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Sustainable solutions for solar energy driven drinking water supply for rural settings in Sub-Saharan Africa: a case study of Nigeria

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Abstract. The lack of safe drinking water and electricity in rural areas of Sub-Saharan Africa is extremely alarming and, together with progressing climate change and political conflicts, increasingly impairing economic development. Only robust technologies of autonomous water treatment systems driven by solar electricity based on sustainable economic concepts can provide clean water and electricity at affordable prices. Technologies for water cleaning combined with off-grid electrification are analyzed for their suitability under different conditions, exemplified for Nigeria, and economically feasible concepts are developed for different target groups: (i) single-farmer concept providing electricity from PV, UV-treated drinking water and irrigation water, and generating income from selling increased crop yields; (ii) farmer cooperative; (iii) community concept, with additional income generation from selling water and electricity; and (iv) rural kiosk concept selling electricity and water, and offering further goods and services. In the latter three concepts, high quantities of drinking water and electricity are supplied by an autonomous, PV-driven water cleaning system with disinfection based on anodic oxidation and *in situ* chlorine production. Only if economically sustainable can drinking water and electricity supply be achieved at a global level, and the UN sustainable development goals be reached. In the framework of a rural community concept, a pilot project starts in Abuja/Nigeria based on the anodic oxidation system for water treatment with an intelligent payment systems and provision of solar-based electricity. © *The Authors. Published by SPIE under a Creative Commons Attribution 4.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.JPE.9.043106]

Keywords: photovoltaics; drinking water; rural communities; farmers; economic feasibility; disinfection.

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1 Introduction

1.1 *Water Availability and Quality in Sub-Saharan Africa*

Water stress is a serious problem for over 2 billion people worldwide, while 2.6 billion lack access to basic sanitation. Physical water stress is described as the ratio of total freshwater withdrawn annually by all major sectors, including environmental water requirements, to the total amount of renewable freshwater resources expressed as a percentage. Thus 31 countries suffer under water stress between 25%, the minimum threshold of water stress, and 70%, while 22 countries experience above 70% of water stress.[1,2] Consumptive water use—water from a watershed that is lost by direct evaporation or plant transpiration—by all human activities has been estimated to be 1800 to 2100 km^3/year, of which food production uses 1400 to 1800 km^3/year,[3,4] thus 90% of water consumption and more than 70% of all fresh water (surface and groundwater) withdrawal is by agriculture.[5,6,7] Irrigation represents 95% of all water uses; specifically, in Southern Asian countries, about 35% of the agricultural land is under irrigation,

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while in Africa less than 1% is irrigated.[8] However, in some areas in Nigeria up to 10% of arable land is irrigated, mostly with surface water, but also 23% of that area is supplied by groundwater.[9] The global groundwater abstraction rate has at least tripled over the last 50 years, and the availability of nonrenewable groundwater resources has already reached critical limits in some areas.[2] In addition to the expected increase in global water demand by 20% to 30% above the current level of water use until 2050,[10] it is projected that due to climate change in Africa additionally 75 to 250 million people will suffer from increased water shortage, going in hand with yield reductions of up to 50% in rain-fed agriculture in some countries.[8,9] Also, global renewable water resources will be reduced by 25% in 2050, and in developing countries, the per capita available quantity will be far more affected than in developed countries.[6,7]

The present and the projected water scarcity will also affect the quality of drinking water, and water sources not suitable for drinking water will increasingly be used, which further limits specifically the availability of drinking water. Therefore, viable solutions for provision of drinking water in rural areas have become even more important. Safe and reliable water supply and sanitation and hygiene practices are defined as basic needs for human well-being and socioeconomic development,[7,11] while poor quality water is a major cause of water-related diseases. Human agglomerations and industries that dispose their wastewater into river streams are an important source of microbial and chemical pollution. Globally more than 80% of wastewater is released into the environment without any pollution removal.[12] Other sources of pollution can be agricultural waste (fertilizers), power plants, and household chemicals.[13] Thus contamination due to the presence of natural and anthropogenic pollutants poses a severe threat to human health.[14]

According to the United Nations (UN),[12] 91% of the world's population in 2015 had access to an improved drinking water source.[15] However, the so-defined water clearly differs from safe drinking water for which standards are defined by the World Health Organization (WHO) drinking-water quality guidelines, as an improved drinking water source only needs to be protected from outside contamination, specifically fecal matter,[15] and its quality is not considered (see Wydra et al., this issue). At least 1.8 billion people use drinking water sources contaminated with feces, and 2.1 billion people are lacking safe drinking water at home.[16]

1.2 *Electricity Supply in Sub-Saharan Africa*

At the same time, about 1 to 1.2 billion people worldwide lack access to electricity, which are mostly the same people who are without access to safe water.[17,18] Ninety-five percent of people without electricity access live in Sub-Sahara Africa (SSA) or Asia and 80% live in rural areas. While more than 600 million people in SSA are without access to electricity,[17] it is the only region in the world where this number is even increasing. Since 2000, the number of people without access to electricity in SSA rose by 100 million. Nevertheless, the percentage of people with electricity supply rose from 23% in 2000 to 32% in 2012.[19]

Power supply in rural areas mostly relies on fuel-based power generators, and shortages of diesel, due to fluctuating costs or transport and delivery problems, directly affect agriculture and small business. Energy features play a dominant role in the water value chain, from (ground-) water pumping for irrigation for food production and provision with drinking water, to powering desalination plants or water treatment and disinfection technologies, additionally to the energy needs in conveying and distribution—representing sectors, which are interlinked in the water–energy–food nexus.[7,20,21] Thus the energy-dependent supply with water for irrigation and drinking water is highly vulnerable to conditions outside the control of the rural population. Off-grid solar energy systems provide sustainable solutions for rural areas and form the basis for socioeconomic development in agriculture, the related food supply chain, and whole rural areas. However, without a technical and economic assessment adapted to the prevailing conditions, a sustainable solution for energy and water supply in rural areas cannot be provided.

1.3 *Water Treatment*

WHO standards represent the minimum requirements for safe drinking water.[22] Water treatment technologies suitable for different rural scenarios in SSA can be categorized into conventional,

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mostly based on cleaning by filtration or combinations of adsorption and filtration (see also Wydra, this issue), and disinfection technologies. New technologies combine provision of drinking water with electricity supply by PV.

1.3.1 *Conventional water treatment technologies*

Multimedia filtration for precleaning of muddy water uses three layers of anthracite coal, sand, and garnet to prevent scaling and fouling, possibly followed by flocculation/sedimentation and microsieves' filtration. This precleaned water is not considered safe drinking water. Another option is the natural process of river bank filtration,[23] which is traditionally used in some countries, mostly in Europe, but also in Egypt, when rivers are in the vicinity. For disinfection, most frequently used procedures are boiling, chlorination, hypochlorite, chlorine dioxide, ozone, UV, addition of chlorine dioxide, hypochlorites NaClO, $Ca(ClO)_2$, electrolysis (+ Cl), and reverse osmosis (RO). These technologies are associated with diverse challenges, such as availability, production, and dosing, use of wood for heating, besides the cost factor of RO.

Activated carbon (AC) filters are widely used in industry and residential water systems. AC can adsorb contaminants such as organic compounds, nonpolar contaminants, disinfection byproducts (e.g., trihalomethanes during chlorination), industrial pollutants, pesticides, and some heavy metals such as lead, mercury, cadmium, chromium manganese, silver, and tin, though the latter effect is variable, and the adsorption of bacteria is low.[24,25] Moreover, bonechar, magnetic nanoparticles, activated alumina, and metallic iron (Fe^0 filters) can be used to remove various impurities from the water, e.g., several classes of aqueous contaminants, some negatively charged molecules, and pathogens.[26–29] For removal of fluoride, a major contaminant of groundwater, mainly in the Great Rift Valley, activated alumina, and other technologies are reported.[30–33]

For the above described (pre-) filtration technologies, as for pure sand filtration, energy is only needed to provide a hydraulic gradient. Energy need is inreasing with decreasing filter pore size, from sieve filters (0.1 to 1 mm), to fine filters (10 μm to 0.1 mm), particle filters (1 to 10 μm), microfilters (0.1 to 1 μm), ultrafilters (10 nm to 0.1 μm), nanofilters (1 to 10 nm), and RO (5A-100A), purifiying water from fine particles to bacteria, from micro- and macromolecules, and ionic impurities [e.g., $SO_4{}^{2-}$, NO^{3-}, Fe^{2+} (ferrous) Fe^{3+}].

1.4 *New Opportunities by PV for Water Supply in Rural Areas*

Irradiance levels of almost 2000 $kWh/m^2/year$ and an average of more than 320 days of bright sunlight make PV systems highly favorable for SSA.[19] For solar PV systems in rural areas—besides costs of the module itself—, additional costs for transportation, installation, mounting, and further equipment such as inverters have to be taken into account. The average costs for a system >1 kW vary between € 2.24 and 6.27/W in African countries[34] and do not include batteries or inverters, since many systems are designed for direct current application. Battery costs in such systems' size vary between € 0.44 and 5.64/ W, costs for systems smaller than 1 kW vary between € 1.61 and 12.45/W, battery costs vary between € 2.24 and 6.09/W, and these prices are steadily falling. For decisions on the type of PV system to be chosen, it has to be considered that solar PV systems have higher investment costs compared to diesel fuel, but benefit from having no fuel and low operational as well as low maintenance costs. Additionally, to assure a successful implementation, technical and economic features such as customers' demand and the offers on the market as well as specific conditions in rural areas need to be evaluated in feasability studies to decide on the most suitable technologies (Table 1).

A relatively new technology specifically suitable for autonomous systems powered by PV is anodic oxidation, which is used by only a few manufacturers worldwide. The chemical process uses naturally occurring salts (NaCl, sodium chloride) to produce *in situ* chlorine by an inline-electrolytic cell using the natural chloride content of the water and by that substituting the external dosing of strong oxidants. The free chlorine disinfects water by killing bacteria and inactivating viruses.[35] A German company Autarcon produces such a system which is used in rural communities in developing countries. Depending on water quality, a filtration system is installed prior or past the chlorination process, which usually is a pressure filter, using either sand or

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Table 1 Options for water and electricity supply for different rural settings, oriented at customers' demand and offers on the market.

Demand	Area	Offer
Safe water, affordable electricity	Remote, rural, or urban periphery	Electricity and water supply
User	**SSA, Southeast Asia**	**Water treatment system**
Individuals	Areas without access to electricity (electricity poverty)	Filtration
Villages	High population growth rate	Electrolytic disinfection
Hotels, lodges, and schools	Need of substitution of diesel generator sets	Anodic oxidation
Health Care Stations	Regions without access to improved/piped water	RO
Small crafts (textile, laundries, and food)		Boiling water
Source		**Solar home systems**
Groundwater		**PV systems**
Rainwater		PV generator and storage
Surface water		**PV minigrids**
Application		PV generator, storage, and distribution
Drinking water		**DC appliance**
Sanitation		Mobile charging and refrigeration
Cooling, process water		**PV diesel hybrids**
Agriculture		**Eco center**
Production capacity		
Water 5 to 30 m^3/day		
Electricity (single user, minigrid)		

manganese dioxide as medium. The filter medium also uses chlorine as an oxidizing agent to precipitate iron, manganese and also arsenic through a co-precipitation process, which are then removed through sedimentation and filtration steps of the system by Manganese GreensandPlus® filtration[36,37] (see also Jaskolski et al., this issue). The system has been successfully implemented in West Bengal. A similar approach of cleaning polluted water from arsenic has also been described by Banerji and Chaudhari,[38] where through corrosion of zero valent iron hydrous ferric oxide is formed, and through oxidation of Fe, As(III) is oxidized to As(V) which both adsorb arsenic. However, the water always needs to be tested before system selection and installation and monitored from time to time specifically for inorganic contaminants (e.g., fluoride and uranium). The actual power consumption of the autonomous system provided by solar PV modules ranges between 10 and 50 W, while an attached pump additionally needs 10 and 70 W, depending on specifications and water volume being pumped.[36,37]

Sustainable economic models for water and energy supply are not available or scarce—successfully implemented mainly for solar energy businesses—and greatly hinder the provision of clean drinking water for large parts of the population. Based on the energy supply by PV

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technology, four concepts for drinking water provision for different target groups in rural SSA, case study Nigeria, were developed and their socioeconomic feasibility accessed.

2 Sustainable Concepts for Solar Energy Driven Drinking Water Supply

The technical solutions suggested for the four concepts are based on energy supply by PV, and for water cleaning UV-water treatment or the combination of filtration technologies with anodic oxidation: single-farmer concept, farmers' cooperation, community concept, and kiosk concept. Three of the concepts include opportunities for income generation through provision of water and electricity to the people in the area with water and electricity, while one concept provides a solution for a single, dispersed farm in a remote area. Additionally, the pay-as-you-go payment scheme is evaluated. Various financing options are integral parts of the calculations, and credit schemes are evaluated. Calculations for amortization are based on calculation 1: without inflation rate, or calculation 2: inflation rate of 18%, where calculation 2 results in earlier amortization. Interests for credits of 18% p.a. were assumed.[39] The concepts are based on the assumption that groundwater is available, and borehole drilling is part of the calculations.

2.1 *Single-Farmer Concept*

For small-scale farmers not located closely to other farms, an implementation concept of PV powered water cleaning is suggested. Nonpurified water shall be pumped from a borehole for irrigation, while a part of it is being treated to make it potable by eliminating microbiological contaminations. A UV-water cleaning system can be installed directly at the farmer's house, so it is not strictly necessary to have a residual disinfectant in the water. However, in case of sharing with remote living neighbors, transported and stored water will need additional residual disinfection to avoid recontamination. The technical concept would also be valid for a large family/small village with houses nearby, where household water is replenished daily. The economic feasibility assessment resulted in investment costs of € 150 for the UV water cleaning system and a PV solar home system of € 200 to be purchased by the individual farmer. The UV-systems' electricity consumption is low (24 W) and electricity is also provided for light and cell phone charging. Additional electricity is needed for an irrigation pump to increase crop production in farmer's field. A PV system not larger than 200 W delivers sufficient electricity to power all devices including the pump.

2.1.1 *Economic sustainability*

Investment costs comprise costs for borehole drilling, water analysis before installation, a tank, and the UV system, and, additionally, solar pumps including a PV module for small-scale irrigation with costs of about € 1200[40] (Table 2). Thus the initial investment sums up to € 6.906, while maintenance costs are about € 228/year. The farmer would need to take a credit with the usual interest fees of 18% p.a.[39]

Serving small-scale farmers with water solutions improve health and reduce costs for medicine and other health related expenses. Providing water for irrigation through borehole installation increases yields and food security, both contributing to farmers' income. The potential for increasing yields through irrigation is high, if surface or ground water is available. Estimates on yield gains by irrigation vary between 35% to more than doubling the yield.[51,52] In Zambia farmers irrigating their fields earned around 35% more than nonirrigating farmers according to results of the AgWater Solutions project, and the United Nations International Food Policy Research Institute identified an internal rate of return of 28% through irrigation in small-scale farmers' fields in various African countries.[51,52] Considering the often poor water management and conditions of irrigation equipment, we estimate for our calculations a yield increase of 35%. Additional income through higher yields would, therefore, make up € 1255/year.

Public and private expenditures on health are reported to be $ 107 to 197 per capita per year in Nigeria in 2016,[53] or $ 79 in 2016 according to the World Bank Group.[49] In Africa, diarrhea is listed as third among the top five causes of death in year 2016,[50] with 2 to 10 deaths/1000

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Table 2 Single-farmer concept with system costs, additionally generated income and savings through reduced expenses (exchange rate 1 € = 370 Nigerian Naira).

Single-farmer concept			
A. Investments		€	Source
A1	Water analysis	50	41
A2	Bore hole installation	4000	42
A3	Small tank	400	42
A4	UV system	150	43
A5	Pump incl. 140-W solar panel + 260-Ah battery	1200	44
A6	Filter	200	42
A7	Additional PV modules, 100 W	200	42
A8	GPS + production stopping device	500	Estimate
A9	LED lights, 3	6	45
A10	Installation and travel costs	200	Estimate
	Total	6906	
B. General overhead			
B1	Import duty	8	46
B2	Cost of finance (calculation 1)	4441	39
	Total	4449	
C. Operational costs/year			
C1	UV spare parts	121	42
C2	General maintenance costs	57	Estimate
C3	AC replacement	50	47
	Total	228	
D. Additional income and savings for farmers			
D1	Increase of crops sale by 35%	1255	48
D2	Less expenses for health	100	49 and 50
D3	No kerosene and mobile charging expenses	180	34
	Total	1535	

children depending on region in Nigeria,[54] caused by contaminated drinking water and poor sanitation. Therefore, when preventing diarrhea through safe drinking water, it is discretely estimated that each farmer's family (>5 individuals) saves € 100 on diarrhea related expenditures per year. Additional cost reductions occur on kerosene through electricity being supplied by the PV system and mobile phone charging, ranging between € 145 to 207/household/year in Nigeria,[34] resulting in savings of € 280/year and household.

According to the calculations, the initial investment of around € 6900 cannot be paid back within six years from the additional income and the lower expenses of € 1535/year, mainly due to the costs of borehole drilling and the associated interest fees for the sum of € 4000 and € 4441, respectively, based on calculation 1 (no inflation) (Table 2). Only with borehole costs of € 1000 or less the additional income from farming as well as avoided costs can be used to pay off the

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investment after more than 48 months (calculation 1, without inflation rate) or after 45 months (calculation 2, inflation of 18%), and the project is feasible.

2.2 *Farmer Cooperative Concept*

In the farmer cooperative scenario, a small group of three farmers will be enabled to irrigate their fields and install a water cleaning and electrification system. The farms should be closely located to each other, so that the borehole to be drilled will be in reach of the farmers for installation of irrigation hoses and a water cleaning system for drinking water, which should contain a residual disinfectant to keep water and containers clean. The anodic oxidation system[35] is the technology of choice for this concept, since it can purify sufficient water for the farmers' families as well as additional villagers and produces free chlorine for disinfection (Fig. 1). Additional solar pumps for field irrigation have to be installed, since the pump of the Autarcon system delivers about 10 to 20,000 L of drinking water.

A photovoltaic system, backed up by a battery will power the water system, which has a maximum electricity demand of 120 W, provided by a 1-kW PV system delivering electricity all over the year (e.g., in Nigeria), mostly even twice as much. A maximum of 1.44 kWh are needed each night to power the water treatment system, which is provided by batteries. Instead of using batteries, a reservoir tank can be filled to provide water at night. If the installations are made in a village, the purified water can be sold to the inhabitants to generate additional income to pay off the system. Therefore, a prepaid system should be installed at the site. The prepaid system has a peak electricity demand of 2 W for about 100 ms (for each tapping station), when the controller unit builds up a contact voltage to operate the outlet. A combination of a prepaid system and mobile payment appears to be the best solution. Mobile money can be used to load credits onto the watercard. In SSA, more than 60% of the population has a mobile phone and even 80% of individuals in countries such as Cameroon, Ethiopia, Rwanda, Tanzania, and Uganda.[55] Since electrification rate is much lower in these countries, most mobile phone users do not have a home power supply[34] and thus are not able to charge their phones.

Fig. 1 Autonomous PV powered system for cleaning and disinfection of drinking water based on anodic oxidation and *in situ* production of chlorine by an inline-electrolytic cell. Autarcon system installed in a rural setting. Water tapping with prepaid cards. (a)–(c) Photos courtesy of Philipp Otter, Tina Jaskolski.

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Table 3 Farmer cooperative concept (three households) with system costs, additionally generated income and savings through reduced expenses (exchange rate 1 € = 370 Nigerian Naira).

Farmer cooperative concept			
A. Investments		€	Source
A1	Water analysis	50	41
A2	Bore hole installation	4000	42
A3	Small tank	400	42
A4	Pump for irrigation water	2000	40
A5	Autarcon system incl. pump and batteries	15,000	42
A6	Prepaid system with 1 tap and 100 customer cards	1660	56
A7	PV system, 1300 W	2000	42
A8	GPS + production stopping device	500	Estimate
A9	LED lights, 3 per farmer's household	18	45
A10	Installation and travel costs	1000	Estimate
	Total	26,628	
B. General overhead			
B1	Import duty	750	46
B2	Cost of finance (calculation 1)	10,399	39
	Total	11,149	
C. Operational costs/year			
C1	Autarcon spare parts	750	42
C2	General maintenance costs	125	Estimate
	Total	228	
D. Additional income and savings for farmers			
D1	Increase of crops sale by 35%	3764	48
D2	Sale of water to other villagers	5926	Estimate
D3	Less expenses for health	300	49 and 50
D4	No kerosene and mobile charging expenses	540	34
	Total	10,530	

Investment costs shared per customer comprise costs for borehole drilling, a tank, the water treatment and the PV systems, the prepaid system, and, additionally, solar pumps including a PV module for small-scale irrigation with costs for each of about € 600.[40] Thus the initial investment sums up to € 26,628, while maintenance costs are about € 875/year. Additionally, farmers who would form an investment group to receive a bank credit need to pay off of the credit (Table 3).

2.2.1 *Economic sustainability*

It is estimated that crop production can be increased by about 35% due to irrigation.[51] The average income of a farmer's household in the year 2013 in Nigeria, Ekiti State, has been about Naira (NGN) 900,000.[48] Nigeria has a high inflation rate of 8% to 15% p.a.,[57] but also raising income. Considering inflation rates from 2013 to 2017, the average income of a farmer household is

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about Naira 1,324,862/year in 2017—estimating 8% inflation in 2017—, corresponding to about € 3585 at current exchange rates. For the calculation, it is assumed that 3000 L/day are sold at the price of 2 Naira/L to other villagers, providing 5L of safe water per person and day to 600 villagers. The price of 2 Naira is required to make the concept financially feasible. The system is capable of supplying more people with safe water, whereby the income would increase.

Additional income through higher yields and selling crops, sale of water, and the cost reductions through lower medical and health expenses and savings for kerosene and mobile phone charging add up to € 10,530/year, for all three farmer households. In the calculations for this concept, it is assumed that the farmers are willing to use the additional money to pay the installments for the system. Calculation 1 results in the credit being paid back after four years whereas in calculation 2, payback time would be three years and six months. After the investment has been paid back (break-even point), the water can be purified at the costs of € 0.0002 (less than 1 Naira) per L. At an income of only € 2000/year, both calculations have a payback time that is too long to be considered by investors. The interests sum up to more than € 10,400 (18% p.a. interest rate), which is around 40% of the initial investment sum, turning the project uneconomic. If more than three farmer households participate, the income is largely increased, while the investment rises only slightly, and with four farmers participating, the payback time shortens to 36 to 39 months. Other factors, such as costs for borehole drilling, could be higher or lower, depending on the project area. If the water treatment system can be used to its capacity (20,000 L/day) serving about 4000 customers with water, a payback time can be reduced, and, after break-even, the cost per liter of water is reduced accordingly.

2.3 *Community Concept*

The community concept is an expansion of the farmer cooperative concept. This concept is based on solidarity and trust among the 316 households with 1900 individuals involved, where each participant pays regular installments for the use of electricity and safe water, and the rate of installment equals avoided costs for kerosene, mobile phone charging, and health. Different to the cooperative farmer concept, no additional income is generated through crop irrigation. The water treatment system is based on the PV powered anodic oxidation system described above, providing 5 L of water per person and day. The installation of PV modules of 2000 W and an additional prepaid system for the community members is foreseen.

2.3.1 *Economic sustainability*

The sum of the initial investment is € 30,000 under prevailing economic and financial conditions. Since the farmers would probably not receive a loan from a bank, the company providing the water treatment system has to prefinance and install the system and thus give a credit to the community. The community members form a group to enable a larger investment and need to pay off the credit in regular installments. Concepts of large farmers' associations are well established in many African countries, facilitating the purchase of agricultural inputs. Thus community or village members would form a drinking water association. It is suggested that the company operating the drinking water system takes a credit by a local bank. It should be able to provide securities, therefore, the interest rate will be lower than the rate offered to a community. To avoid the exchange rate risk, the credit should be taken in the local currency. The community needs to pay regular installments to pay off the system via mobile money and in combination with the prepaid system. If mobile money is not an option, cash has to be used and to be transferred via a bank in regular periods. In case of payment defaults, mechanisms to stop production should be installed within the system. Yet, it should always be considered why payments default. If a region is suffering from unforeseen climate events, catastrophes, or similar, the peoples' situation should not be worsened by stopping their water treatment system.

In addition to supply with drinking water, further savings will occur (see above). Calculating the savings results in a sum of € 88,480 of less expenses per year over all households (Table 4), which serves to pay off the credit for the system with about 23 Euro per month and family. Thus the credit would be paid back within few months. After the investment costs and a profit for the company are covered, the system is transferred into possession of the community. Then the fees

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Table 4 Community concept (316 households) with system costs, additionally generated income and savings through reduced expenses.

Community concept			
A. Investments		€	Source
A1	Water analysis	50	41
A2	Bore hole installation	4000	42
A3	Tank	800	42
A4	PV system, 2000 W	3000	42
A5	Autarcon system incl. pump and batteries	15,500	42
A6	Prepaid system with 3 taps and 500 customer cards	2980	42
A7	GPS + production stopping device	500	Estimate
A8	Mobile phone charger × 50	250	58
A9	LED lights, for 316 households	1896	59
A10	Installation and travel costs	1000	Estimate
	Total	29,976	
B. General overhead			
B1	Import duty	775	46
B2	Cost of finance (calculation 1)	1805	39
	Total	2580	
C. Operational costs/year			
C1	Autarcon spare parts	750	42
C2	General maintenance costs	169	Estimate
C3	Share of wage for company employees	2000	59
	Total	2919	
D. Additional income and savings for farmers			
D1	Less expenses for health	31,600	49 and 50
D3	No kerosene and mobile charging expenses	56,880	34
	Total	88,480	

at the prepaid system can be lowered significantly to € 0.0008 (less than 1 Naira) per liter of water. The villagers' surplus from sale of water and electricity should be used for purchase of spare parts and maintenance.

The concept should be supported by strong community solidarity, with a sense of responsibility and trust in the other participants, in terms of payment of their share as well as the use of the system. Supervision of the system and direct technical support are assured. Because of the fast payback time and the subsequent low price for the water, the concept can also be used freely to supply the poorest members of communities, which would not be able to pay the installments (Table 4).

2.4 *Kiosk Concept*

An expansion of the community concept is the kiosk concept. The kiosk concept has a high potential to supply underserved populations with both water and electricity. The anodic

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oxidation system described above providing up to 20,000 L water per day is installed and operated within the kiosk. Three tapping points for water supply and a prepaid system will be installed, with an electricity demand of 6 W. Additionally to charging LED lights or dismantled car batteries, which are used to power electrical devices at the customer's home, the facility can be used to offer further goods and services, e.g., connection to the internet via Wi-Fi. As above, a maximum of 200 phones will be charged per day. Electricity and a battery are further needed for charging and powering diverse devices, including a fridge or a television. A PV system of 3500 W supplying all devices is installed on the roof of the kiosk.

2.4.1 *Economic sustainability*

It is assumed that the company running the kiosk is domestic. However, in case a foreign company is investing, an exchange rate risk occurs, and the choice would be a credit in the currency of the nation where the kiosk is being operated. Further costs such as wages, costs for restocking, and maintenance as well as loan payments for the credit can be paid by the income from the kiosks in local currency (Table 5). Therefore, exchange rate risk is minimized, however, if profits should be transferred into the investor's country, losses could occur. However, this is not seriously impeding business rollout in the nation itself. The customer (kiosk) would pay the installments to the company, which then pays off the credit in the local currency. One option is that the company itself is installing kiosks in Nigeria, supported by the government, placing the system on Health Facility grounds (see below). Another way to finance the kiosks is the idea of a franchise model[62] which is not presented here.

The kiosk concept has an investment cost of ∼ € 37,000, operational costs of ∼ € 11,000 p.a., and a generated income of ∼ € 27,000 p.a. through sales of safe water, electricity, goods, and services. In calculation 1, payback time is 37 months, and calculation 2, 32 months. After the investment has been paid back, and if all operational costs of the kiosk are considered, 1 L of safe water can be purified at the costs of € 0.003 (1.2 Naira), which corresponds to the price that street sellers charge in Nigeria for less than 1 L sold in small plastic sachets. However, the quality of this water is an issue. Costs per mobile charge are set to be 25 Naira, whereas LED-light charges cost 15 Naira. If instead of one car battery five are charged at the station each day, income rises to € 35,000, and the payback time decreases to 22 months.

2.5 *Pay-as-You-Go Scheme*

Pay-as-you-go is a scheme that has been newly introduced in developing countries in the small-scale solar photovoltaic market in the past few years. While $ 114 million have been spent on small scale, off-grid solar products in cash payments, $ 41 million have been spent on the same products via pay-as-you-go in SSA. The company Mobisol thus provided over 600,000 people in small households across 12 SSA countries—focusing on East Africa—with PV modules summing up to 12 MW installed and 60,000 ton CO_2 saved per year.[63] In this scheme, all system costs, the devices, overhead costs, interest fees, payment defaults, loan payments, maintenance services, and all other expenses have to be prefinanced by the company, while customers pay off monthly.

3 Conclusions

Energy and water are determining nearly all areas of human activity; achieving access to renewable energy and clean drinking water provides huge opportunities for economic development and is basic to achieve several of the SDGs. For the various implementation concepts presented, technologies of water treatment and electrification were combined and economically evaluated to different target groups. Autonomous power supply by PV is a prerequisite for each system. People are provided with drinking water, and with irrigation water, electricity, and further goods and services, depending on the concept and the needs and opportunities in the area. The concepts with one exception turned out to be financially feasible. The community concept based on cost reductions for each household through provision with electricity and water and subsequent

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Table 5 Kiosk concept with system costs and generated income (exchange rate 1 € = 370 Nigerian Naira).

Kiosk concept			
A. Investments		€	Source
A1	Site assessment and acquisition	2000	Estimate
A2	Water analysis	50	41
A3	Bore hole installation	4000	42
A4	PV system, 3500 W	5250	42
A5	Container cost and conversion to kiosk	3000	Estimate
A6	Autarcon system incl. pump and batteries	15,500	42
A7	Tank	800	42
A8	Prepaid system with 3 taps and 500 customer cards	2980	42
A7	GPS + production stopping device	500	Estimate
A8	Mobile phone charger × 10	50	58
A9	Small fridge for cold drinks	100	60
A10	Installation and travel costs	2500	Estimate
	Total	39,930	
B. General overhead			
B1	Import duty	800	46
B2	Cost of finance (calculation 1)	10,445	39
	Total	11,245	
C. Operational costs/year			
C1	Autarcon spare parts	750	42
C2	General maintenance costs	257	Estimate
C3	Wage for salesman	3000	59
C4	Share of wage for administration employees	1000	59
C5	Inventory for goods to sell	4000	Estimate
C6	Logistic costs	2000	Estimate
C7	WiFi data connection	300	Estimate
	Total	11,307	
D. Additional income			
D1	Sale of water to customers	9482	46
D2	Sale of products	9000	Estimate
D3	Charging mobile phones	4938	Estimate
D4	Charging LED lights	1852	Estimate
D5	Charging car batteries	1975	61
D6	Sale of WiFi connections	494	Estimate
	Total	27,248	

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savings was identified as specifically promising. The major hurdle in this concept is to identify communities with high interest of farmers in participation and willingness to pay the amount of avoided costs until the investment has been paid back. In the single-farmer concept, a combination of provision with irrigation water and water cleaning is only sustainable when several farmers participate, whereby investment costs can be divided, and the farmers are willing to invest the additional income in water treatment systems. In the kiosk concept, a large number of people can be supplied with safe water, electricity, and other goods. When people are willing to pay for water, the concept should be feasible for widespread implementation. Though, a social responsibility network should always be identified to supply poorest people with a minimum quantity of drinking water.

For all technologies, analysis of water quality before installations and regularly during operation of the system should be panned. If using an existing water source—a lake or river—costs for borehole drilling could be avoided and would make the concepts even more feasible. However, depending on water quality, additional cleaning devices may be necessary.

In all concepts, the affected people have sufficient access to safe water, as long as the installments are being paid. A possibly existing initial source of water for the people is not touched, but an additional source is provided. In case that the poorest people might not be able to afford the costs for drinking water, the farmers could provide them with water, since the price for water is set very low. To avoid environmental damage from exhausted systems, a collection and recycling concept for waste from spare parts, batteries, and replacements has to be elaborated, as well as the recycling of wastewater for irrigation purpose to save the valuable sweet water.

The calculations have shown that three of the four concepts are sustainable and investments can be paid back within few years, exclusively through financial benefits that arise through the implementation of the concept. Under certain conditions—borehole costs under € 1000 also the single-farmer concept is economically feasible. In this case, the farmers/customers do not need additional money, but can profit from increased incomes through higher yields and savings due to supply with clean water and electricity, but should be willing to use the saved money to pay back the investments. After that, the costs for the purified water are extremely low, and electricity is supplied freely. Since the water itself is not being sold to nonmembers of the groups, except for the kiosk concept, the water is not being privatized.

Based on the rural community concept, a pilot project started with our collaboration in Abuja/Nigeria, by the subsidiary of SC Sustainable Concepts, the local partner PVWater International Limited. The solar powered water disinfection system (Autarcon) was placed on grounds of a Rural Health Center and delivers up to 20,000 L of safe drinking water/day to the community. Payment is made by an intelligent prepaid card system providing different tariffs for the sale of drinking water and electricity to various customers, with prices below the market price of water sold by plastic bags.

To accomplish the UN sustainable development goals of water and electricity supply for all, interlinked concepts have to be developed specifically for rural areas in developing countries and adapted to local conditions and needs. Socioeconomic factors are of decisive importance for the implementation and success of technologies. Sustainable concepts for provision of people with water and electricity, as presented in this study, are a prerequisite for achieving several other SDGs.

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