.

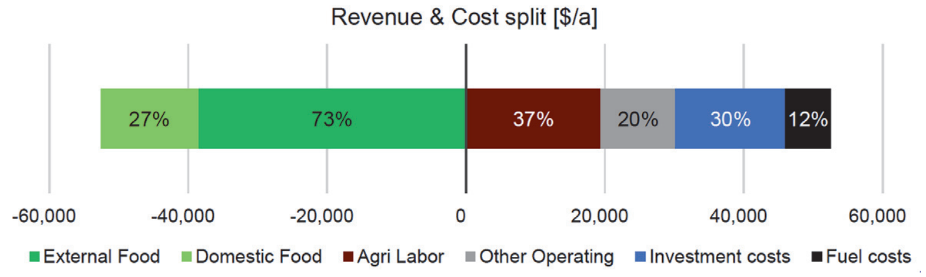

Figure 5.
Costs and revenues for EWFS with WACC = 15%.

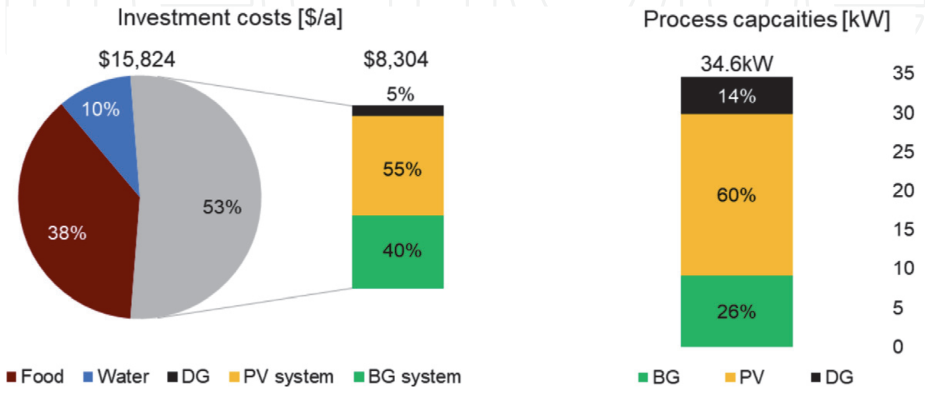

Figure 6.
Investment costs and capacities of power generation technologies.

costs—consisting of depreciation expenses (9%) and cost of capital (21%). Diesel expenses (fuel costs) account for 12% of total costs.

Provided that the domestic community purchases its food from the system and water is provided free of charge, the 2 USD loss must be allocated to the total domestic electricity consumption of 42.5 MWh/year equaling an electricity fee of 0.01 USD/kWh. The total annual costs for energy, water, and food equal 45.52 USD per capita.

Total capital expenditure (CapEx) for long-term assets amount to 98.4 k USD, which is only 30% of the cumulative investment costs over the respective useful life of the assets. The remaining 70% of the cumulative investment costs originates from the WACC and is distributed to investors. Analyzing the annual investment costs on a technology level, as depicted in **Figure 6**, it is observed that the majority of the annual investment costs is invested in electricity-related technologies (53%), while 38% is spent on food-related assets and 10% on water-related assets. Within the costs for energy-related investments, the majority (55%) is invested in solar photovoltaics and only 5% in nonrenewable electricity generation technologies (diesel generator). However, the diesel generator accounts for a drastically greater share of total installed capacity (14%) then of total investment costs (5%) illustrating the low specific investment costs of this technology. In contrast, the relatively lower ratios of installed capacity to investment costs for photovoltaic and biogas systems reflect the high CapEx intensity of renewable energy technologies.

The unit costs of the respective commodities, as shown in **Table 2**, depict that the costs related to producing 1 ton of maize grain (164 USD) are below the sales price of 200 USD. The profit generated from this revenue-cost difference is used to provide water free of charge and subsidize electricity prices to the domestic community. The unit cost of electricity (LCOE) is at 0.22 USD/kWh. Due to the relatively high cost of capital as well as the CapEx-intensive photovoltaic and battery system, LCOE from PV (0.18 USD/kWh) is still above values around

Commodity	Unit	Costs
Electricity total	USD/kWh	0.22
Electricity from diesel generator	USD/kWh	0.41
Electricity from solar photovoltaics	USD/kWh	0.18
Electricity from biogas generator	USD/kWh	0.14
Water	USD/m^3	0.05
Food	USD/ton	164

Table 2.
Unit costs of electricity, water, and food.

Stakeholder	Financial value generated [USD/year]
Labor	19,425
Community	−2
Return to investors	10,869
Total financial value generated [USD/year]	30,293

Table 3.
Total financial value generated.

0.13 USD/kWh, which is the benchmark for small-scale PV systems in Germany [34]. Sufficient profits from maize grain production enable an almost complete subsidization of electricity for the local community and burden households with only 0.03 USD for electricity per year to cover the loss of the system.

The financial attractiveness of the project for all major stakeholders is shown in **Table 3**. This analysis does not include a financial valuation of the water and electricity that is provided to the domestic community free of charge, nor does it account for social and environmental value added. Some system expenses can be considered as income to the respective shareholders. Consequently, labor expenses of 19,426 USD are income to the domestic community. The system loss of 2 USD is allocated among the entire domestic community. The net cash flow from labor and system losses to the community of 19.4 k USD exceed total community expenses of 14 k USD for food. Annual returns to investors of 10.9 k USD match the market cost of capital (15%). The total financial value added to the main stakeholders amounts to 30.3 k USD per year.

Altogether, the base scenario presents an economically feasible solution to provide the domestic community of Kpori with electricity and water free of charge as well as to produce enough maize grain to meet the domestic demand and sell crop surpluses on an external market. Total funds of 98.4 k USD must be raised to finance long-term assets. The maximum capacity of farmland and biogas is utilized; 82% of the consumed electricity is from renewable resources.

4.4 Results of WACC variation scenario S2

Profit overview illustrates an almost linear relationship between the cost of capital and the system profitability. Results show that for all scenarios between WACC 0% and 20%, the cost-minimizing system is designed in a dimension that the maximum farmland capacity of 15 ha is cultivated. Consequently, the annual demand and supply for all three resources energy, water, and food are almost constant at 80 MWh, 205,000 m^3, and 263 tons, respectively. For the WACC 30%

scenario, maize grain production is still at 104 tons per year and hence more than sufficient to meet the annual domestic demand of 70 tons. The domestic demand for electricity and water remains constant, but cultivable farm land decreases.

Figure 7 provides an overview of the annual revenues and costs of the respective profit maximizing system design. Revenues move proportionally to the food production, remaining constant all through the WACC 20% scenario (52.6 k USD), and decrease by 60% for WACC 30% to 20.9 k USD per year. Agriculture-related labor costs and other operating costs move in line with revenues, accounting for approx. 37 and 21%, respectively. Investment costs and fuel costs increase with higher WACC as they cover investor returns and an increase in consumed diesel; thus, investment costs and fuel costs are the main drivers of profitability.

Figure 8 shows the EWFS profitability. A fully socially financed system (WACC 0%) generates 14.1 k USD in annual profits, equivalent to a profit margin of 27%. In the case of a WACC 10%, which could represent the support of a financial cooperative, costs would increase by 24%, resulting in an annual net profit of 4.8 k USD, equivalent to a 9% net profit margin. The profit break-even point is reached for a WACC value slightly below the expected market rate of 15%; for WACC 15% a net loss of 1.8 USD is generated. Under the premise of free electricity and water, increasing net losses are generated for WACC values greater than 15%, which implies that the business model is no longer economically sustainable. For the scenario of WACC 30%, costs exceed revenues by the factor of 0.5, resulting in an annual net loss of 10.4 k USD. The profit overview illustrates an almost linear relationship between the cost of capital and the system profitability. An increase in WACC by one percentage point results in a decrease in profits by 880.42 USD.

Regarding the cost analysis, investment costs are the only cost category factored in the cost of capital, as it is assumed that all other expenses can be financed internally going from period to period. Consequently, it is intuitive that with an

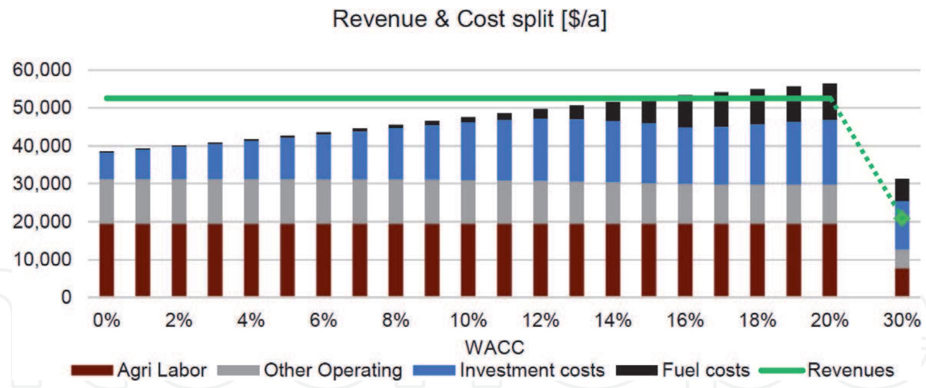

Figure 7.
Costs and revenues for EWFS for WACC variation from 0 to 30%.

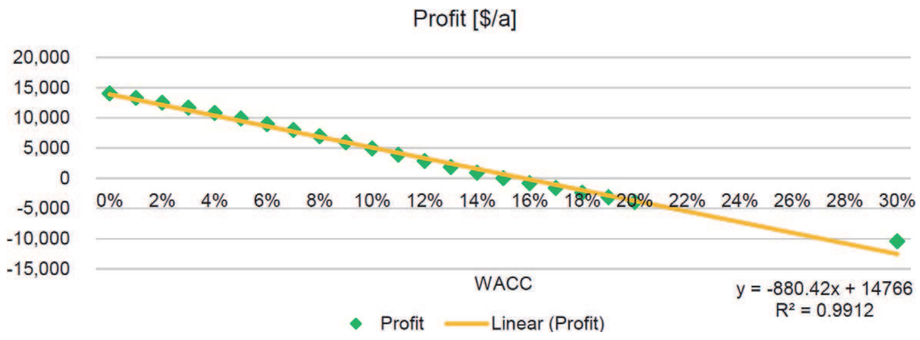

Figure 8.
EWFS profitability for WACC variation from 0 to 30%.

increase in cost of capital, the system design shifts towards CapEx-light technologies. Therefore, the share of CapEx in the cumulative investment costs continuously decreases, and the share of investment costs in total costs tendentially increases (**Figure 9**). This in turn implies that investment costs are generally impacted stronger by the increasing returns to investors than by the reduction in CapEx. Nevertheless, there are some exceptions which explain the dip around WACC 16% where the increase in cost of capital is overcompensated by a drastic decrease in CapEx of 11%. Highest capital expenditures and thus largest external funding requirements occur in the WACC 0% scenario, in which 139.0 k USD is invested in long-term assets. With an increase in WACC, the required funding decreases by 70% to 41.7 k USD in the WACC 30% scenario. At the WACC market rate of 15%, total required funding amounts to 98.4 k USD and accounts for 30% of cumulative investment costs. **Figure 10** shows the variation of process capacity and electric power generation with the increase of WACC. Since PV is the most CapEx-intensive power generation technology with 1400 USD/kW of installed capacity followed by the biogas generator with 675 USD/kW and diesel generator with 500 USD/kW (see Appendix), PV is continuously substituted by diesel generators as the WACC increases. With the decrease in installed capacity of the inflexible but volatile solar power source—and the limited storage capacity due to high investment costs related to the corresponding battery system—diesel-generated electricity increases as biogas is already fully utilized. For low WACC values, diesel power accounts for only a small share of the total electricity, but starting at WACC 13%, diesel-generated electricity already accounts for a substantial share of 12% and continues to increase to around one third of total produced electricity for WACC 20%. Biogas capacity and energy remain almost constant at their maximum levels.

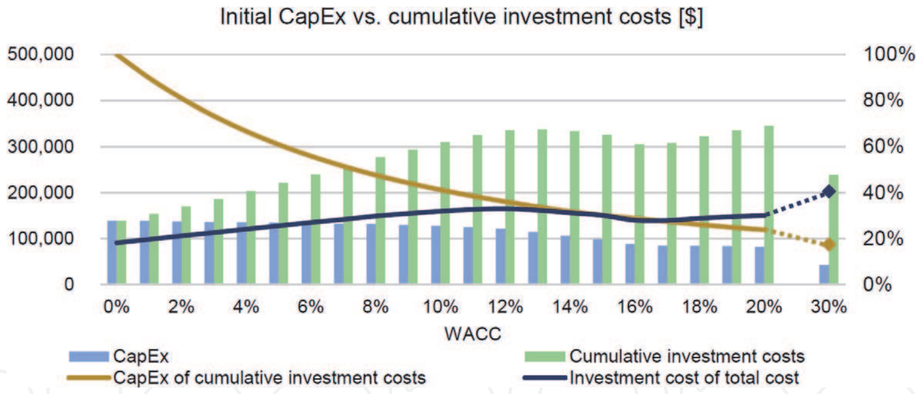

Figure 9.
Capital expenditure and cumulative investment costs for WACC variation from 0 to 30%.

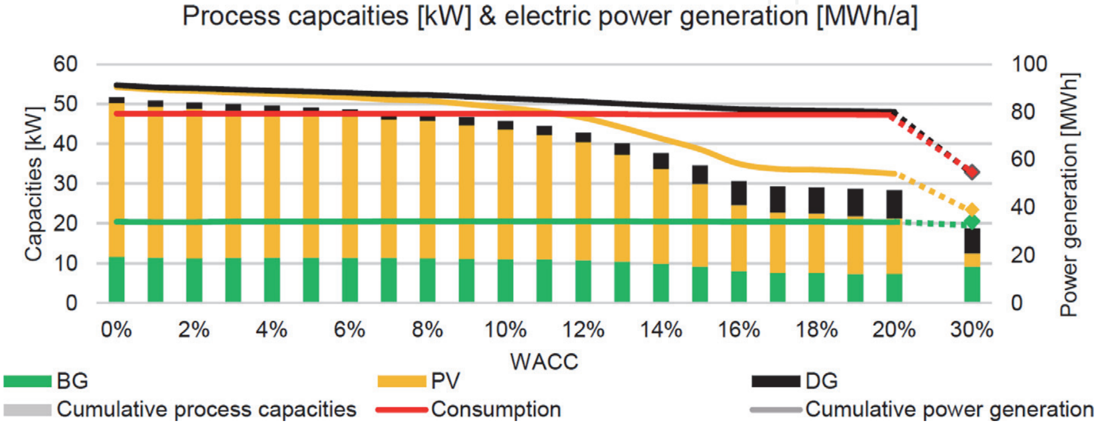

Figure 10.
Process capacities and electric power generation for WACC variation from 0 to 30%.

Table 4 outlines the variation of the unit costs of electricity, water, and food with increasing WACC. With an increase in WACC, the weighted average LCOE increases from 0.08 USD/kWh (WACC 0%) to 0.29 USD/kWh (WACC 30%). This is not only because the LCOE from PV and LCOE from biogas system (BG) increase by a factor of 3.9 and 2.6, respectively, but predominantly because the electricity mix shifts from the relatively cheaper technologies with high CapEx (PV and BG) to the more expensive but investment light diesel generator (DG). The LCOE from DG slightly decrease from 0.46 USD/kWh (WACC 0%) to 0.41USD/kWh for WACC 15% before again increasing to 0.45 USD/kWh (WACC 30%). This variation in LCOE from DG is related to the opposing impact of an increasing utilization rate and increasing specific investment costs. The development of LCOE is also reflected in the development of the unit costs of water and food as both—the access to water and the production of food—require a substantial amount of electricity.

The total financial value generated, visualized in **Figure 11**, includes the system costs 19.4 k USD (WACC 0–20%) of annual labor expenses related to farming that can be paid to domestic workers. Because the WACC 30% scenario does not utilize the maximum farmland capacity, labor costs are as low as 7.7 k USD. As the WACC represents the relative return to investors, this increases as long as CapEx decreases slower than the increase in cost of capital compensates for. Net profits to the domestic community behave reversely and decrease with an increasing WACC. The maximum total financial value added by the system to the major stakeholders is reached for WACC 0%, where the annual cumulative financial value added to the domestic community and investors adds up to 33.5 k USD and continuously decreases from there on.

Commodity	Unit	Costs		
		WACC 0%	**WACC 15%**	**WACC 30%**
Electricity total	USD/kWh	0.08	0.22	0.29
Electricity from diesel generator	USD/kWh	0.46	0.41	0.45
Electricity from solar photovoltaics	USD/kWh	0.08	0.18	0.31
Electricity from biogas generator	USD/kWh	0.08	0.14	0.22
Water	USD/m^3	0.03	0.05	0.05
Food	USD/ton	132	164	178

Table 4.
Unit costs of electricity, water, and food.

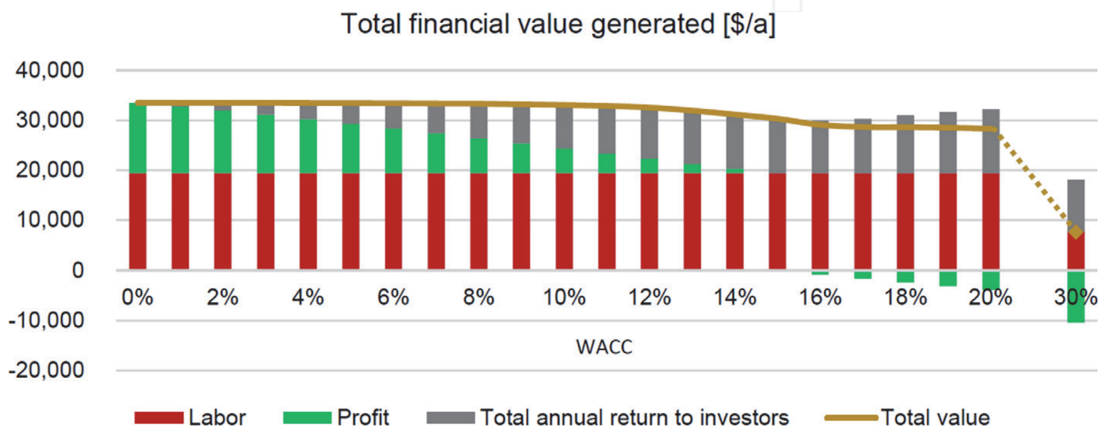

Figure 11.
Total financial value generated for WACC variation from 0 to 30%.

For WACC 0%, the system profits of 14.1 k USD are distributed to the domestic community, corresponding to 45.61 USD per capita—0.10 more than the total expenses required for food. The market-based financing scenario (WACC 15%) breaks even (net loss of 1.8 USD). A finance system with WACC 30% generates a loss of 10.4 k USD, which implies an electricity price of 0.25 USD/kWh or annual costs of 33.84 USD per capita for electricity and total costs of 79.45 USD per capita for energy, water, and food.

Altogether, there is a strong impact of the costs of capital on the financial and technical parameters of the system. The maximum field capacity is utilized up to the WACC 20% scenario, and even for WACC 30%, the food production of a least-cost system would be sufficient to meet the domestic demand. An increase in the cost of capital by 1% leads to a decrease in system profits by 880 USD. The required funds to finance long-term assets amount to 139.0 k USD for WACC 0% and decrease from there on as CapEx-intensive technologies such as PV are increasingly substituted with investment light technologies such as diesel.

4.5 Results of technology variation scenario S3

The costs, revenues, and profit for scenario S3 are depicted in **Figure 12**. For WACC 0%, the cost-minimizing system is designed in a dimension that the maximum farmland capacity is utilized, regardless of the available power generation technologies. Since revenues are directly proportional to the maize grain production, annual revenues are constant at 52.6 k USD. It can be clearly seen that system costs rise with the constraints on combination of power generation technologies. While the total annual costs for the fully fledged system amount to 38.5 k USD, the omission of biogas leads to a cost increase by 29%, while the omission of biogas and photovoltaics leads to an increase by 74% to 66.8 k USD. Hence, a system in which electricity is exclusively generated from diesel is not even net-profitable in a fully socially financed scenario and thus cannot sustainably provide the domestic community with energy and water free of charge. In order to cover the net losses, 46.4 USD per capita and year or 0.34 USD/kWh are charged for electricity. As the WACC increases to 15%, only the fully fledged EWF system operates at full food production, while the omission of biogas reduces the agricultural productivity by 16% and the absence of both renewable energy sources reduces the productivity by 68% to 70 tons per year, which is just sufficient to feed the domestic community. While the fully fledged EWF system breaks even, the unavailability of biogas prevents the systems from being profitable. Net losses for the DG + PV EWF system of 15.4 k USD and 17.3 k USD for the pure DG EWF system imply annual electricity and water expenses of 50 USD and 56.3 USD per capita, respectively; allocated to power consumption, this equals 0.36 USD/kWh and 0.41 USD/kWh, respectively.

In the WACC 30% scenario, none of the EWF systems utilizes the maximum field capacity. While the fully fledged system still produces enough maize grain to provide for the domestic community (104 tons), the DG + PV EWF system and the pure DG EWF system produce just 13 tons and 8 tons, respectively. As the trend of declining profitability with an increase in WACC continues to proceed, even the

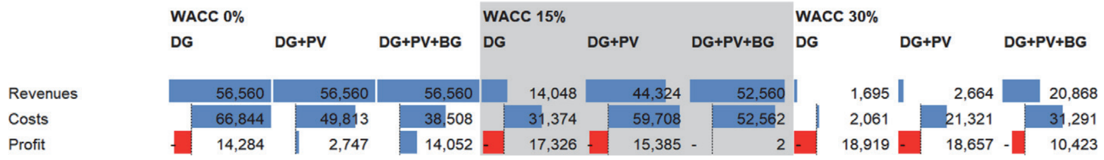

Figure 12.
Costs and revenues variation in power generation technology choice for WACC = 0, 15, and 30%.

fully fledged EWF system generates an annual net loss of 10.4 k USD, while the DG + PV EWF system loses 18.7 k USD and the pure DG EWF system 18.9 k USD. On a per capita level, this means that total annual costs for energy and water for a domestic inhabitant amounts to 33.8 USD (DG + PV + BG), 60.6 USD (DG + PV), and 61.4 USD (DG). In terms of consumed electricity, this implies a price of 0.25 USD/kWh for the fully fledged EWF system, 0.44 USD/kWh for the DG + PV EWF system, and 0.45 USD/kWh for the pure DG EWF system.

Out of this analysis, it is clear that a purely diesel-based EWF system is not sufficiently economical to provide the domestic community with free electricity and water on a sustainable basis, regardless of the cost of capital. The extension of this system by photovoltaics is only the first step towards a superior economic solution in which biogas generators are included as well. Especially for higher cost of capital, the positive financial impact of photovoltaics decreases as investor returns increase and the area of application decreases as agricultural activities decline. Regardless of the WACC, from a financial standpoint, the deployment of biogas systems is indispensable.

5. Conclusions and outlook

This contribution presents an economic analysis of decentralized energy-water-food systems and their capability to provide economic-feasible solutions for rural electrification and thus the potential to enable economic development of the rural population in sub-Saharan Africa. Their decentralized design avoids the financial and governmental obstacles coming with electrification through grid extension. Biogas motors as controllable power generators substitute the costly and environmental unfriendly use of diesel generators. Although the deployment of water pumps increases the system investment costs, they lead to two major advantages compared to micro-grids without their utilization. Firstly, they are flexible loads opposite to most private power consumers (e.g., light bulbs). The water pumps are powered by cheap solar power during daytime with little or even without use of costly battery storage. Secondly, water pumps are productive power consumers opposite to private consumption, because their utilization enables year-round agriculture, which increases local productivity. Hence the local population is enabled to pay back the investment costs despite their formerly low purchase power. The least-cost modeling on the case study of the rural community Kpori, a 300-inhabitant farming village in northern Ghana, confirmed this hypothesis. The system integration of biogas generators and water pumps to closed-loop energy-water-food systems reduces the costs significantly compared to current electrification approaches with diesel generators only or diesel generators combined with solar photovoltaics and batteries. The decreased demand of costly batteries and diesel and increased profits from year-round agriculture lead to annual costs of 2 USD for the for electricity and water supply of the community compared to 17,326 USD for power supply just with diesel, assuming WACC of 15% and that the profits from agricultural sales subsidize the power supply. The cost analysis of these modeling results shows that 37% of the costs are spent for farming salaries and just 9% on CAPEX but 21% on capital costs due to the WACC of 15%. The remaining costs result from costs for fuel and other operation costs such as maintenance. The conducted variation of WACC showed on the one hand that this has a strong impact on the LCOE, which are 0.08 USD/kWh for WACC of 0%, 0.22 USD/kWh for WACC of 15%, and 0.29 USD/kWh for WACC of 30%. On the other hand, increasing WACC leads to significant reduction of installed PV capacities and increased share of power from diesel generators. The utilization of biogas is almost independent of the WACC because of its low CAPEX and constrained maximum capacity due to shortage of livestock manure as input. Based on this model results, decentralized energy-water-food systems have shown their potential to enable LCOE below state-of-the-art off-grid systems and local job creation through improved agricultural productivity.

In order to prove the potential of decentralized energy-water-food systems, they must be implemented on-ground including research on the optimal management and ownership structures; professional requirements for its managers, technicians, and farmers; as well as possible investment strategies. Also, the least-cost model shall be improved regarding more detailed modeling of groundwater availability, nutrients in the soil, water consumption of different crops, and biogas digestion of various inputs. After adding these improvements of the model, it shall be disseminated to and used by interested NGOs and social enterprises. Thereby, decentralized energy-water-food systems could prove their potential to improve access to reliable energy, water, and food supply, to create local jobs, and thus to fight extreme poverty of the population in rural sub-Saharan Africa.

Nomenclature

BG	biogas generator
DG	diesel generator
EWFS	energy-water-food system
E + W	energy and water
HH	household
LCOE	levelized costs of electricity
OpEx	operational expenses
PV	solar photovoltaics
SSA	sub-Saharan Africa

Appendix A: model inputs

	Unit	Value
Load efficiency	%	28
Minimum load	%	25
Investment costs	USD/kW	500
Fixed costs	USD/kW/year	10
Variable costs	USD/kWh	0.01
Lifetime	Year	15

Table A1.
Techno-economic parameters for diesel generator.

	Unit	Value
Module type	—	Crystalline silicon
Tracking system	—	Fixed
Investment costs	USD/kW	1400

	Unit	Value
Fixed costs	USD/kW/year	20
Variable costs	USD/kWh	0
Lifetime	Year	25

Table A2.
Techno-economic parameters for solar photovoltaics.

	Unit	Value
Technology	—	Lead-acid
Depth of discharge	—	60
Energy investment cost capacity	USD/kWh	350
Power investment costs	USD/kW	300
Energy fixed costs	USD/kWh/year	10
Power fixed costs	USD/kW/year	30
Variable costs	USD/kWh	0
Round-trip efficiency	%	85
Lifetime	Year	10

Table A3.
Techno-economic parameters for battery.

	Unit	Value
Load efficiency	%	29
Minimum load	%	40
Investment costs	USD/kW	675
Fixed costs	USD/kW/year	10
Variable costs	USD/kWh	0.01
Lifetime	Year	15

Table A4.
Techno-economic parameters for biogas generator.

	Unit	Value
Maximum installed capacity	ton/h	0.0153
Investment costs	USD/ton/h	788.4 k
Fixed costs	%	3.5% of investment costs
Variable costs	USD/ton	2.1
Lifetime	Year	20

Table A5.
Techno-economic parameters for biogas digester.

	Unit	Value
Material	—	Plastic (PVC)
Investment costs	USD/m^3	60

	Unit	Value
Fixed costs	USD/m^3/year	0
Efficiency	%	100
Lifetime	Year	10

Table A6.
Techno-economic parameters for biogas tank.

	Unit	Value
Technology	—	3-phase AC submersible pump
Total dynamic head	m	50
Rated volume	m^3/kWh	4.4
Investment costs	USD/kW	900
Fixed costs	USD/kW/year	10% of investment costs
Variable costs	USD/kWh	0.01
Lifetime	Year	15

Table A7.
Techno-economic parameters for water pump.

	Unit	Value
Material	—	Ferrocement
Investment costs	USD/m^3	35
Fixed costs	USD/m^3/year	1% of investment costs
Efficiency	%	100
Lifetime	Year	25

Table A8.
Techno-economic parameters for water tank.

	Unit	Value
Arable land	ha	15
Modeled crop	—	Maize
Maize growth time	day	125
Maize yield	ton/ha	6
Annual crop evapotranspiration	mm/year	1330.7
Crop residue to maize grain ratio	—	1.69
Fertilizer costs	USD/ton	400
Labor requirement	day/ha	144
Labor wage	USD/day	3.08
Drip irrigation investment costs	USD/ha	2000
Drip irrigation efficiency	%	90
Fixed costs	USD/ton/h/year	2% of investment costs
Lifetime	Year	20

Table A9.
Techno-economic parameters for maize field.

	Unit	Value
Material	—	Ferrocement
Investment costs	USD/m^3	35
Fixed costs	USD/m^3/year	1% of investment costs
Efficiency	%	100
Lifetime	Year	25

Table A10.
Techno-economic parameters for waste silo.

	Unit	Value
Diesel fuel	USD/kWh	0.106
Maize grain	USD/ton	200

Table A11.
Economic parameters of commodities bought from market.

	Unit	Value
Maize grain	USD/ton	200

Table A12.
Economic parameters of commodities sold to market.

Appendix B: model results

Output variable/technology	DG	DG + PV	DG + PV + BG (=EWFS)
Food production (ton/year)	263	263	263
Total revenues (USD/year)	56,560	56,560	56,560
Total costs (USD/year)	66,844	49,813	38,508
Profit (USD/year)	−14,284	2747	14,052
Profit per HH (USD/year)	—	39	201
Cost per HH for E + W (USD/year)	204	—	—
Electricity costs (USD/kWh)	0.34	—	—
LCOE (USD/kWh)	0.39	0.14	0.08
Unit costs of water (USD/m^3)	0.08	0.04	0.03
Unit costs of food (USD/ton)	189	163	132
Investment costs - Electricity (USD/year)	644	8198	3959
Investment costs - DG (USD/year)	644	104	52
Investment costs - PV (USD/year)	—	8095	2567
Investment costs - BG (USD/year)	—	—	1341
Total installed power (kW)	19	71	52
Installed power - DG (kW)	19	3	2
Installed power - PV (kW)	—	68	39
Installed power - BG (kW)	—	—	12

Output variable/technology	DG	DG + PV	DG + PV + BG (=EWFS)
Total electricity generated (kWh)	78,838	101,197	91,318
Electricity generation - DG (kWh)	78,838	1696	853
Electricity generation - PV (kWh)	—	99,501	56,517
Electricity generation - BG (kWh)	—	—	33,948

Table B1.
Model results for technology variation for WACC = 0%.

Output variable/technology	DG	DG + PV	DG + PV + BG (=EWFS)
Food production (ton/year)	70	222	263
Total revenues (USD/year)	14,048	44,324	52,560
Total costs (USD/year)	31,374	59,708	52,562
Profit (USD/year)	−17,326	−15,385	−2
Profit per HH (USD/year)	—	—	—
Cost per HH for E + W (USD/year)	284	220	0
Electricity costs (USD/kWh)	0.41	0.36	0.00
LCOE (USD/kWh)	0.41	0.34	0.22
Unit costs of water (USD/m^3)	0.06	0.07	0.05
Unit costs of food (USD/ton)	193	203	164
Investment costs—Electricity (USD/year)	1291	5722	8304
Investment costs—DG (USD/year)	1291	1090	408
Investment costs—PV (USD/year)	—	4631	4549
Investment costs—BG (USD/year)	—	—	3347
Total installed power (kW)	15	32	35
Installed power—DG (kW)	15	13	5
Installed power—PV (kW)	—	19	21
Installed power—BG (kW)	—	—	9
Total electricity generated (kWh)	50,349	75,290	81,967
Electricity generation—DG (kWh)	50,349	46,916	17,583
Electricity generation—PV (kWh)	—	28,374	30,292
Electricity generation—BG (kWh)	—	—	34,092

Table B2.
Model results for technology variation for WACC = 15%.

Output variable/technology	DG	DG + PV	DG + PV + BG (=EWFS)
Food production (ton/year)	8	13	104
Total revenues (USD/year)	1695	2664	20,868
Total costs (USD/year)	2061	21,321	31,291
Profit (USD/year)	−18,919	−18,657	−10,423
Profit per HH (USD/year)	—	—	—
Cost per HH for E + W (USD/year)	270	267	149
Electricity costs (USD/kWh)	0.45	0.44	0.25

Output variable/technology	**DG**	**DG + PV**	**DG + PV + BG (=EWFS)**
LCOE (USD/kWh)	0.44	0.43	0.29
Unit costs of water (USD/m^3)	0.06	0.06	0.05
Unit costs of food (USD/ton)	208	207	179
Investment costs—Electricity (USD/year)	2163	3228	8278
Investment costs—DG (USD/year)	2163	2163	974
Investment costs—PV (USD/year)	—	1065	1394
Investment costs—BG (USD/year)	—	—	5910
Total installed power (kW)	14	17	19
Installed power—DG (kW)	14	14	6
Installed power—PV (kW)	—	3	3
Installed power—BG (kW)	—	—	9
Total electricity generated (kWh)	43,853	44,324	54,781
Electricity generation—DG (kWh)	43,853	40,617	15,851
Electricity generation—PV (kWh)	—	3707	4852
Electricity generation—BG (kWh)	—	—	34,144

Table B3.
Model results for technology variation for WACC = 30%.

Author details

Johannes Winklmaier*†, Sissi Adeli Bazan Santos*† and Tobias Trenkle†
Chair of Renewable and Sustainable Energy Systems, Technical University of Munich, Munich, Germany

*Address all correspondence to: johannes.winklmaier@tum.de
and adeli.bazan@tum.de

† These authors contributed equally.

References

[1] Food and Agriculture Organization of the United Nations. FAO Migration Framework: Migration as a Choice and an Opportunity for Rural Development. 2019

[2] Lopez-Ekra S. Workshop on Migration and Climate Change Held. 2017. Available from: https://ghananewsagency.org/social/workshop-on-migration-and-climate-change-held-115501 [Accessed: 10 January 2019]

[3] Food and Agriculture Organization of the United Nations. Migration, Agriculture and Rural Development: Addressing the Root Causes of Migration and Harnessing its Potential for Development. 2016

[4] Food and Agriculture Organization of the United Nations. The State of Food and Agriculture 2018. Migration, Agriculture and Rural Development. 2018

[5] Food and Agriculture Organization of the United Nations. Atlas: Rural Africa in Motion. Dynamics and Drivers of Migration South of the Sahara. 2017

[6] Winklmaier J, Bazan Santos S. Promoting Rural Electrification in Sub-Saharan Africa: Least-Cost Modelling of Decentralized Energy-Water-Food Systems: Case Study of St. Rupert Mayer, Zimbabwe, Africa-EU Renewable Energy Research and Innovation Symposium. 2018. DOI: 10.1007/978-3-319-93438-9

[7] Bazan S, Winklmaier J, Ramde E, Hamacher T. Towards rural development in Sub-Saharan Africa through least-cost modeling of decentralized Energy-Water-Food systems: Case study Kpori, Ghana. (forthcoming)

[8] United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. In A New Era in Global Health. 2018. DOI: 10.1891/9780826190123.ap02

[9] International Energy Agency. WEO-2017 Special Report: Energy Access Outlook. 2017. DOI: 10.1787/20725302

[10] The World Bank. State of Electricity Access Report 2017. 2017. DOI: 10.1596/26646

[11] Mandelli S, Barbieri J, Mereu R, Colombo E. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renewable and Sustainable Energy Reviews. 2016;**58**:1621-1646. DOI: 10.1016/j.rser.2015.12.338

[12] Holmes J. 2016 Findings and Recommendations from the Smart Villages Initiative 2014–2017. 2017

[13] Brivio C, Mandelli S. Rural electrification in developing countries via autonomous micro-grids. 2014. Available from: http://gdee.eu/index.php/resources.html

[14] Williams N, Jaramillo P, Taneja J, Ustun T. Enabling private sector investment in microgrid-based rural electrification in developing countries: A review. Renewable and Sustainable Energy Reviews. 2015;**52**:1268-1281. DOI: 10.1016/j.rser.2015.07.153

[15] Stevens L, Gallagher M, Practical Action. The Energy-Water-Food Nexus at Decentralized Scales: Synergies, Trade-Offs, and How to Manage Them. Poor People's Energy Briefing. Vol. 3. 2015

[16] United Nations Development Programme. Human Development

Reports. 2017. Available from: http://hdr.undp.org/en/data [Accessed: 10 January 2019]

[17] Labordena M, Patt A, Bazilian M, Howells M, Lilliestam J. Impact of political and economical barriers for concentrating solar power in sub-Saharan Africa. Energy Policy. 2017;**102**: 52-72. DOI: 10.1016/j.enpol.2016.12.008

[18] German Federal Ministry for Environment, Nature Conversation and Nuclear Safety (BMU), German Federal Ministry for Economic Cooperation and Development (BMZ). Bonn 2011 Conference: The Water, Energy and Food Security Nexus – Solutions for a Green Economy. 2012

[19] International Renewable Energy Agency. Renewable Energy in the Water, Energy and Food Nexus. 2015

[20] The Water, Energy & Food Security Resource Platform. Resources. Available from: https://www.water-energy-food.org/resources/recent [Accessed: 11 January 2019]

[21] RES4Africa. WEF Nexus Publication:Applying the Water-Energy-Food Nexus Approach to Catalyse Transformational Change in Africa. 2019

[22] Kempener R, Lavagne O, Saygin D, Skeer J, Vinci S, Gielen D. Off-Grid Renewable Energy Systems: Status and Methodological Issues. 2015

[23] United Nations Human Rights Council. Safe Drinking Water as a Human Right. 2015. Available from: https://www.un.org/waterforlifedecade/human_right_to_water.shtml

[24] Energy4Impact. Strategic Advice Helps Solar Irrigation Company Overcome Barriers To Market Scale. Available from: https://www.energy4impact.org/news/strategic-advice-helps-solar-irrigation-company-overcome-barriers-market-scale [Accessed: 11 January 2019]

[25] Bahramara S, Moghaddam M, Haghifam M. Optimal planning of hybrid renewable energy systems using HOMER: A review. Renewable and Sustainable Energy Reviews. 2016. DOI: 10.1016/j.rser.2016.05.039

[26] Mandelli S, Barbieri J. Off-grid systems for rural electrification in developing countries: Definitions, classification and a comprehensive literature review. Renewable and Sustainable Energy Reviews. 2016;**62**: 609-620. DOI: 10.1016/j.rser.2015.12.338

[27] Albrecht T, Crootof A, Scott C. The water-energy-food Nexus: A systematic review of methods for nexus assessment. Environmental Research Letters. 2018;**13**:043002. DOI: 10.1088/1748-9326/aaa9c6

[28] Tum-Ens. urbs: A Linear Optimisation Model for Distributed Energy Systems. 1999. Available from: https://urbs.readthedocs.io/en/latest/ [Accessed: 10 January 2019]

[29] Kumi E. The Electricity Situation in Ghana: Challenges and Opportunities. Washington: CGD Policy Paper; 2017

[30] Arandamola M, Quansah D, Agelin-Chaab M, Paul S. Multipurpose renewable energy resources based hybrid energy system for remote community in northern Ghana. Sustainable Energy Technologies and Assessments. 2017;**22**:161-170

[31] Ghana Statistical Service. Poverty Map for Ghana. 2015

[32] Ghana Statistical Service. Population and Housing Consensus. 2012

[33] Darko A. Cost-minimizing food budgets in Ghana. Journal of Development and Agricultural Economics. 2013;**5**:135-141. DOI: 10.5897/jdae12.097

[34] Frauenhofer ISE. Levelized Cost of Electricity - Renewable Energy Technologies. 2018