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Impact of investment subsidy allocation schemes on levelized costs of renewable electricity-water systems in rural West Africa

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ABSTRACT

Access to electricity and drinking water are among the main obstacles in rural West Africa. They could be mitigated by implementing PV systems with battery storage and electrical water pumping systems. To assess the impacts of electricity supply in Dar Es-Salam village, a rural West African community, the economics of a PV system with battery storage and electrical water pumping are scrutinized. These systems will facilitate electricity and water access and provide the village with uninterrupted supply. Within the rural context, electricity can be used for direct residential consumption and to operate an electric water pumping system to supply clean drinking water to the households, making it an integrated, linearly linked PV/battery and water pumping system. As access to financial resources illustrates another constraint, especially in the context of West Africa and the Sahel region, the paper further assesses impacts of an investment costs subsidy on the economics of electricity and water. By examining different allocation schemes of a constrained investment costs subsidy, the paper estimates their impact on the Levelized Costs of Electricity and Water, compares these results with the current state costs reported by local villagers, and identifies a superior subsidy allocation scheme. In our case, allocating the investment costs subsidy to the PV/battery system is identified as the superior allocation scheme. This is due to the high upfront PV/battery costs in relation to the water system but also reflects the villagers' preferences as to electricity and water costs. Based on the case data for Dar Es-Salam village, the Levelized Cost of Electricity and of Water, respectively, resulted to 0.210€/kWh and 0.520 €/m^3, without subsidy. A subsidy of approximately 2/3 of the total investment costs and allocating the subsidy to the PV/battery system offers to drastically reduce the Levelized Costs for Electricity and Water to 0.045€/kWh and 0.306 €/m^3, respectively.

Introduction

Electricity access and provision of drinking water belong to the main obstacles for residents in rural West African communities and in many cases are intertwined with energy poverty [1]. For instance, in Niger, where over 80% of the population resides in rural areas, the rate of rural electrification is less than 20%. Other West African countries, such as Liberia, Guinea-Bissau and Sierra Leone, have even lower rural electrification rates [2]. In addition, continuous access to safe and clean water remains an important issue in water resources management and development [3]. At the same time, there is huge potential for renewable energy, e.g., photovoltaic (PV) systems, to provide electricity in an environmentally and climate friendly way [4,5]. Together with battery storage of electricity (BES), this can not only serve the general local provision of decentralized electricity to residents, but it also facilitates installation of electric water pumps (EWP) providing drinking water. Nevertheless, the high upfront cost for PV-BES and EWP installations presumably is bearable for rural residents only if investment costs subsidy is available, from either national or international institutions [6]. In light of the disastrous financial state of several Sub-Saharan countries [7], especially low-income countries, subsidies from international institutions (governments, transnational governmental institutions, or private) are essential.

Many studies calculate the subsidies necessary to incentivize

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reaching a certain target, e.g., deployment of renewable energy technologies, e.g., [8,9] for China and Korea. On the other hand, if a certain amount of subsidies is available, how do you allocate subsidies to investment costs, e.g., for PV-BES and/or EWP systems, to reach a social optimum cost level for integrated electricity and water provision? This aspect usually is not addressed. The novelty of the study is to present a methodology to derive such a social optimal allocation of investment costs subsidy for an integrated PV-BES-EWP system, without the need to formulate an explicit utility function for electricity and water. The case study focuses on Dar Es-Salam village in rural Niger.

The objective of the paper is to analyze the impact of investment costs subsidies to identify minimum sales prices for electricity and water and as sales price proxy, we use the Levelized Cost of Electricity (LCOE) and of Water (LCOW) for an integrated PV-BES-EWP system. The methodology comprises a framework to allocate a constrained investment costs subsidy to PV-BES and/or EWP, using a multi-criteria assessment approach to identify socially optimal sales prices for electricity and water. Reflecting the situation in Dar Es-Salam village, the starting points are the costs for electricity and water, the residents currently must bear.

The paper is arranged as follows. After the introduction, a literature review is presented in Section II. The methodology, which can also be applied to other developing countries, follows in Section III, comprising the post-subsidy Levelized Costs model for electricity and water in an integrated PV-BES-EWP system, a scenario approach for different subsidy allocation schemes, a multi-criteria assessment approach to select the superior subsidy allocation solution based on local resident's preferences as to bearable electricity and water costs, and a sensitivity approach to identify sensitive parameters. The focus is on investment cost subsidies as one of the main options to foster technologies with high up-front capital expenditures. Section IV presents the technologies, a socio-economic case description for Dar Es-Salam village, Niger, and corresponding base data. In section V, we present the results, and finally, we discuss and interpret the results in section VI and conclude in section VII.

Literature review

There is literature available focusing on the specific African context from a macro perspective. Adeoye and Spataru developed an energy demand forecasting model for 14 West African countries including Niger [10], estimating a significant rise in energy demand for residential and non-residential needs by 2030. Bissiri et al. study the various options for the pooling of electricity in order to meet the growing energy needs of West African states [11]. The results of their dispatch model show that West African countries, including Niger, are in need of improvements in cross-border energy transmission [11]. Karbasssi et al. analyze the African energy system focusing on different methods to spread the costs of renewable energy systems and to enable a cost-effective way forward [12]. Njoke et al. assessed the effect of investment and financing policies for developing photovoltaic power generation in Cameroon, based on a dynamic Computable General Equilibrium model [13].

Szabo et al. [14] identify a huge potential for PV-based electricity generation in the solar belt of West Africa, and for Niger, where approximately 17 million people live unelectrified. They determine decentralized PV as a no-regrets investment option for at least 4.4 million residents, accounting for 25.5% of the unelectrified population. Furthermore, electric water pumps combined with water storage in tanks offer the opportunity for reliable drinking water provision [15,16]. Dibaba et al. address the topic of rural electrification in Namibia and focus on the analysis of the willingness-to-pay of rural residents for electricity [17]. For solar-driven water heating systems, Thomas et al. [18,19] discuss the impact of internalizing externalities on full cost recovery policy.

In addition, several studies are available focusing in detail on technologies (PV, BES, micro-grids, EWP) and cost-effectiveness in the West-African and Sub-Saharan context, operating PV-BES systems either separately or integrated with electric water systems (PV-BES-EWP). Table 1 lists some studies focusing on country-wide electricity systems [20,21], on local electricity systems [22–26], and on local systems for integrated electricity and water provision [27–30]. While the figures provide some insight, a direct comparison is not feasible due to different costing approaches, differences in system boundaries, technical concepts (PV, PV-BES, hybrid micro-grids, off-grid/on-grid), varying regional conditions that can affect the results, differences in currencies, different discounting approaches and base years. Additional aspects like governmental intervention influencing the costs through subsidies or full environmental or social costs accounting through inclusion of external costs often differ, but in the studies listed in table these aspects do not prevail. However, despite these differences and although the study list is not complete, Table 1 serves to present an overview of specific electricity and water costs in SSA countries.

Egli et al. use a Weighted LCOE approach and find that solar-powered mini-grids and standalone systems drastically lower the cost of electrifying remote and high-cost areas in Sub-Saharan countries. They estimate that for households with low energy demand in 40 Sub-Saharan countries electricity can be provided on average at 0.14 €/kWh or 0.07 €/person-day by 2030, based on the OnSSETT electrification model [20]. Based on a utility-scale technical concept including PV, fuel cells, electrolyzer for hydrogen, and on-grid options Nouadje et al. [21] calculate LCOE of 0.22–0.32€/kWh for CAMES countries in West, Central, and East Africa.

Sakiliba et al. [26] use a Life Cycle Cost approach and address a stand-alone residential solar PV-BES application for Banjul, The Gambia, and calculate cost of 0.19 €/kWh. Odou et al. [24] use a Net Present Cost approach and calculate cost of 0.21 €/kWh for rural electrification in Fouay, Benin, by community-based hybrid PV-BES with diesel generator. Ayodele et al. [22] also use a Life Cycle Cost approach and estimate cost of 0.20–0.25€/kWh for an industry-scale application of PV-BES-EWP in Ibadan, Nigeria. Lewis et al [23] analyze lower LCOE of 0.09 €/kWh for Kabuiri, Nigeria. Rangel et al. scrutinize hybrid rural microgrids for the Lindi region in rural Tanzania, revealing LCOE of 0.51–0.55 €/kWh, depending on electricity demand scenarios and different technology configurations [25].

Girma [30] uses a Life Cycle Costing approach and calculates cost of 0.35 €/kWh for electricity and of 0.06 €/m^3 for water for Arba Minch, Ethiopia, focusing on a residential solar PV-BES-EWP system. De la Frasneye [27] also uses a Life Cycle Costing approach and calculates 0.24 €/m^3 for solar-pumped water in Ouagadougou, Tenkodogo, Garango, and Gogma, Burkina Faso. Falk et al. [28,29] on the other hand use a static profit accounting approach for a community-based PV-BES-EWP microgrid and estimate 0.26 €/kWh for electricity and 0.32 €/m^3 (up to 0.70 €/m^3 for water if EWP capacity is appr. 50% used) for water for the island Kibumba, Tanzania.

Other studies [31,32] focus on other economic metrics (Internal Rate of Return IRR, Payback Time PB) for South Africa and Nigeria. Again, the figures are not easily comparable, however, in the vast majority of case studies economic feasibility of PV-BES and PV-BES-EWP systems is stated.

Solar-powered electrification and solar water pumping systems are also important for other parts of the world, e.g., North African countries, Iran, and India [33–37] and there are further purposes for solar-driven technologies, e.g., Rout et al. discuss solar-driven hot-water systems [38–40].

While most studies focus on technical integrity, cost-effectiveness, and institutional aspects, they do not primarily address the question of how to finance the substantial investment needs for rural electrification in West Africa. For many West African countries, the transition to green energy is increasingly challenging due to a lack of financing options, making the discussion of investment costs subsidies, e.g., for PV-BES-EWP systems, increasingly relevant. Muzenda [41] identifies the weakness of local financial markets, under development of alternative

Table 1
Study overview.

Author/Study	Country/ Region	Technology	Cost approach	Electricity (€$_{2024}$/ kWh)	Water (€$_{2024}$/ m^3)
System boundary: Country, electricity					
Egli et al. [20]	40 SSA countries	Utility scale generation + solar-powered mini-grids + stand-alone PV-BES	Weighted LCOE	0.14	–
Nouadje et al. [21]	African and Malagasy Council Countries	Utility-scale Grid-FC-PV-Electrolyzer	LCOE	0.22–0.32	–
System boundary: Village/Town, electricity					
Sakiliba et al. [26]	Banjul, Gambia	Stand-alone residential PV-BES	LCC	0.29	–
Odou et al. [24]	Fouay, Benin	Community hybrid off-grid-PV-BES + Diesel generator	Net Present Cost	0.21	–
Ayodele et al. [22]	Ibadan, Nigeria	Industry-scale PV-BES-EWP	LCC	0.20–0.25	–
Lewis et al. [23]	Kabuiri, Nigeria	Local hybrid microgrid PV-BES	LCOE	0.09	–
Rangel et al. [25]	Lindi Region, Tanzania	PV-BES + Diesel Generator-based micro-grid	LCOE	0.51–0.55	–
System boundary: Village/Town, electricity and/or water					
Girma [30]	Arba Minch, Ethiopia	Residential solar PV-BES-EWP	LCC	0.35	0.06
De la Fresneye [27]	Ouagadougou, Tenkodogo, Garango, Gogma, Burkina Faso	Solar water pump	LCC	–	0.24
Falk et al. [28,29]	Island Kibumba, Tanzania	Community-based PV-BES-EWP microgrid	Static profit accounting	0.26	0.32*

* adapted to full EWP capacity use

Currency conversion: $\text{currency}_{\text{study year}} \times \left(\frac{€_{\text{study year}}}{\text{currency}_{\text{study year}}}\right) \times €\ \textit{inflation}_{\text{study year}-2024} = €_{2024}$

Sources: (i) Currency calculator [https://bankenverband.de/service/waehrungsrechner/historicalcurrencies/?betrag=1&dezimalstellen=2&von=USD&in=EUR&mit_kurs_vom=2024–10–30&interbank=0] (ii)€ Inflation rate [https://de.statista.com/statistik/daten/studie/156,285/umfrage/entwicklung-der-inflationsrate-in-der-eu-und-der-eurozone/]

financing opportunities, and low resident income as hindering private and communal investment in energy and water infrastructures. Agutu et al. underline the importance of accounting for regional and technology-specific finance in electrification models for Sub-Saharan Africa [42]. Antonanzas-Torres et al. [43] identify the reduction of capital expenditure (CAPEX) as one of the major challenges mini-grids in West Africa are faced with. Although from a top-down level financing aspects and incentivization of investments are relevant [41,44,45], most economic feasibility studies do not account for these aspects. Polzin et al. qualitatively analyze how policies mobilize private finance for renewable energy from an investor's perspective [46]. Sweerts et al. scrutinize de-risking to unlock Africa's renewable energy potential [47], focusing on financial conditions by analyzing different WACC (Weighted Average Cost of Capital) configurations for 46 African countries and the impacts on LCOE.

However, accounting for investment costs subsidies leads to new aspects of Levelized Cost analysis, especially for integrated systems like PV-BES-EWP. Lower investment costs due to subsidizing PV-BES and EWP investment costs results in new post-subsidy Levelized Costs. Additionally, the absolute amount of a subsidy is relevant as it directly influences the subsidy shares for PV-BES and EWP, which are interdependent for a constrained subsidy. Technoeconomic approaches are less prepared to reflect social conditions. This also holds for the question of which costs for electricity and water reflect affordability according to local conditions. We use the preferences of local people concerning bearable electricity and water costs to identify the social optimal subsidy allocation scheme. These points are addressed in our study.

Study approach for the provision of electricity and drinking water in a west African rural context

The central question of the study is how to allocate a constrained investment costs subsidy to PV-BES and EWP to reach socially optimal prices for electricity and water in a rural context in SSA. After identification of current prices for electricity and water, the villagers currently must bear, which is already done in a previous study by Schloer et al. [48] for the case study of Dar Es-Salam village, Niger, we define the steps a-c (Fig. 1):

a. Definition and use of a Levelized Costs approach to identify the impact of investment costs subsidies on Levelized Costs of Electricity (LCOE) and Levelized Costs of Water (LCOW) as proxies for electricity and water minimum sales prices.
b. Definition of subsidy allocation schemes to distribute a constrained subsidy z to PV-BES and EWP investment costs, identification of corresponding subsidy parameters s_{PV} and s_{EWP}, and calculation of the corresponding after-subsidy Levelized Costs, which reflect minimum sales price combinations for electricity and water.
c. Definition and use of a multi-criteria assessment approach for the identification of a socially optimal (based on preferences for electricity and water) minimum sales price combination for electricity and water. Keeping in mind that investment costs subsidies help to reduce the after-subsidy Levelized Costs of Electricity and Water, we use the preferences of the villagers concerning bearable electricity and water costs to identify the social optimal subsidy allocation scheme. This procedure is reflected by the multicriteria assessment with social preferences for electricity and water.

Integrated electricity and drinking water provision processes

In many rural West African villages without access to an electricity grid, diesel-based electricity generation may be substituted by renewable energy sources, e.g., PV electricity generation, providing local electricity in an environmentally and climate-friendly way. Combined with battery electricity storage (BES), reliable and continuous access to electricity can be provided. At the same time, in many municipalities access to drinking water is low and may increase through installation of an EWP. Locally, this affords investment in and operation of a PV-BES and of an electric water pumping system (EWP). To address the

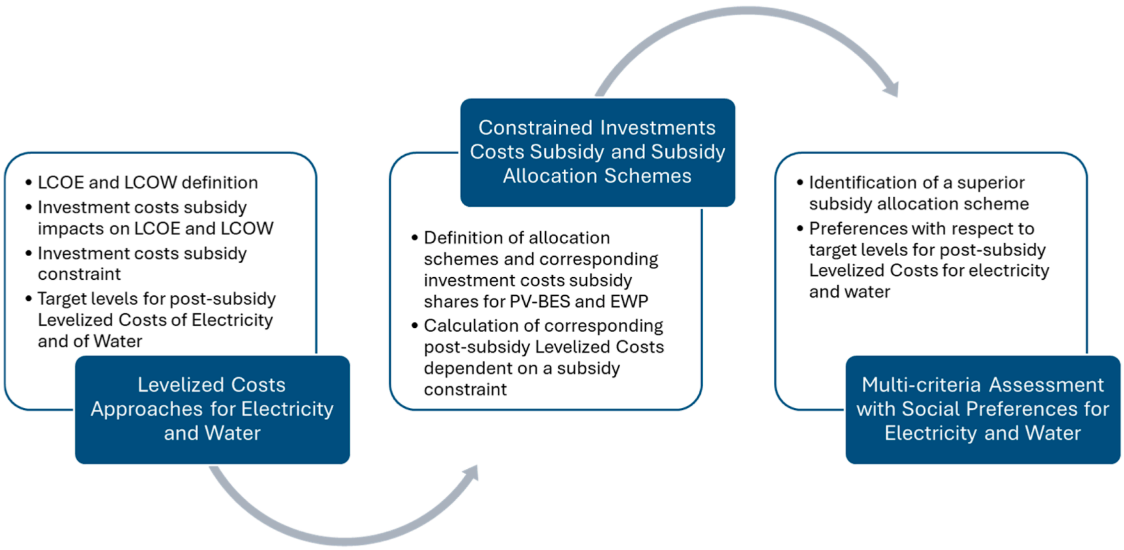

Fig. 1. Methodological steps.

challenges of operating and managing these facilities as an integrated infrastructure in a rural SSA context, a community kiosk [32,49,50] may serve. Therefore, the integrated system comprises two technologies with corresponding cost structures (investment costs and operating costs for PV-BES and EWP) and the kiosk, representing an institution operating a PV-BES-EWP system under rural SSA local conditions, where no single private owner of the plants is responsible, but the community of residents is the owner, delegating tasks to a local manager, who must be paid.

- PV-BES as an off-grid hybrid system: A PV-BES system provides electricity used for private consumption, e.g., for lighting or running a smartphone, or for running an electric water pump for drinking water supply. The technology used in this study is a PV system coupled with 2nd life batteries [29].
- Electric Water Pumping system (EWP): An EWP system provides drinking water based on electricity to run the pump and further components. The technology used in this study is a coupled electric water pump and storage system [28] providing water reliably and clean.
- Kiosk: It induces additional institutional costs for the management of the integrated PV-BES-EWP system, e.g., training residents with respect to PV-BES-EWP systems or preparing financial settlements. Typically, such management costs for integrated systems cannot be directly attributed to electricity or water provision. In such cases, a simple allocation factor (all) can be used to impute the kiosk costs to electricity and water provision.

Fig. 2 shows the basic elements of the PV-BES and EWP systems. Adapted from Falk et al. [28,29]

Economic metrics: levelized cost and subsidy allocation

Levelized costs and investment subsidies

The Levelized Cost of X (LCOX) is a commonly used metric for evaluating the economic attractiveness of technologies providing a

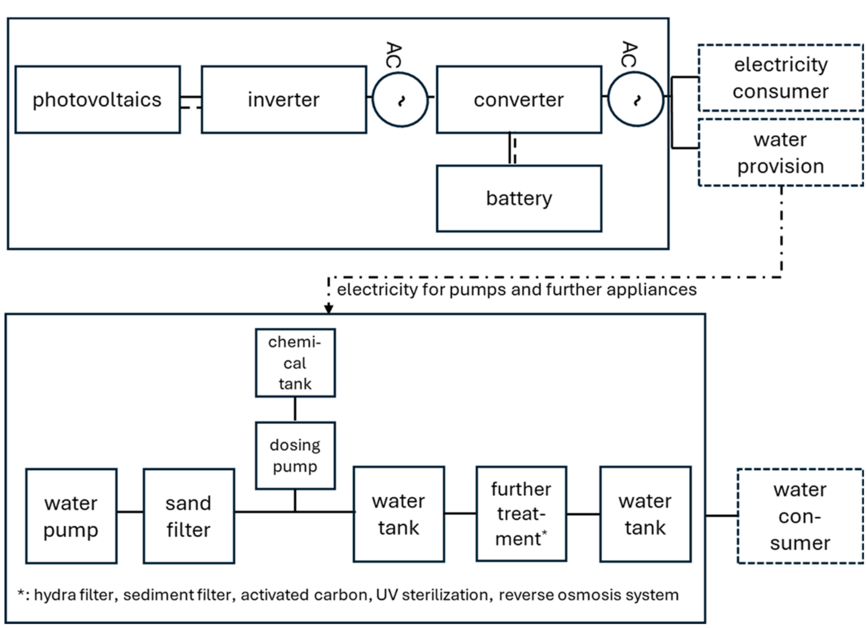

Fig. 2. PV-BES and EWP systems.

product. It is used, e.g., for PV and BES systems [51–54] and also for a wider range of applications, e.g., water systems [55]. It can be considered as the price per unit (e.g., kWh electricity or m^3 water) at which electricity or water must be sold over the technology's lifetime in order to break even [56]. Levelized costs can also be understood in terms of specific revenue – namely, the specific revenue that a technology must generate over its lifetime, providing a reasonable return to the investor [57] to motivate investment. A third, often overlooked, interpretation is that it defines the sales price of a product so that the Internal Rate of Return (IRR) of the investment is equal to the interest rate.

Eq. (1) shows the Levelized Cost formula in its basic variant (see, e.g., the definition of the US NREL [58] and Kabeyi and Olanrewaju [59]). In our interpretation, basic means without governmental incentives like subsidies. The Levelized Costs depend on investment costs (I_t) and operating and management costs (O_t) over the lifetime (T) of the technology, the quantity of the product (X_t) provided over the lifetime, and the interest rate (r). It might also be appropriate to separate energy costs (E_t).

$$\mathbf{LCOX_{basic}} = \frac{\sum_0^T \frac{I_t}{(1+r)^t} + \sum_1^T \frac{O_t}{(1+r)^t} + \sum_0^T \frac{E_t}{(1+r)^t}}{\sum_0^N \frac{X_t}{(1+r)^t}} \tag{1}$$

Eq. (1) translates to (2) for the PV-BES system and (3) for the water pumping system. The investment costs for PV-BES comprise the initial investment costs at t=0 ($I_{PV,0}$) and the replacement investments at T_1 ($I_{PV,T1}$) for, e.g., the inverter. For water pumping, the investment costs comprise the initial investment costs at t=0 ($IE_{WP,0}$) as well as replacement investments at T_2 ($IE_{WP,T2}$) for, e.g., the electric pump. Operating and management costs for PV-BES ($O_{PV,t}$) comprise, in our case, direct costs ($M_{PV,t}$) and the attributed share of the kiosk costs ($K_{PV,t}$). Similarly, operating and management costs for water pumping comprise direct costs ($M_{EWP,t}$) and the attributed share of the kiosk costs ($K_{EWP,t}$). The kiosk cost allocation factor is all for PV-BES and (1-all) for EWP. Energy costs (E_t) are relevant for the EWP system, as it uses electricity. The basic Levelized Costs of Electricity ($LCOE_{basic}$) is derived from Eq. (2) and the basic Levelized Costs of Water ($LCOW_{basic}$) from Eq. (3).

$$\mathbf{LCOE_{basic}} = \frac{I_{PV,0} + \frac{I_{PV,T1}}{(1+r)^{T1}} + \sum_0^T \frac{O_{PV,t}}{(1+r)^t}}{\sum_0^T \frac{E_t}{(1+r)^t}} \tag{2}$$

$$\mathbf{LCOW_{basic}} = \frac{I_{WP,0} + \frac{I_{EWP,T2}}{(1+r)^{T2}} + \sum_0^T \frac{O_{EWP,t}}{(1+r)^t} + \sum_0^T \frac{E_t}{(1+r)^t}}{\sum_0^T \frac{W_t}{(1+r)^t}} \tag{3}$$

Eq. (4) describes electricity cost for EWP with $elec_{EWP}$ the specific electricity required per unit water.

$$\mathbf{E_t = elec_{EWP} \times LCOE_{basic}} \tag{4}$$

Reformulating (2) and (3), Eqs. (5) and (6) presents the basic Levelized Costs shares for investment costs ($LCOE_I$, $LCOW_I$) and operating costs ($LCOE_O$, $LCOW_O$), see Castillo-Ramirez et al. for a similar presentation [60]. Additionally, $LCOW_E$ represents the Levelized Costs of water share arising from electricity use for water.

$$\mathbf{LCOE_{basic} = LCOE_I + LCOE_O} \tag{5}$$

$$\mathbf{LCOW_{basic} = LCOW_I + LCOW_O + LCOW_E} \tag{6}$$

The basic concept of Levelized Cost does not cope with institutional aspects such as who bears which parts of the cost or what is the impact of financial support mechanisms, e.g., investment costs subsidies. To identify the impact of investment costs subsidies the following equations show new parameters for electricity and for water provision. s_{PV} stands for the share of PV-BES investment costs subsidized and s_{EWP}, respectively, for EWP.

$$\mathbf{I_{PV,Sub} = (1 - s_{PV}) \times I_{PV}} \tag{7}$$

$$\mathbf{I_{EWP,Sub} = (1 - s_{EWP}) \times I_{EWP}} \tag{8}$$

After a few basic mathematical operations, Eqs. (9) and (10) show the post-Subsidy Levelized Costs of Electricity and of Water ($LCOE_{Sub}$, $LCOW_{Sub}$).

$$\mathbf{LCOE_{Sub} = (1 - s_{PV}) \times LCOE_I + LCOE_O} \tag{9}$$

$$\mathbf{LCOW_{Sub} = (1 - s_{EWP}) \times LCOW_I + LCOW_O + LCOW_{E,Sub}} \tag{10}$$

It should be noted that subsidies on PV-BES investment costs not only directly impact $LCOE_{Sub}$, but additionally indirectly impact the $LCOW_{Sub}$ due to the electricity costs of water provision ($LCOW_E$). Therefore, $LCOW_{Sub}$ extends to Eq. (11). We refer to direct impacts as channel 1 impact and to indirect impacts as channel 2 impact.

$$\mathbf{LCOW_{Sub} = (1 - s_{EWP}) \times LCOW_I + LCOW_O + elec_{EWP} \times [(1 - s_{PV}) \times LCOE_I + LCOE_O]} \tag{11}$$

With a bit of reformulation, Eqs. (9) and (11) evolve to (12) for PV-BES and (13) for EWP. We see that after-Subsidy Levelized Costs depend on the basic Levelized Costs ($LCOE_{basic}$, $LCOW_{basic}$), the shares of investment costs subsidies (s_{PV}, s_{EWP}), and the investment cost shares of the basic Levelized Costs ($LCOE_I$, $LCOW_I$). Additionally for water pumping, the specific electricity use parameter ($elec_{EWP}$) is relevant.

$$\mathbf{LCOE_{Sub} = LCOE_{basic} - s_{PV} \times LCOE_I} \tag{12}$$

$$\mathbf{LCOW_{Sub} = LCOW_{basic} - s_{EWP} \times LCOW_I - elec_{EWP} \times s_{PV} \times LCOE_I} \tag{13}$$

Subsidy constraints

If the total subsidy is constrained to z, it can be allocated to the investment costs of PV-BES and of EWP, necessarily fulfilling the constraint $z = s_{PV} \times I_{PV} + s_{EWP} \times I_{EWP}$. Therefore, the shares of PV-BES and EWP investment costs subsidized are interdependent, see Eq. (14). If z is allocated solely to PV-BES, the share of investment subsidized is $s_{PV,max}$. For the subsidy allocation shares the boundary conditions $0 \leq s_{PV}, s_{WP} \leq 1$ are valid.

$$\mathbf{s_{EWP} = \frac{z - s_{PV} \times I_{PV}}{I_{EWP}}} \tag{14}$$

with $s_{PV,max} = \frac{z}{I_{PV}} \leq 1$ and $s_{PV,min} = \frac{z - I_{EWP}}{I_{PV}} \geq 0$

With s_{EWP} from Eq. (14) $LCOW_{Sub}$ is shown in Eq. (15).

$$\mathbf{LCOW_{Sub} = LCOW_{basic} - \left(\frac{z - s_{PV} \times I_{PV}}{I_{EWP}}\right) \times LCOW_I - elec_{EWP} \times s_{PV} \times LCOE_I} \tag{15}$$

In case an electricity cost target P_{Ea} is assumed for $LCOE_{Sub}$, it can be shown after some reformulations that the share of PV-BES investment costs subsidized must be $\overline{s_{PV}}$ (16). Analogously, in case a water cost target P_{Wa} is assumed for $LCOW_{Sub}$, the share of EWP investment costs subsidized must be $\overline{s_{EWP}}$ (17).

$$\mathbf{\overline{s_{PV}} = \frac{LCOE_{basic} - P_{Ea}}{LCOE_I}} \tag{16}$$

$$\mathbf{\overline{s_{EWP}} = \frac{LCOW_{basic} - elec_{EWP} \times s_{PV} \times LCOE_I - P_{Wa}}{LCOW_I}} \tag{17}$$

If the electricity cost target P_{Ea} is expected to equal a fraction γ_E of $LCOE_{basic}$ ($P_{Ea} = \gamma_E$ x $LCOE_{basic}$) or, analogously for water, a fraction γ_W of $LCOW_{basic}$ ($P_{Wa} = \gamma_W$ x $LCOW_{basic}$) it becomes evident after some reformulations that the corresponding subsidy shares are $\overline{s(\gamma_E)_{PV}}$ (18)

and $\overline{s(\gamma_W)_{EWP}}$ (19). With γ_E=1 the target P_{Ea} for electricity is equal to the basic Levelized Cost and the corresponding necessary share of investment costs subsidies equals zero. For water, (19) shows the dependency of $\overline{s(\gamma_W)_{EWP}}$ on PV-BES investment costs subsidies due to the impact channel 2. Generally, the lower the fractions γ_E and γ_W are, the higher the necessary shares of investment costs subsidies.

$$\overline{\mathbf{s(\gamma_E)_{PV}}} = (1-\gamma_E)\frac{\mathbf{LCOE_{basic}}}{\mathbf{LCOE_I}} \tag{18}$$

$$\overline{\mathbf{s(\gamma_W)_{EWP}}} = (1-\gamma_W)\frac{\mathbf{LCOW_{basic}}}{\mathbf{LCOW_I}} - \frac{\overline{\mathbf{s(\gamma_E)_{PV}}} \times \mathbf{elec_{EWP}} \times \mathbf{LCOE_I}}{\mathbf{LCOW_I}} \tag{19}$$

If it is requested, that Eqs. (18) and (19) are simultaneously fulfilled, meaning that the relative change from basic to after-subsidy Levelized Costs is equal for electricity and water, some basic mathematical operations show the result for $\gamma_{E,W}$ in Eq. (20). This equation shows the maximum equal relative change from basic to after-subsidy Levelized Costs for electricity and water. It depends on the investment costs subsidy constraint z, the investment costs for PV-BES and EWP, the basic Levelized Costs ($LCOE_{basic}$, $LCOW_{basic}$), and the investment cost shares of the basic Levelized Costs ($LCOE_I$, $LCOW_I$). If there is no investment cost subsidy ($z = 0$), the fraction γ equals 1, so that there is no decrease in Levelized Costs. With investment cost subsidy $z > 0$, resulting fraction$\gamma_{E,W}$ is smaller than 1. To our knowledge, the explicit derivation of the fraction$\gamma_{E,W}$, depending on the investment costs subsidy z, and its presentation via the Levelized Costs elements $LCOE_I$, $LCOW_I$, and $LCOW_E$ are not seen before in the literature.

$$\gamma_{E,W} = 1 - \frac{\mathbf{z}}{\left[\frac{I_{PV}}{LCOE_I} \times \mathbf{LCOE_{basic}} + \frac{I_{EWP}}{LCOW_I} \times (\mathbf{LCOW_{basic}} - \mathbf{LCOW_E})\right]} \tag{20}$$

In this case, the investment costs subsidy shares for electricity (18) and water (19) evolve to (21) for electricity and (22) for water, guaranteeing that relative Levelized Costs changes for electricity and water are equal and that the investment subsidy constraint z is met.

$$\overline{s(\gamma_{E,W})_{PV}} = (1-\gamma_{E,W})\frac{LCOE_{basic}}{LCOE_I} \tag{21}$$

$$\overline{s(\gamma_{E,W})_{EWP}} = (1-\gamma_{E,W}) \times \left(\frac{LCOW_{basic} - elec_{EWP} \times LCOE_{basic}}{LCOW_I}\right) \tag{22}$$

A scenario approach to determine subsidy allocation schemes

Key in our scenario approach is to describe different subsidy allocation approaches and to specify case-specific parameters s_{PV} and s_{WP} for the investment costs subsidy shares for PV-BES and EWP, conditional on the subsidy constraint z. The post-subsidy Levelized Costs are derived based on the following scenarios considering subsidy allocation options. Columns 4 and 5 in *Table 2* show the corresponding investment costs subsidy shares for PV-BES (s_{PV}) and EWP (s_{EWP}). Scen 1 examines the case without investment costs subsidies ($z = 0$). Representing different options for investment subsidy allocation to PV-BES and EWP systems, scen 2–5 can be plausible for policy makers, as the subsidy constraint z remains fulfilled. However, the different schemes result in different levels of post-subsidy Levelized Costs for Electricity and for Water.

- Base case: this case describes the current situation in Dar Es-Salam village, as previously studied by Schloer et al. [48], who have analyzed the current costs of electricity and water in Dar Es-Salam village as of 2022, the villagers currently bear.
- Scen 1: there is no investment costs subsidy (z=0).
- Scen 2: as PV-BES inhibits by far the largest capital expenditure, the idea is to fully allocate the subsidy to the PV-BES investment. According to (14) the subsidy share for PV-BES (s_{PV}) is maximal and for EWP (s_{EWP}) zero.
- Scen 3: the idea is to allocate the total subsidy to reach equal subsidy shares s_{PV} and s_{EWP}. According to (14) the subsidy shares for PV-BESS and for EWP solely depend on the constraint z and the investment costs for PV-BES and EWP.
- Scen 4: this scenario grounds on the idea to allocate total subsidy to induce the same relative change for both electricity and water Levelized Costs, meaning to rely on the fraction $\gamma_{E,W}$ (20). Eqs. (21) and (22) show the corresponding investment costs subsidy shares $\overline{s(\gamma_{E,W})_{PV}}$ and $\overline{s(\gamma_{E,W})_{EWP}}$.
- Scen 5: in this scenario we allocate the subsidy to EWP to the amount of full investment costs, the remaining subsidy is allocated to PV-BES. In this case, the subsidy shares are s_{EWP}=1 and according to (14) s_{PV}<1.

Although the five scenarios do not comprise all possible subsidy allocation schemes, e.g., subsidy according to the relative capacity investment expenditures is additionally possible, they very well cover the spectrum of most relevant schemes.

Multi-criteria assessment

The identification of a superior solution in terms of the scenarios for the allocation of the subsidy z cannot immediately be done, as the results for electricity and water cannot be directly compared given the different units (€/kWh and €/m^3). Therefore, we use a composite index (CI) for assessment which, methodologically, refers to an approach used by the OECD [61]. To make the different units comparable and to substantiate the results, we use two normalization approaches, namely Min-Max and the Distance-to-Reference models [62]. The results of the assessment are summarized by means of the Simple Additive Weighting (SAW) Composite Index (CI) approach, one of the most commonly used assessment approaches for composite indices [61].

Sensitivities

The provision of electricity and water and resulting Levelized Costs

Table 2
Subsidy allocation schemes and resulting subsidy shares s_{PV}, s_{EWP}.

Scenario	Subsidy level	Subsidy allocation approach	Subsidy share PV-BES: s_{PV}	Subsidy share EWP: s_{EWP}
Base case	0	–	–	–
Scen 1	0	No subsidy	–	–
Scen 2	z	Full subsidy of PV-BES investment costs	z/I_{PV}	0
Scen 3	z	Induce equal subsidy shares	$z/(I_{PV}+IE_{WP})$	$z/(I_{PV}+IE_{WP})$
Scen 4	z	Induce same relative change of Levelized Costs by relying on the fraction$\gamma_{E,W}$	$(1-\gamma_{E,W}) \times \frac{LCOE_{basic}}{LCOE_I}$	$(1-\gamma_{E,W}) \times \left(\frac{LCOW_{basic} - elec_{EWP} \times LCOE_{basic}}{LCOW_I}\right)$
Scen 5	z	Full subsidy of EWP investment costs, remaining subsidy allocated to PV-BES	$\frac{(z - I_{EWP})}{I_{PV}}$	1

levels are sensitive to several parameters, e.g., costs, process parameters, financial parameters, and macro parameters might be relevant. The chosen elasticity, ε_{y,x_i}, in Eq. 23 reflects the relative change of the dependent variable y (here: LCOE, LCOW, CI) induced by a relative change of parameter value x_i.

$$\varepsilon_{y,x_i} = \frac{\Delta y}{\Delta x_i} \times \frac{x_i}{y} \quad \begin{aligned} &\varepsilon = 0 : \text{totallyinelastic} \\ &0 < |\varepsilon| < 1 : \text{underproportional} \\ &|\varepsilon| = 1 : \text{proportional} \\ &|\varepsilon| > 1 : \text{overproportional} \\ &|\varepsilon| \to \infty : \text{totallyelastic} \end{aligned} \tag{23}$$

Niger case and data

PV-BES and EWP technology

To provide the village with electricity a PV plant is installed together with a battery storage system. We follow the approach of Falk et al. [29], who present a photovoltaic system integrated with second-life lithium-ion batteries as an off-grid hybrid system for electrification. With a PV capacity of 10.58 kWp, a second-life battery storage capacity of 85 kWh, and under the regional climatic conditions the PV-BES system can provide ca. 19,500 kWh of usable electricity per year. Although keeping in mind the special conditions for West Africa, e.g., technology imports and logistics, the initial investment cost for PV-BES of 35,800€ (Table 3) is comparably high. Including replacement investment, e.g., for inverters, the present value investment is 42,900€. However, Falk's study presents a balanced technical concept, a real operating system, and corresponding cost data, gathered with local African partners.

For the second part, the electric water pumping system with water storage, the same arguments hold. The EWP system has a capacity of 10,950 m^3/y, the initial investment cost is 10,640€, and including replacement costs the present value investment is 17,200€. The investment cost data is taken from Falk et al. [28].

The kiosk serves as a hub for electricity and water provision. Given the institutional conditions, we additionally calculate the operation of a kiosk, which implies only operation and maintenance costs, e.g., for labor. According to the Daressalam conditions, the kiosk operation results in 1800 €/y. Its cost cannot be directly attributed to electricity or water provision. An allocation factor (all) is used to impute the cost of electricity and water provision, and the cost shares are assumed to be equally distributed, i.e., 50% (details see Annex, Table 8).

Electricity here is used for household needs (phone charging, radio, security bulbs, lighting bulbs, and random loads) and continuous provision to the electric water pump. For the daily load profile of the households, an approximation from Nouadje et al. [21] for low-consuming households, principally depending on farming, with peaks in the morning (4–6 am) and the evening (18–22 pm) is considered.

Table 3
Aggregated costs.

System	Capacity	Investment Cost (present value)	Operational Cost	Data Sources and Comments
PV-BES	• PV: 10.58 kW_p • BES: 85 kWh	42,900€	205€/y	• Specific PV-BES and EWP costs from [28, 29] • Kiosk cost: estimation for Dar Es-Salam, Niger [63]
EWP	10,950 m^3/y	17,200€	1100 €/y	
Kiosk	–	–	1800 €/y	

All monetary values are expressed in real terms, eliminating inflation.

Socio-economy

Table 4 comprises data for financial and socio-economic parameters. The subsidy shares s_{PV} and s_{WP} related to the initial investment costs are case-specific and, generally, the range is from 0–100%. Given the assumption on the maximum total subsidy of 40,000€, the s_{WP} in our case might range from 0–100%, as the EWP present value investment cost is 17,200€. For the PV-BES system, the maximum subsidy share s_{PV} is approximately 93% of the present value investment costs of 42,900€, summing up to the subsidy constraint (z = 40,000€). The total subsidy is high relative to the total present value capital expenditure of 60,000€, resulting in a subsidy share of 2/3, but plausible, though it depends on the ability and willingness of national or international institutions to offer subsidies.

For an average household (HH), yearly consumption of drinking water and electricity is 77 m^3 and 167 kWh, respectively. Average current prices are 0.4615€/m^3 for water and 0.1015€/kWh for electricity, respectively. The corresponding yearly household budget for water and electricity is approximately 53.5€. These data are generated based on a questionnaire and a survey of the village population in Daressalam in the Dosso region in Niger [48].

Case study results

We show the results for the case study Dar Es-Salam village, Niger. Subsequently, the results comprise:

- $LCOE_{basic}$ and $LCOW_{basic}$ for the integrated PV-BES-EWP system, for electricity and water provision without investments costs subsidies
- $LCOE_{Sub}$ and $LCOW_{Sub}$ for the integrated system, in case a constrained investment costs subsidy z is available, and for the different scenarios concerning the investment costs subsidy allocation schemes. This includes the calculation of scenario-specific subsidy shares for PV-BES (s_{PV}) and EWP (s_{WP}). It also includes the calculation of the factor γ for the relative change from basic to after-subsidy Levelized Costs, requesting the same relative change for electricity and water Levelized Costs in scenario 4.
- Finally, we present the results of the multi-criteria assessment calculating the Composite Index representing the socially preferable set of Levelized Costs for electricity and water. Keeping in mind that Levelized Costs may be interpreted as minimum sales prices over the lifetime of the technology to break even, we therefore identify the socially optimal sales price combination for electricity and water, based on the preferences of the villagers.
- The main findings for sensitivities.

Table 4
Financial and socio-economic data.

Parameter	unit	Value	Data Source and Comment
Interest rate r	%	5	• Interest rate approximation, see https://tradingeconomics.com/niger/interest-rate (12. March 2024) • Subsidy shares are scenario-specific; maximum shares $\overline{s_{PV}}$ and $\overline{s_{EWP}}$ based on investment costs (PV-BES, EWP) and subsidy constraint z • Policy assumption for subsidy constraint z • Data for initial prices for an average household in Dar Es-Salam, Niger, questionnaire source: Schlör et al. [48]
Subsidy share of PV-BES investment cost s_{PV}	%	scenario-specific	
Subsidy share of EWP investment cost s_{EWP}	%	scenario-specific	
Subsidy constraint, z	€	40,000	
Water price P_{W0}	€/m^3	0.4615	
Electricity price P_{E0}	€/kWh	0.1015	

All monetary values are expressed in real terms, eliminating inflation.

The key inputs comprise the technology cost data for PV-BES and EWP published by Falk et al. [28,29], (Table 3), results of the previous questionnaire for socio-economic data for Dar Es-Salam village, Niger, published by Schloer et al. [48,63], (Table 4), and assumptions on the interest rate and on the investment cost subsidy constraint, (Table 4). It is explicitly relevant that the available subsidy is constrained and does not suffice to fully subsidize investment costs for the PV-BES-EWP system, reflecting financial capital scarcity.

Basic levelized costs

Fig. 3 shows the basic Levelized Cost for electricity and water and the corresponding cost structures. Generally, there are high upfront costs for PV-BES systems and in our case the corresponding Levelized Cost share for investments ($LCOE_I$) is dominant (84%). Whereas for EWP the upfront cost share for investments ($LCOW_I$) is much lower (22%), the share of electricity cost $LCOW_E$ (52%) is very important. In both cases, the operation and maintenance costs ($LCOE_M$ and $LCOW_M$ for direct costs; $LCOE_K$ and $LCOW_K$ for the kiosk costs) are less important (16–25%), with the kiosk cost share being higher for PV-BES (11%) and the direct operation cost being higher for EWP (18%). The basic Levelized Costs equal 0.2095€/kWh for electricity and 0.5199 €/m^3 for water. For electricity, this is significantly higher (+106%) and for water it is moderately higher (13%) than the current state prices for customers in Dar Es-Salam village (Table 3).

Investment subsidy allocation and levelized costs results

For the different allocation schemes of the total subsidy according to the scenario approaches, Table 5 shows the resulting subsidy shares for PV-BES (s_{PV}) and EWP (s_{EWP}). It must be kept in mind that with a subsidy constraint (z=40,000€ in our case), the subsidy allocation parameters s_{PV} and s_{EWP} are interdependent. According to the scenarios, the subsidy share for electricity is shrinking, whereas for water it is increasing. If the subsidy is totally attributed to PV-BES, the corresponding subsidy share (s_{PV}) is 93% of the investment costs. In case the investment costs for EWP are fully subsidized, the corresponding subsidy share (s_{EWP}) is 100% and there is still subsidy left for PV-BES resulting in a corresponding subsidy share (s_{PV}) of 53%.

The corresponding after-subsidy Levelized Costs for electricity and water ($LCOE_{Sub}$, $LCOW_{Sub}$) are shown in Fig. 4. Obviously, without subsidies the increase compared to the current state is drastic for electricity, whereas for water it is relevant but not drastic. Allocating the subsidies solely to PV-BES (scenario 2) the Levelized Cost for electricity is drastically lower than in scenario 1 and still significantly lower compared to the current state. By indirectly subsidizing water the Levelized Costs for water are also significantly lower than in scenario 1 and compared to the current state. The reduction of the subsidy shares for PV-BES (s_{PV}) and the corresponding increase of the subsidy share for EWP (s_{EWP}) in scenarios 3–5 results in higher Levelized Costs for electricity up to the current state level. For water, scenarios 3–5 result in further moderately shrinking Levelized Costs. The post-subsidy Levelized Costs level is highest for electricity and lowest for water for scenario 5. Summarizing, allocation of the constrained subsidy z according to the scenarios enables to hold the Levelized Costs nearly equal to the current state cost of electricity or even reduce it coming along with a significant reduction of water costs.

Table 6 shows the contribution of the different subsidy channels. Obviously, for PV-BES, only direct impacts (channel 1) accounts, as there is no backward linkage from EWP subsidies. For EWP, direct and indirect impacts (channel 2) account, as water provision is linearly based on the use of electricity, meaning there is backward linkage. As the high PV-BES upfront cost translates to a high electricity cost share $LCOW_E$ for water, any significant reduction of investment costs for PV-BES induces an explicit reduction of the Levelized Cost of water. The higher the channel 1 impact for PV-BES the higher the channel 2 impact for EWP, wherefore the technical relation of specific electricity demand for water provision is an important factor. It becomes evident that, with decreasing subsidy shares for PV-BES, the scenarios result in decreasing relative changes of LCOE (from 79% to 45%). In contrast, the relative changes of LCOW increase, however only moderate (from 41% to 46%). Along with the different subsidy allocation schemes with decreasing subsidy of PV-BES, the channel 2 impact for EWP loses. For scenario 4 the allocation parameters s_{PV} and s_{EWP} are equal to reach the same relative change to Levelized Costs (here 46%). For scenario 5 with the

Table 5
Scenarios and subsidy allocation parameters.

Case	s_{PV} (%)	s_{EWP} (%)
No subsidy		
Base case	-	-
Scen 1	0	0
Subsidy z=40,000€		
Scen 2	93.22	0
Scen 3	66.57	66.57
Scen 4	54.29	97.27
Scen 5	53.20	100.0

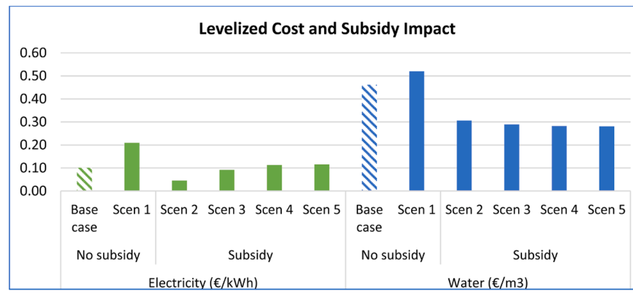

Fig. 4. Subsidy allocation and Levelized Costs.

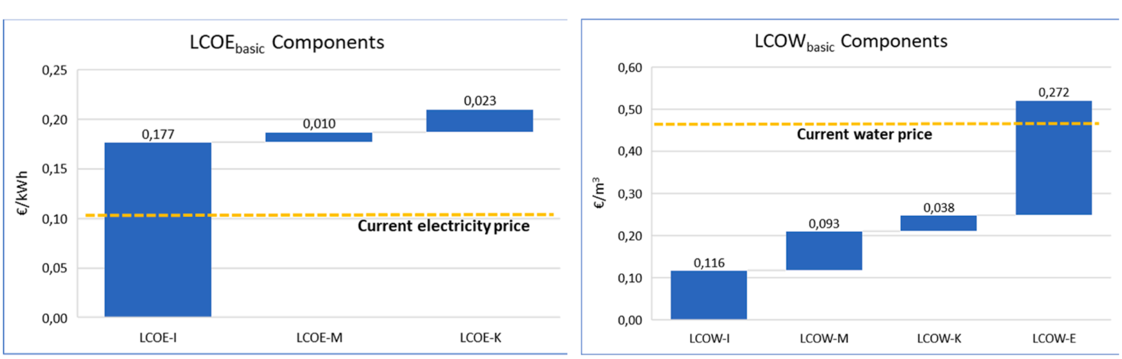

Fig. 3. Basic Levelized Costs of electricity (left) and water (right).

Table 6
Subsidy impact channels and contribution to relative levelized costs change.

Case	Subsidy Channel	PV-BES $LCOE_{Sub}$ relative to $LCOE_{basic}$	EWP $LCOW_{Sub}$ relative to $LCOW_{basic}$
Scen 1	Channel 1	–	–
	Channel 2	–	–
Scen 2	Channel 1	78.6%	–
	Channel 2	–	41.2%
Scen 3	Channel 1	56.1%	14.9%
	Channel 2	–	29.4%
Scen 4	Channel 1	45.8%	21.8%
	Channel 2	–	24.0%
Scen 5	Channel 1	44.9%	22.4%
	Channel 2	–	23.5%

Multi-criteria Assessment

lowest s_{PV} and highest s_{EWP} the changes relative to $LCOX_{basic}$ consequently are lowest for electricity (45%) and highest for water (46%).

For scenarios 1–5, Table 7 shows the indicators for assessment, more precisely the current state prices for electricity and water and the calculated post-subsidy Levelized Costs, interpreted as the necessary prices for the two products to guarantee the economic feasibility of the PV-BES-EWP system. As prices for electricity and water are not directly comparable, the absolute differences of the LCOX to the current state prices give no clear signal to identify a superior subsidy allocation scheme from the perspective of the villagers.

For the calculation of the Composite Index (CI), we use two normalization approaches (MinMax and Distance-to-Reference) and two weighting schemes for electricity (0.5 and 0.33) and correspondingly for water (0.5 and 0.67) to substantiate the results as shown in Fig. 5. The weighting schemes are approximated from the previous questionnaire [48,63]. The results clearly show that CI is highest for scenario 2 for all combinations of the normalization approaches and weighting schemes, meaning that villagers prefer this solution. However, with reduced weight for electricity, the advantage of scenario 2 shrinks for both normalization approaches, being better visible in the distance-to-reference case (as the CI is not limited to 1 in that case). Scenario 2 allocates the full subsidy to PV-BES, the system components with the highest upfront capital expenditures.

Sensitivities

For sensitivity analysis, scenario 2 is chosen, the one attributed superiority, and the focus is on parameters for the process (elec), costs (CAPEX), finance (subsidy constraint z), and the weighting factor for the CI (Fig. 6). For the post-subsidy Levelized Costs, sensitivities to elec and CAPEX for EWP are under-proportional, whereas sensitivities to CAPEX PV-BES and z are over-proportional. The high sensitivity to CAPEX PV-BES can be explained by the fact that, additionally to a higher CAPEX, the subsidy allocation share s_{PV} shrinks due to the fixed subsidy level z. The explanation for the high sensitivity to z is similar, as with reduced total subsidy z additionally the subsidy allocation share s_{PV} shrinks. Although in scenario 2 subsidy is allocated solely to PV-BES, the $LCOW_{Sub}$ is also highly sensitive to CAPEX PV-BES due to the indirect effect of subsidy (impact channel 2) (see Table 6). As to the high upfront cost for PV-BES, the high sensitivity to CAPEX is in line with the literature results. Surprisingly, at first sight, for PV-BES the $LCOE_{Sub}$ is sensitive to elec, too, although on a very low level. The explanation is that with higher elec there is an effect on the level of electricity and battery use, which in turn results in slightly lower $LCOE_{Sub}$.

With respect to the Composite Index, for the equal weighting case (w =½) sensitivity is proportional for both normalization approaches, but under-proportional and very low in the case of higher weight for water (w = 1/3). It must be kept in mind that a variation of the weighting factor for electricity automatically changes the weighting factor for water and vice versa. However, the sensitivities do not change the rank of the scenarios, as scenario 2 remains superior.

Table 7
Multi-criteria indicators.

Case	Electricity (€/kWh)	Δ to Current State	Water (€/m^3)	Δ to Current State
No subsidy				
Base case	0.1015	-	0.4615	-
Scen 1	0.2095	0.1080	0.5199	0.0584
Subsidy				
Scen 2	0.0448	-0.0567	0.3058	-0.1557
Scen 3	0.0919	-0.0096	0.2895	-0.1720
Scen 4	0.1136	0.0121	0.2819	-0.1796
Scen 5	0.1155	0.0150	0.2812	-0.1803

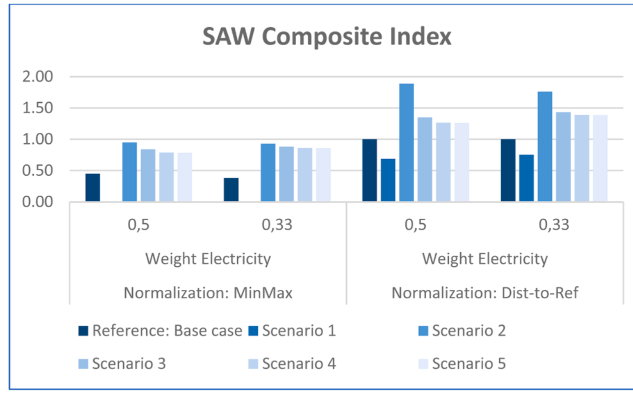

Fig. 5. Composite Index for electricity and water.

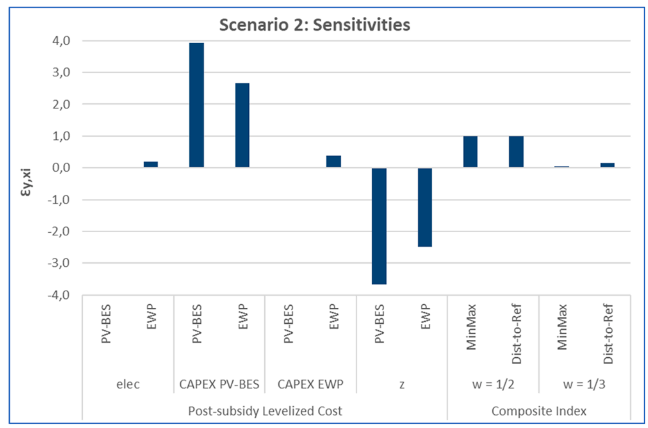

Fig. 6. Levelized Costs and Composite Index sensitivities for scenario 2.

Discussion

Key discussion points

The analysis focuses on the provision of renewable electricity and water by means of PV-BES-EWP systems for rural West African villages, which currently suffer from lacking electricity access and drinking water provision. The socio-economic parameters of Dar Es-Salam village in the Dosso region in Niger are taken as an example. The focus on investment costs subsidies to incentivize socio-economic development is becoming increasingly important in times of soaring debt crisis for low-income countries [64], amplifying challenges to develop infrastructures providing essential daily goods like electricity and drinking water, especially in rural areas. All ECOWAS countries besides Mali, Guinea and Liberia have exceeded the International Monetary Fund's 23% threshold for debt service to revenue, and some (e.g., Niger) are debt distressed [65].

Interpreting Levelized Costs as the minimum price for the product to achieve economic viability for investing in and operating the technical systems, the results can be easily compared to current electricity and water prices and future price targets, acceptable for residents in rural West African villages. The results for Dar Es-Salam show that the allocation of investment costs subsidies to PV-BES and EWP considerably impacts the resulting Levelized Costs for Electricity and for Water. This is highly relevant in case the total subsidy is less than the investment expenditures for both PV-BES and EWP, a case characterized by subsidy scarcity. Different subsidy allocation schemes ranging from subsidizing only PV-BES to prioritizing EWP show that the impact on reduction of electricity prices shrinks the more subsidy is allocated to the water provision and vice versa. But water prices indirectly benefit from PV-BES subsidies due to the shrinking electricity costs for water, additionally to the direct impact on water prices by EWP subsidies. However, as the comparison of electricity and water prices and the impact of subsidy allocation schemes is meaningless because of the different units for electricity and water, the identification of a superior subsidy scheme and corresponding prices for electricity and water is based on a Composite Index for electricity and water prices, reflecting Dar Es-Salam village residents' preferences. The results are substantiated by using two normalization approaches and two approaches for weighing electricity and water. The results for Dar Es-Salam village reveal prioritizing PV-BES subsidies as the superior subsidy allocation scheme implicating a price set for electricity and water, coming as closest to the perspectives of the village people.

The results mainly reflect 3 characteristics. Firstly, it is the cost and cost structures of the PV-BES and EWP systems, especially the relatively high upfront cost for PV-BES compared to EWP in the Dar Es-Salam village case. In the case of very different local conditions, e.g., water resources access, electricity use and number of people there might be other parameters. However, in all accessible literature on integrated PV-BES-EWP systems the upfront costs of the PV-BES system are higher. Corresponding structures of Levelized Costs of electricity and water are very different, with the investment cost share dominating in the case of PV-BES and the operating cost share much higher for EWP, keeping in mind that the operating costs of EWP mainly comprise electricity costs. The disclosure of the kiosk's cost reveals moderate impacts, which is due to the relatively low kiosk operating costs and the absence of investment costs. Nevertheless, this kiosk concept is important as it offers an opportunity to manage the PV-BES-EWP system and to lay the foundation for successfully and trustfully operating the system over the entire projected economic lifetime in a rural community context in West Africa. Secondly, the level of the available subsidy, which is assumed as lower than the total investment costs, is a further aspect promoting the superiority of allocating subsidy to PV-BES. The higher the available subsidy the less subsidy scarcity prevails, however, the availability of subsidies depends on the ability and willingness of governments, national and international institutions, as well as private initiatives. Thirdly, the village people's preferences as to bearable electricity and water prices determine the resulting set of prices corresponding with the costs and cost structures for electricity and water, technical interdependencies (water extraction uses electricity), and chosen subsidy allocation scheme.

The representativity of the socio-economic data of the Dar Es-Salam village for rural West Africa may be questioned as the data grounds on a questionnaire and survey conducted with Dar Es-Salam residents. However, although the socio-economic backgrounds of rural villages in West African countries differ, lacking electricity and drinking water access and resource scarcity prevail in most countries, however on different levels. The formulation of results generalized for West African rural communities needs more extensive socio-economic research, e.g., representative surveys conducted together with local institutions. The same holds for the representativity and accuracy of techno-economic data for the PV-BES-EWP system, as local conditions impacting the investment and operating expenditures are different. Nevertheless, the methodology developed for the Niger case provides a basis for further research.

Given the case data, reflecting main assumptions like the constrained investment costs subsidy, and considering the high upfront costs for PV-BES compared to EWP, the findings are in the expected range. But, for cases with other costs and cost structures for PV-BES and EWP as well as other preferences as to bearable electricity and water costs, the identified superior subsidy allocation scheme might differ.

Nevertheless, the results are suggestive of some policy implications. Investment costs subsidies help to reduce the costs for providing electricity and water, both essential goods, of villagers in rural areas of West Africa. As in low-income countries capital accumulation of local people for investment in PV-BES-EWP is practically not available, subsidies are essential. In case of subsidy scarcity, which usually prevails, it is most relevant how to allocate subsidies to different technologies to induce cost reductions. Levelized costs of electricity and water give a clear indicator as to the necessary returns to make the PV-BES-EWP system economically viable and the preferences of local people as to bearable costs are an ideal indicator. However, detailed data for the socioeconomic situation of local people is hardly available. It is worthwhile investing in data acquisition, clarifying local socio-economic situation and people's preferences before deciding on subsidy allocation.

Further insights

The availability of financial resources has far-reaching consequences beyond subsidies, at least in a world of constrained subsidies. The socioeconomic conditions in rural villages like Dar Es-Salam in Niger, where most households live as subsistence farmers with low incomes, are not in favor of private or communal investments like PV-BES-EWP. Subsistence farming hardly provides opportunities to save money and build a capital stock. The study is also relevant for other developments contexts, e.g., for rural areas in South African countries and other regions in the world, facing similar problems as to electricity and water access for residential use. In areas with subsistence farming, electricity and water access may also contribute to improving people's livelihoods. In a broader context, the study serves as useful in the water-energy-food (WEF) nexus discussion.

However, the study has limitations. From a microeconomic perspective, the impacts of price-elastic demands may be further considered as well as of utility functions addressing interdependencies of electricity and water preferences. With respect to a broader sustainability context, especially environmental impacts may be further considered as well as consequences for natural resources use. The contribution to development economics may be further highlighted, e.g., on adequateness of the level of subsidies in PV-BES-EWP and further contexts, as well as on aspects how to allocate subsidies to several rural villages from a top-down perspective. Generally, there is a need for further socio-economic field research with African partners to gain a better understanding, collect representative data, explore ways to increase access to financial resources, and increase the involvement of villagers, especially in developing countries to increase access to financial resources, electricity, and water.

Conclusion

Access to electricity and water is one of the biggest obstacles facing residents of rural communities in West Africa. This study uses the village of Dar Es-Salam, Niger, as a case study to highlight these challenges. PV with battery electricity storage (PV-BES) and electric water pumping

(EWP) systems illustrate viable options to address these issues and provide sustainable solutions to improve the quality of life in these communities. The implementation of such technologies can make a meaningful contribution to overcoming the barriers to energy and water access in rural West Africa.

However, PV-BES and EWP are associated with high up-front investment costs, which with West African rural conditions are rarely affordable for residents of low-income, subsistence farming communities. Therefore, external funding sources to subsidize investments in PV-BES and EWP are essential. Yet, external funding is limited, and the question of how to allocate a limited subsidy to the system components (PV-BES and EWP) of an integrated technical system arises, as there is subsidy competition for the system components. The allocation of subsidies to PV-BES and EWP significantly impacts the post-subsidy Levelized Cost of Electricity and Water. From a techno-economic point of view, however, the superiority of an allocation scheme is not evident, as the direct comparison of electricity and water costs is not meaningful due to the different units for electricity and water.

A Composite Index calculation based on multi-criteria methodology representing local villager's preferences helps to identify a superior subsidy allocation scheme. The results show that allocating the constrained subsidy fully to PV-BES, the system component with the higher upfront capital expenditure, is superior in the Dar Es-Salam village case. However, it must be kept in mind that the results are based on the subsidy constraint, which in our case covers about two-thirds of the present value investment cost for the whole PV-BES-EWP system, but nearly the full present value investments costs for the PV-BES component. Secondly, the Levelized Cost of Water considerably benefits from PV-BES subsidies as the electricity cost share is the main cost component for water provision. And thirdly, the solution is grounded on the assessment of post-subsidy Levelized Cost relative to the average prices paid by Daressalam villagers for electricity and water in 2022.

The methodology presented can be applied to other developing countries confronted with similar problems as to uninterrupted and safe provision of electricity and water in rural environments and the use is not limited to West African countries. The formulation of results applicable for further African rural communities require more extensive socio-economic research, including representative surveys conducted together with local institutions. The same applies to the representativeness and accuracy of the techno-economic data for the PV-BES-EWP system, as local conditions affecting investment and operating costs are different.

Overall, the availability of financial resources is crucial, particularly in areas with limited subsidies. In villages like Dar Es-Salam, Niger, where most households are low-income subsistence farmers, investments in PV-BES-EWP systems are difficult. Subsistence farming leaves little room for savings or capital accumulation. Further socio-economic research with African partners is needed to collect data and better understand communities and villager's preferences. This is mandatory to better match possible investment costs subsidy induced cost reductions and local preferences as to bearable costs for electricity and water.

CRediT authorship contribution statement

Wilhelm Kuckshinrichs: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Holger Schlör:** Writing – review & editing, Funding acquisition, Data curation, Conceptualization. **Boubacar Ibrahim:** Writing – review & editing, Data curation. **Florian Siekmann:** Writing – review & editing, Data curation. **Sandra Venghaus:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Annex

Nomenclature

all	allocation factor for kiosk costs
BES	battery electricity storage
CAMES	Conseil Africain et Malgache pour l'Enseignement Supérieur
CAPEX	capital expenditures
CI	composite indicator
deg_{Bat}	technical degradation of battery
deg_{PV}	technical degradation of PV
$elec_{EWP}$	specific electricity uses for pumping and storing water
E	energy cost
EWP	water pumping and storing system
E_{AC}	AC generation through PV
E_{Bat}	electricity from battery
E_{dir}	directly usable electricity (no storage)
E_{U}	usable electricity
HH	household
I_{PV}	investment cost for photovoltaic system
I_{EWP}	investment cost for water pumping system
K	operational cost of kiosk
LCOE	Levelized Cost of Electricity (general)
LCOW	Levelized Cost of Water (general)
LCOX	Levelized Cost of Product (general)
$LCOE_{basic}$	Levelized Cost of Electricity, no investment costs subsidies
$LCOE_{I}$	share of Levelized Cost of Electricity due to investment cost
$LCOE_{M}$	share of Levelized Cost of Electricity due to direct operation and maintenance cost for PV-BES
$LCOE_{O}$	share of Levelized Cost of Electricity due to direct operation and maintenance cost for PV-BES plus attributed kiosk cost
$LCOE_{Sub}$	after-subsidies Levelized Cost of Electricity
$LCOW_{basic}$	Levelized Cost of Water, no investment costs subsidies
$LCOW_{I}$	share of Levelized Cost of Water due to investment cost

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(*continued*)

$LCOW_E$	share of Levelized Cost of Water due to electricity cost
$LCOW_M$	share of Levelized Cost of Water due to direct operation and maintenance cost for EWP
$LCOW_O$	share of Levelized Cost of Water due to direct operation and maintenance cost for EWP plus attributed kiosk cost
$LCOW_{Sub}$	after-subsidies Levelized Cost of Water
O	operation and maintenance cost, general
OPEX	operational expenditures
PV	photovoltaic system
$P_{E,a}$	targeted electricity price
$P_{W,a}$	targeted water price
r	discount rate
SSA	Sub-Saharan Africa
s_{EWP}	share of EWP investment costs subsidy
s_{PV}	share of PV-BES investment costs subsidy
$\overline{s(\gamma)}$	necessary subsidies share to guarantee (general)
$\overline{s(\gamma_E)_{PV}}$	necessary subsidies share for PV investment to guarantee γ_E
$\overline{s(\gamma_W)_{EWP}}$	necessary subsidies share for EWP investment to guarantee γ_W
T	lifetime of technology
w	weighing factor
WACC	weighted average cost of capital
W_U	usable water
X	product
y	year
z	Constrained investment subsidies (for PV-BES and EWP together)
γ	relation for relative Levelized Cost changes due to subsidization, general
γ_E	relation for relative LCOE changes due to subsidization of PV-BES
γ_W	relation for relative LCOW changes due to subsidization of EWP
$\gamma_{E,W}$	relation for equal relative LCOE and LCOW changes due to subsidization of PV-BES and EWP
ε	elasticity
η	BES efficiency

PV-BES Modeling

The system operates as a coupled PV-BES system and the formulas for the technical model are derived from Kuckshinrichs et al. [66]. We have adapted the original approach, as in the Dar Es-Salam village case there is no feed-in to the overarching grid. The used approach is summarized in Eqs. (24), see also [67], to (27) with electricity generation $E_{AC,t}$, directly usable electricity $E_{dir,t}$, electricity from battery $E_{Bat,t}$, and usable electricity E_t. deg_{PV} describes technology degradation for PV cells and deg_{Bat}, respectively, degradation of batteries. η stands for battery storage efficiency.

$$\mathbf{E_{AC,t}} = \mathbf{E_{AC,0}} \times \left(1 + \mathbf{deg_{pv}}\right)^{\mathbf{t}} \tag{24}$$

$$\mathbf{E_{dir,t}} = \overline{\mathbf{E}} \tag{25}$$

$$\mathbf{E_{Bat,t}} = \left(\mathbf{E_{AC,t}} - \overline{\mathbf{E}}\right) \times \boldsymbol{\eta} \times (1 + \mathbf{deg_{Bat}})^{\mathbf{t}} \tag{26}$$

$$\mathbf{E_t} = \overline{\mathbf{E}} + \mathbf{E_{Bat,t}} = \overline{\mathbf{E}}\left(1 - \boldsymbol{\eta}(1 + \mathbf{deg_{Bat}})^{\mathbf{t}}\right) + \boldsymbol{\eta}\mathbf{E_{AC,0}}\left(1 + \mathbf{deg_{PV,t}}\right)^{\mathbf{t}}\left(1 + \mathbf{deg_{Bat,t}}\right)^{\mathbf{t}} \tag{27}$$

Levelized Cost Modeling

For the PV-BES system initial investment $I_{PV,0}$ comprises the PV cells, inverters, and batteries. Lifetime of cells is T and at the time T_1 new investments for inverters and batteries $I_{PV,T1}$ is necessary. $M_{PV,t}$ covers all direct operation and maintenance costs, e.g., for labor, except for the kiosk service. The kiosk cost is expressed as K_t and the factor all defines the share of total kiosk cost allocated to PV-BES. Similarly, for water initial investment for the pump and storage system is $IE_{WP,0}$, new investments at T_2 for equipment is $I_{EWP,T2}$. M_{EWP} stands for direct operating costs except for kiosk service and electricity cost. (1-all) allocates kiosk cost to EWP. $elec_{EWP}$ stands for the specific electricity needed for pumping and storing water.

$$\mathbf{LCOE_{basic}} = \frac{\mathbf{I_{PV,0}} + \frac{\mathbf{I_{PV,T1}}}{(1+\mathbf{r})^{\mathbf{T1}}} + \sum_0^{\mathbf{T}} \frac{\mathbf{M_{PV,t}}}{(1+\mathbf{r})^{\mathbf{t}}} + \quad + \sum_0^{\mathbf{T}} \frac{\mathbf{all} \times \mathbf{K_t}}{(1+\mathbf{r})^{\mathbf{t}}}}{\sum_0^{\mathbf{T}} \frac{\mathbf{E_{U,t}}}{(1+\mathbf{r})^{\mathbf{t}}}} \tag{28}$$

$$\mathbf{LCOW_{basic}} = \frac{\mathbf{I_{EWP,0}} + \frac{\mathbf{I_{EWP,T2}}}{(\mathbf{1}+\mathbf{r})^{\mathbf{T2}}} + \sum_0^{\mathbf{T}} \frac{\mathbf{ME_{WP,t}}}{(\mathbf{1}+\mathbf{r})^{\mathbf{t}}} + \sum_0^{\mathbf{T}} \frac{(\mathbf{1} - \mathbf{all}) \times \mathbf{K_t}}{(\mathbf{1}+\mathbf{r})^{\mathbf{t}}}}{\sum_0^{\mathbf{T}} \frac{\mathbf{W_t}}{(\mathbf{1}+\mathbf{r})^{\mathbf{t}}}} + \mathbf{elec_{EWP}} * \mathbf{LCOE_{basic}} \tag{29}$$

Referring to the Levelized Cost shares for investment I, operating cost O, kiosk cost K, and electricity cost (in case of water) Eqs. (30) to (36) hold.

$$\mathbf{LCOE_I} = \frac{\mathbf{I_{PV,0}} + \frac{\mathbf{I_{PV,T1}}}{(1+\mathbf{r})^{\mathbf{T1}}}}{\sum_0^{\mathbf{T}} \frac{\mathbf{E_{U,t}}}{(1+\mathbf{r})^{\mathbf{t}}}} \tag{30}$$

$$\mathbf{LCOE_M} = \frac{\sum_0^{\mathbf{T}} \frac{\mathbf{M_{PV,t}}}{(1+\mathbf{r})^{\mathbf{t}}}}{\sum_0^{\mathbf{T}} \frac{\mathbf{E_{U,t}}}{(1+\mathbf{r})^{\mathbf{t}}}} \tag{31}$$

$$\mathbf{LCOE_K} = \frac{\sum_0^T \frac{all \times K_t}{(1+r)^t}}{\sum_0^T \frac{E_{U,t}}{(1+r)^t}} \quad (32)$$

$$\mathbf{LCOW_I} = \frac{I_{EWP,0} + \frac{I_{EWP,T2}}{(1+r)^{T2}}}{\sum_0^T \frac{W_{U,t}}{(1+r)^t}} \quad (33)$$

$$\mathbf{LCOW_M} = \frac{\sum_0^T \frac{M_{EWP,t}}{(1+r)^t}}{\sum_0^T \frac{W_{U,t}}{(1+r)^t}} \quad (34)$$

$$\mathbf{LCOW_K} = \frac{\sum_0^T \frac{(1-all) \times K_t}{(1+r)^t}}{\sum_0^T \frac{W_{U,t}}{(1+r)^t}} \quad (35)$$

$$\mathbf{LCOW_E} = \mathbf{elec_{EWP}} \times \mathbf{LCOE_{basic}} \quad (36)$$

For ease of representation in the main text, we summarize PV-BES and EWP direct operating costs M and kiosk costs K to operating costs O.

$$\mathbf{LCOE_O} = \mathbf{LCOE_M} + \mathbf{LCOE_K} \quad (37)$$

$$\mathbf{LCOW_O} = \mathbf{LCOW_M} + \mathbf{LCOW_K} \quad (38)$$

Detailed Technology Parameters and Cost Data for PV-BES and EWP

Table 8
Technology parameters and cost data.

	Factor	Abbr.	Technical Parameters	Cost Parameters				Data Source
				Investment Costs		O+M Costs		
				Specific €	Total €	Specific €/y	Total €/y	
PV	Cell	I_{PV}	10.58 kWp	330	**3491**			[29]
	O+M	M_{PV}	1 %/y of I_{PV}			3.3	**35**	
	Lifetime	T	20 y					
	Degradation	deg_{PV}	-0.5 %/y					Assumption
Inverter	Inverter (Offgrid+PV)	I_{PVI}	13.25	753	**4944**			[29]
	O+M	M_I	1 %/y of I_{PVI}			7.53	**100**	
	Lifetime	T_1	10 y					
Battery	2nd life battery	I_{Bat}	85 kWh	82	**7000**			[29]
	O+M	M_{Bat}	1 %/y of I_{BAT}			0.82	**70**	
	Lifetime	T_1	10 y					
	Degradation	deg_{Bat}	-0.1 %/y					Assumption
Aux	Small parts/ cables			142	**1500**			[29]
	Logistics			362	**3825**			
	Craft			1418	**15,000**			
Total				3086	**35,760**		**205**	
Water	Electric water pump	I_{EWP}			**10,640**			[28]
	O+M	M_{EWP}					**300**	
	Electricity input	$elec_{EWP}$	1.3 kWh/m^3					Assumtion
	Lifetime	T_2	10 y					[28]
Kiosk	O+M	K	–				**1800**	[63]

All monetary values are expressed in real terms, eliminating inflation

Data availability

Data will be made available on request.

References

[1] M. Mukhtar, et al., Juxtaposing Sub-saharan Africa's energy poverty and renewable energy potential, Sci. Rep. 13 (2023) 11643.

[2] M. Agoundedemba, C.K. Kim, H.-G. Kim, Energy status in Africa: challenges, progress and sustainable pathways, Energies 16 (2023) 7708.

[3] J.O. Akelo, D.M. Nzengya, How household water use characteristics and sense of water kiosk ownership influence financial sustainability of community-managed borehole water kiosk service in Isumi Country, Kenya. Afr. J. Empir. Res. 4 (2) (2023) 630–645.

[4] S. Ishman, et al., Mapping local green hydrogen cost potentials by a multidisciplinary approach, Int. J. Hydrog. (2024) **accepted**.

[5] C. Winkler, et al., Participatory mapping of local green hydrogen cost potentials in Sub-Saharan Africa, Int. J. Hydrog. (2024) **accepted**.

[6] I. Hoeck, et al., Challenges for off-grid electrification in rural areas. Assessment of the situation in Namibia using the examples of Gam and Tsumkwe Energy, Ecol. Environ. 7 (5) (2022) 508–522.
[7] International Monetary Fund, Regional Economic outlook. Sub-Saharan Africa: the Big Funding Squeeze, International Monetary Fund, Editor, 2023.
[8] S.-T. Lee, S.-M. Jung, Subsidizing the shift to renewable energy in Korea: a levelized cost analysis and computation of required subsidies, SAGE Open (2024) 1–13. **April-June**.
[9] X. Ouyang, B. Lin, Levelized cost of electricity (LCOE) of renewable energies and required subsidies in China, Energy Policy 70 (2014) 64–73.
[10] O. Adeoye, C. Spataru, Modelling and forecasting hourly electricity demand in West African countries, Appl. Energy 242 (2019) 311–333.
[11] M. Bissiri, et al., Generation capacity expansion planning with spatially-resolved electricity demand and increasing variable renewable energy supply: perspectives from power pooling in West Africa, Appl. Energy 364 (2024) 123115.
[12] V. Karbassi, P.A. Trotter, G. Walther, Diversifying the African energy system: economic versus equitable allocation of renewable electricity and e-fuel production, Appl. Energy 350 (2023) 121751.
[13] M.L. Njoke, Z. Wu, H. Abudu, The effect of investment and financing optimization policies for developing photovoltaic power generation in Cameroon; a dynamic CGE model assessment, Front. Energy Res. 11 (2023) 1238112.
[14] S. Szabó, et al., Mapping of affordability levels for photovoltaic-based electricity generation in the solar belt of sub-Saharan Africa, East Asia South Asia. Sci. Rep. 11 (2021) 3226.
[15] R.J. Chilundo, U.S. Mahanjane, D. Nevens, Design and performance of photovoltaic water pumping systems: comprehensive review towards a renewable strategy for Mozambique, J. Power Energy Eng. 6 (2018) 32–63.
[16] C. Zhai, et al., Improving drinking water access and equity in rural Sub-Saharan Africa, Prod. Oper. Manag. 32 (2023) 2921–2939.
[17] H. Dibaba, et al., Feasibility of rural electrification and connectivity—a methodology and case study, Appl. Energy 315 (2022) 119013.
[18] S.J. Thomas, et al., Urban water management with full cost recovery policy: the impact of externalities on pricing, Sustainability 14 (2022) 14495.
[19] S.S. Thomas, et al., Sustainability analysis on rural livelihood systems with interventions in energy-water-food nexus, Int. J. Energy Clean Environ. 23 (8) (2022) 41–52.
[20] F. Egli, et al., The cost of electrifying all households in 40 Sub-Saharan African countries by 2030, Nat. Commun. 14 (2023) 5066.
[21] B.A.M. Nouadje, P.T. Kapen, V. Chegnimonham, Techno-economic analysis of a grid/fuel cell/PV/electrolyzer system for hydrogen and electricity production in the countries of African and Malagasy council for higher education (CAMES), Energy Strategy Rev. 53 (2024) 101392.
[22] T.R. Ayodele, A.S.O. Ogunjuyigbe, O.A. Adeniran, Evaluation of solar powered water pumping system: the case study of three selected abattoirs in Ibadan, Niger.. Int. J. Sustain. Eng. 12 (1) (2019) 58–69.
[23] C.G. Lewis, et al., Achieving universal energy access in remote locations using Homer energy model: a techno-economic and environmental analysis of hybrid microgrid systems for rural electricification in northeast Nigeria, Front. Energy Res. 12 (2024) 1454281.
[24] A. Odou, R. Bhandari, R. Adamou, Hybrid off-grid renewable power system for sustainable rural electrification in Benin, Renew. Energy 145 (2020) 1266–1279.
[25] N. Rangel, H. Li, P. Aristidou, An optimisation tool for minimising fuel consumption, costs and emissions from Diesel-PV-battery hybrid microgrids, Appl. Energy 335 (2023) 120748.
[26] S.K. Sakiliba, et al., Assessment of stand-alone residential solar photovoltaic applications in Sub-Saharan Africa: a case study of Gambia, J. Renew. Energy (2015) 640327.
[27] E.A. De la Fresnaye, A financial and technical assessment of solar versus hand water pumping for offgrid area - the case of Burkina Faso. Energy Futures Lab, Imperial College London, London, 2018.
[28] J. Falk, et al., Drinking water supply in rural Africa based on a mini-grid energy system - a socio-economic case study for rural development, Sustainability 14 (2022) 9458.
[29] J. Falk, et al., Applying lithium-ion second life batteries for off-grid solar powered system - a socio-economic case study for rural development, Z. Energiewirtschaft 44 (2020) 47–60.
[30] Z. Girma, Techno-economic analysis of photovoltaic pumping system for rural water supply in Ethiopia, Int. J. Sustain. Energy 36 (3) (2017) 277–295.
[31] N. Jovanovic, et al., Feasibility of solar-powered groundeater pumping systems in rural areas of Greater Giyani Municipality (Limpopo, South Arica), Appl. Sci. 13 (2023) 3859.
[32] K. Wydra, P. Becker, H. Aulich, Sustainable solutions for solar energy driven drinking water supply for rural settings in Sub-Saharan Africa: a case study of Nigeria, J. Photonics Energy 9 (4) (2019) 043106.
[33] N.M. Ahmed, et al., Reliability and performance evaluation of a solar PV-powered underground water pumping system, Sci. Rep. 13 (2023) 14174.
[34] M. Irandoostshahrestani, D.R. Rousse, Status of photovoltaic water pumping systems in Iran: a comprehensive review, Water Sci. Technol. 89 (12) (2024) 3270.
[35] H.A. Kazem, A. Quteishat, M. Younis, Techno-economical study of solar water pumping system: optimum design, evaluation, and comparison, Renew. Energy Environ. Sustain. 6 (2021).
[36] A.O.M. Maka, M. Mehmood, T.N. Chaudhary, Design, simulation and performance analysis of photovoltaic solar water pumping system, Energy Harvest. Syst. 10 (2) (2023) 287–299.
[37] P. Pachaivannan, S. Manimuthu, V. Jegadeesan, Comparative energy performance analysis of solar watr pumping systems across diverse climate zones, J. Eng. Res. (2024).
[38] A. Rout, et al., in: M.E.H. Assad, M.A. Rosen (Eds.), Benefit-cost Analysis and Parametric Optimization Using Taguchi method For a Solar Water heater, in Design and Performance Optimization of Renewable Energy Systems, Elsevier, 2021. Editors.
[39] A. Rout, et al., Development of customized formulae for feasibility and break-even analysis of domestic solar water heater, Int. J. Renew. Energy Res. 7 (1) (2017) 386–398.
[40] A. Rout, et al., A Monte-Carlo based approach for exergo-economic modeling of solar water heater, Energy Sources A: Recovery Util. Environ. Eff. (2020).
[41] D. Muzenda, Incresing Private Investment in African energy infrastructur, Secretariat of the NEPAD-OECD Africa Investment Initiative, OECD, 2009. Editor.
[42] C. Agutu, et al., Accounting for finance in electrification models for Sub-Saharan Africa, Nat. Energy 7 (2022) 631–641.
[43] F. Antonanzas-Torres, J. Antonanzas, J. Blanco-Fernandez, State-of-the-art of mini grids for rural electrification in West Africa, Energies 14 (2021) 990.
[44] Husein, M., et al., The impacts of incentive policies on improving private investment for rural electrifaction in Nigeria - a spatial study Heliyon, 2024. 10: p. e27440.
[45] B.O. Menyeh, Financing electricity access in Arica: A choice experiment study of household investor preferences for renewable energy investments in Ghana, Renew. Sustain. Energy Rev. 146 (2021) 111132.
[46] F. Polzin, et al., How do policies mobilize private finance for renewable energy? A systematic review with an investor perspective, Appl. Energy 236 (2019) 1249–1268.
[47] B. Sweerts, F.Dalla Longa, B. van der Zwaan, Financial de-risking to unlock Africa's renewal energy potential, Renew. Sustain. Energy Rev. 102 (2019) 75–82.
[48] H. Schlör, W. Kuckshinrichs, S. Venghaus, in: The rural-urban energy-water gap of West African households - Marshallian demand functions and the utility function of the household, in 15th ICAE conference 'Energy transitions towards carbon neutrality, Doha, Qatar, 2023.
[49] S. Godfrey, Redesigning a solar PV kiosk in high-temperature environments of Burundi, Afr. Sustain. 15 (2023) 5514.
[50] R. Bhandari, et al., Sustainability assessment of electricity generation in Niger using weighted Multi-criteria decisison approach, Sustainability 13 (2020) 385.
[51] R. Gupta, et al., Levelized cost of solar photovoltaics and wind supported by storage technologies to supply firm electricity, J. Energy Storage 27 (2020) 101027.
[52] K. Kappner, P. Letmathe, P. Weidinger, Optimisation of photovoltaic and battery systems from the prosumer-oriented total cost of ownership, Energy Sustain. Soc. 9 (2019) 44.
[53] C.S. Lai, M.D. McCulloch, Levelized cost of electricity for solar photovoltaic and electrical energy storage, Appl. Energy 190 (2017) 191–203.
[54] P. Lazzeroni, et al., Economic, energy, and environmental analysis of PV with battery storage for Italian households, Electronics 10 (2021) 146.
[55] G. Friedl, et al., Applications of the levelized cost concept, J. Bus. Econ. 93 (2023) 1125–1148.
[56] S.B. Darling, et al., Assumptions and the levelized cost of energy for photovoltaics, Energy Environ. Sci. 4 (9) (2011) 3133–3139.
[57] W. Kuckshinrichs, T. Ketelaer, J.C. Koj, Economic analysis of improved alkaline water electrolysis, Front. Energy Res. 5 (2017) 1.
[58] NREL. Simple levelized cost of energy (LCOE) calculator - documentation. 2020; Available from: https://www.nrel.gov/analysis/tech-lcoe-documentation.html. Upload: 2020, Oct., 8.
[59] M.J.B. Kabeyi, O.A. Olanrewaju, The levelized cost of energy and modifications for use in electricity generation planning, Energy Rep. 9 (2023) 495–534.
[60] A. Castillo-Ramírez, D. Mejía-Giraldo, N. Muñoz-Galeano, Large-scale solar PV LCOE comprehensive breakdown methodology. CT&F - ciencia, Tecnol. Futuro 7 (1) (2017) 117–136.
[61] OECD, Handbook of Constructing Composite indicators, OECD, Editor, OECD: Paris, 2008.
[62] H. Taherdoost, M. Madanchian, Multi-criteria decision making (MCDM) methods and concepts, Encyclopedia 3 (2023) 77–87.
[63] H. Schlör, W. Kuckshinrichs, Measuring the social welfare of a solar power plant in West Africa - A social return on investment (SROI) model, DIEM: Dubrov. Int. Econ. Meet. 1 (2023).
[64] D.J. Penzin, B.N. Akanegbu, Public debt and economic growth in the West African monetary zone (WAMZ), Sci. Afr. 24 (2024) e02200.
[65] West African Debt Management Roundtable, Debt Management, restructuring and sustainabilty in ECOWAS, 2023.
[66] W. Kuckshinrichs, C. Ball, G. Aniello, Levelized profits for residential PV-battery systems and the role of regulatory and fiscal aspects in Germany, Energy Sustain. Soc. 13 (10) (2023).
[67] K. Branker, M.J.M. Pathak, J.M. Pearce, A review of solar photovoltaic levelized cost of electricity, Renew. Sustain. Energy Rev. 15 (2011) 4470–4482.