Socio-economic impacts and challenges associated with the electrification of a remote area in rural Tanzania through a mini-grid system

Joern Falk¹ · Martin Angelmahr¹ · Wolfgang Schade^{1,2} · Heike Schenk-Mathes³

¹ Fraunhofer Heinrich Hertz Institute HHI, Einsteinufer 37, 10587 Berlin, Germany

² Clausthal University of Technology, IEPT, Am Stollen 19A, Goslar, Germany

³ Clausthal University of Technology, Betriebswirtschaftslehre und Betriebliche Umweltökonomie, Julius-Albert-Straße 2, 38678 Clausthal-Zellerfeld, Germany

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Abstract Electricity is an indispensable building block for sustainable development. As national and international electrification measures in rural areas of Tanzania are progressing slowly, a solar-powered mini-grid system with second-life battery storage was commissioned on an island in Lake Victoria in 2019 to support local development. This article evaluates the socio-economic impacts associated with electrification through this system. On average, 42.31 kWh of electricity could be provided per day. The daily demand of the main infrastructure (hospital and school) was 18.75 kWh on average. The remaining capacity thus offers enough potential to supply private households and possible economic activities. In order to evaluate the impact of electrification, a qualitative survey was conducted on site 12 months after commissioning, with 7% of the people living there being interviewed. Language barriers as well as intercultural hurdles made the survey difficult and required an adaptation of the on-site implementation. The focus of the survey was on the areas of health, education and economics. The study revealed that the availability of electricity has enormous potential to improve people's living conditions. Initial successes could

be seen, especially in the areas of health care and the economic sector. So far, electrification has had no influence on the area of education. While the connections for the main infrastructure have been institutionally supported, the system-related electricity price of €1.30/kWh has proven to be a major obstacle for private households. This is far too high for widespread use compared to incomes. The article thus focuses on the observation that full socio-economic development through electrification can only succeed if local people can afford it. Possibilities to solve this problem are analysed. Since the energy is generated on the basis of renewable resources, the analysis focuses on the use of mechanisms of the emissions trading system (ETS). The aim is to generate revenue through the sale of certified emission reductions (CERs) for the saved CO₂ emissions and thus reduce the electricity price. A reference scenario of conventional energy production forms the basis for discussion of the effectiveness of the Clean Development Mechanism (CDM) and the Carbon Initiative for Development (Ci-Dev). In addition, the approach of a monthly free quota of electricity, the free basic electricity initiative (FBE), is included in the evaluation.

✉ Joern Falk
joern.falk@hhi.fraunhofer.de

Graphical abstract

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1 Introduction

In recent years, progress has been made worldwide in providing universal access to electricity. This is reflected in the fact that the number of people without access to electricity fell below the 1 billion mark in 2017 (IEA 2018). Although this is an important interim success, many efforts are still be needed to continue this process, especially as the proportion of the population with access to electricity varies greatly from region to region. In 2017, the coverage in Central and South Asia was 91% of the population and even 98% in Latin America, the Caribbean and East and Southeast Asian countries. However, in Sub-Saharan Africa (SSA) only 45% of the population had access to electricity. Thus, 573 million people in SSA still do not have access to electricity.

In summary, it was found that 14 of the 20 countries in the world with the highest deficit in electricity connections

are African countries (IEA et al. 2019). According to the International Energy Agency report, the per capita consumption in SSA measures 317 kWh per year, which is less than one kWh per person per day (IEA 2014a). This means that the energy demand in SSA is only about 4% of global demand, while 14% of the world's population lives there (United Nations 2019). This global imbalance in electricity supply is shown in Fig. 1.

This undersupply has far-reaching consequences, as limited access to electricity is one of the greatest obstacles to social and economic development (Zhang et al. 2019). It also forces local people to meet their daily energy needs by burning fossil fuels. This leads to the emission of pollutants, which pollute the environment and endanger human health (Hanif 2018). In order to avoid negative impacts from fossil energy sources, there is an increased focus on regenerative technologies (da Silva 2018).

Key international projects such as the Africa renewable energy initiative (AREI) (African Union 2015) are an important part of accelerating the supply of energy with renewable energy solutions (Gielen et al. 2016). However, this may not close the supply gap in the short term. Despite international efforts, the World Bank reported that a significant improvement in comprehensive energy supply will be required at least until 2030 (World Bank 2017).

Fig. 1 Share of world population with access to electricity in 2017. Source: The Energy Progress Report 2019—Tracking SDG7 (IEA et al. 2019)

As the expansion of conventional grid systems is slow, decentralized and local off-grid solutions have become an alternative (Korkovelos et al. 2020). These self-sufficient energy systems are usually referred to as island systems or mini-grid systems, as they are off-grid power generation systems that are not connected to the public grid and generate electricity based on various technologies. In addition to conventional diesel generators, regenerative energy solutions are increasingly being used. Depending on the available resources, these can be photovoltaic systems, hydropower plants and wind turbines. A combination of different technologies is also possible. Hydropower in particular is seen as having great potential for energy generation in developing countries. This is because, for example, so-called run-of-river (RoR) water plants are associated with low installation and maintenance costs and can be realized quickly. However, hydropower is also associated with a direct intervention in natural ecosystems. In order to prevent negative impacts on biodiversity and the associated habitat degradation, sustainable planning and constant monitoring of these projects are required (Kuriqi et al. 2021). The fundamental advantage of mini-grid systems is that they enable faster and more flexible energy supply, especially when combined with additional components such as electricity storage in a hybrid system (Mazzeo et al. 2021).

In this article, the sustainable effectiveness of the electrification of an island in Lake Victoria (Tanzania, Africa) by a mini-grid system is evaluated within the framework of an empirical field study. The photovoltaic (PV) mini-grid system with its so far unique battery storage prototype,

based on a second-life traction battery, was installed in early 2019 and described in detail in a previous publication (Falk et al. 2020). The objective of this article is to evaluate various socio-economic parameters to test the impact on local development related to electrification. The framework is the PDCA method (Plan, Do, Check, Act) to monitor and analyse the respective sections (Johnson 2002), see Fig. 2. In order to assess the sustainability of all measures, a field study was conducted on site twelve months after the installation of the system. First, a technical overview of the condition and effectiveness of the system should be obtained. The annual electricity yield is 15,443 kWh. The hospital as well as the school was electrified. In addition, commercial connections for the local fishery and isolated private connections were realized. The electricity consumption of all connections amounted to 6843 kWh in the first 12 months. In addition, a qualitative survey of the local people was conducted. This serves to identify potential problems but also positive effects that arose in the first year after commissioning. The aim is to understand the complex relationship between electrification and the possible changes in local living conditions associated with it. The focus was therefore on both ecological and economic aspects. This includes the reduction in environmentally harmful emissions as well as the economic potential of electrification. In order to achieve the most authentic survey results possible, topics relevant to the respondents were asked close to the reality of their lives. Multimedia tools were also used to support the survey. To get a detailed overview of possible impacts, the questions were divided into three different groups: health, education and economy.

Fig. 2 PDCA cycle for installed mini-grid system. Source: Author's construct

The survey was conducted by a local interviewer. This is important because intercultural barriers can distort the outcome of a survey. Therefore, bicultural support is necessary for research in a specific cultural context (Cavusgil et al. 1997).

In the course of the evaluation, it became evident that the provision of electricity has enormous potential to improve living conditions and promote socio-economic development; however, it is also associated with additional obstacles. Hence, the success of the project is not automatically guaranteed but depends on the modality electricity is provided to the people and the market price.

In this article we analyse and identify the problems associated with the specific PV mini-grid system installed on Kibumba and derive and discuss general strategies for improvement. It turned out that the high electricity costs are the biggest obstacle for a widespread use of electricity in private households. Therefore, we analyse different cost reduction strategies with specific focus on renewable energies since the mini-grid system uses solar energy. For this purpose, mechanisms of the ETS are evaluated, which allow for selling pollution rights in the form of CO₂ certificates. We analyse if and how these revenues could be used to subsidize the electricity price. For this analysis we compare the mini-grid system with methods of conventional power generation and discuss the effectiveness of the Clean Development Mechanism (CDM) and the Carbon Initiative for Development (Ci-Dev). In addition, we investigate the concept of free basic electricity (FBE), which is a monthly free quota of electricity, as an additional approach for socio-economic improvements on Kibumba.

2 Mini-grid systems as energy sources in remote areas

This section briefly discusses the potential of mini-grid systems based on solar cells and second-life batteries in remote areas. First, we summarize the general problem of energy supply in rural areas, focusing on the relatively high cost of access to electricity in countries with low average incomes. We then analyse photovoltaic energy sources with second-life battery storage as a possible solution. Finally, we show that the secondary use of lithium-ion batteries (LIBs) in mini-grid systems can help to offset the high emissions generated in the production of these batteries by extending their lifetime.

2.1 Power supply for remote areas

Electricity is an indispensable part of any infrastructure and a cornerstone of socio-economic development. Improving access to electricity for people living in countries with low average incomes is one of the greatest challenges. Despite much national and international activity, the provision of electricity outside urban living areas remains inadequate, particularly in SSA. In this region, an estimated 600 million people are still cut off from a comprehensive and reliable energy supply (UNECA 2018). The main reasons are the high cost of expanding and operating the existing grid and low demand in sparsely populated areas. As a result, the high cost of installing and operating the electronic network often has to be borne by only a few users (Golumbeanu et al. 2013). This is a major problem in low-income countries. Although electricity is theoretically available, most people cannot afford it. While studies have shown that even poor households in SSA countries are able to pay more than 10% of their monthly income for basic electricity, this is often not enough (Sievert et al. 2020). In order to supply these areas, nevertheless, small, off-grid solutions, so-called mini-grid systems, have become

established in recent years. These mainly use renewable energy sources and, depending on country-specific resources, can utilize different technologies such as wind power, solar energy via photovoltaics, hydropower, geothermal energy and biogas to provide electricity flexibly and cost-effectively. Off-grid systems allow power parameters to be customized for each location, as they can supply both direct and alternating current, single-phase or three-phase. In addition, they can also be connected to existing power grids to fill supply gaps there (Werner et al. 2012). However, these systems have the disadvantage that they cannot ensure an unrestricted supply without suitable storage systems due to the partial availability of resources (wind, solar, hydropower). For elementary components of the infrastructure, such as drinking water supply and lighting, an uninterrupted supply is necessary. Often, these gaps in supply are compensated for with aggregates that generate energy by burning fossil fuels. However, this has the major disadvantage of producing high on-site emissions. In addition, these systems are unreliable and expensive to operate and maintain. Therefore, system-integrated battery storage, especially LIBs, is suitable to compensate for technology-related supply gaps (Nedjalkov et al. 2019). LIBs offer an ideal basis due to their high energy density, performance and durability. For off-grid applications, PV systems have the highest potential and are therefore currently focus. Although Africa has the best conditions in the world for the use of solar energy, it is hardly used. The 5 GW of installed solar PV in Africa is less than 1% of global capacity (IEA 2019a). One of the biggest challenges in using solar energy as the main energy supply is the need to store energy during the day so that power is available at night. Battery storage systems can be a good solution for this. Figure 3 shows an example of the schematic design of a PV mini-grid system with battery storage, as used on Kibumba Island and the focus of this article.

2.2 Battery storage with second-life batteries

Especially in the field of renewable energy generation with solar power, the storage of energy is important due to the availability of energy at night-time. These gaps in supply are currently bridged by conventional systems such as diesel generators. However, the operation of these systems relies on fossil fuels, which increases pollution and poses a health risk to people. In addition, these systems are often unreliable, expensive to operate and difficult to maintain. Therefore, the use of LIBs, especially second-life batteries previously used in electromobility, is well suited for such applications (Falk et al. 2020). In electromobility, LIBs are the state of the art due to their high energy density, high power and long lifetime (Deng 2015). As part of the global promotion of electromobility, large quantities of high-volume LIBs are being used in the automotive industry. Depending on the manufacturer and application, they are already being replaced with a remaining capacity of 70%–80% (Bobba et al. 2018). As sales of electric vehicles will undoubtedly increase in the coming years, the number of used batteries will also increase accordingly. Figure 4 shows that up to 23 million electric vehicles are expected to be sold globally in 2030. This brings the size of the global electric vehicle (EV) fleet to 130 million, not including two- and three-wheelers (IEA 2019).

Therefore, it is necessary to evaluate the condition of batteries after their first life in the automotive industry in order to either recycle them or to continue using them for different applications (see Fig. 5). From an environmental point of view, it is important to prevent batteries from being recycled too early when the remaining capacity is still sufficient for a second use. From an economic point of view, second-life batteries also have enormous cost advantages (Martinez-Laserna et al. 2018).

Fig. 3 Schematic setup of a PV mini-grid system with battery storage. Source: Author's construct

Fig. 4 Global electric vehicle (EV) sales and stock outlook by 2030 (based on IEA – Global EV Outlook 2019)

2.3 Emissions

Reducing harmful emissions, especially carbon dioxide (CO_2), is a key global issue (UNFCCC 2015). To achieve a reduction in greenhouse gases, it is important to consider this issue in all future approaches to alternative energy supply. Very high levels of pollutant emissions are produced, e.g. when fossil fuels are used for power generation, which has a detrimental effect on both the environment and human health. Efficient diesel generators require 0.3 l–0.4 l to produce one kWh, while 2.4 kg–2.8 kg CO_2 /l are produced (Waqas et al. 2018). However, alternative technologies such as PV and especially LIBs also contribute to CO_2 emissions. Although almost no CO_2 is emitted during use, the manufacturing process causes high emissions. The specific amount of CO_2 emissions during production depends mainly on two factors: the materials used and the production facilities, which vary greatly from country to country. Therefore, the accurate calculation of CO_2 emissions from alternative energy solutions requires the consideration of the entire life cycle of the device (Fthenakis et al. 2008). According to Wiedmann and Minx, the unit CO_2eq (equivalent) can be used to capture CO_2 emissions

throughout the life cycle of a product (Wiedmann et al. 2008). On average, LIBs generate approximately 150 kg–200 kg $\text{CO}_2\text{eq}/\text{kWh}$. This figure takes into account variable factors such as design, inventory data, modelling and production. The high value results primarily from the extraction of raw materials in mining and refining, the production of battery-grade materials and assembly. This complex interaction of different production processes makes it difficult to reduce the high CO_2eq of LIBs by a simple improvement measure (Romare et al. 2017). In contrast, emissions for crystalline silicon PV modules are relatively low at 30 kg–45 kg $\text{CO}_2\text{eq}/\text{kWh}$ (Alsema et al. 2005). It is therefore all the more important to extend the useful life of those products that cause high emissions during the manufacturing process in order to recoup the emissions over a long useful life.

3 Development stimulated by electricity on Kibumba Island (Tanzania)

In the following section, we will outline the on-site activities carried out in 2020 as part of the PDCA analysis. This will first include a brief, basic review of the system installed one year earlier. In particular, we will discuss the methodology of the on-site survey, which also serves to highlight the cross-cultural challenges in the surveys. The qualitative results obtained during the survey will also be evaluated, presented and finally discussed. Socio-economic aspects such as environment, health, education and economy will be considered.

3.1 On-site system check

The starting point for the on-site activities was an inventory of the overall system. As part of this inventory, it was determined that all components installed in 2019 are complete, still functioning and within their standard parameters. The former point is not always a matter of course. It is not uncommon for components, cables or

Fig. 5 Second life of batteries.
Source: Author's construct

complete systems to be stolen in structurally weak countries in order to sell them or to extract valuable raw materials from cables and parts (Gollwitzer et al. 2018). The functionality was also not impaired in any way; all plant components functioned as originally intended. The overall condition of the plant can still be described as very good 12 months after commissioning.

3.2 On-site survey

A key component of the PDCA analysis conducted in this article is a qualitative on-site survey. Generally, surveys are used to obtain valid information on a specific topic and its context. The survey aims to gather information and evidence on relevant characteristics by interviewing people based on previously defined parameters. This can be achieved through empirical, non-empirical and qualitative and quantitative methods. Empirical surveys are the systematic collection of real experiences, while non-empirical methods are based on theoretical knowledge and assumptions of the investigator. Quantitative data are typically used to capture basic, general points, while qualitative data are used to gain detailed insight into facts in order to conclude (Brosius et al. 2012).

The survey was conducted in a qualitative form. This is necessary to clarify the complex relationship between the implementation of a power supply and the associated impact on local living conditions. This is because rational decisions cannot be made without objectives, as these form the basis for comparison with possible alternatives (Laux et al. 2018). Methodological competence is a prerequisite for successfully conducting a survey. In addition, the topic of the survey must be relevant to the respondents, since a high level of interest on the part of the respondent usually ensures authentic results (Scholl 2018). However, strategic responses from the respondents can also be expected. The survey presented in this publication serves as an overview of whether and how the installation of the mini-grid system and the availability of electricity has changed the living situation on Kibumba Island.

For this purpose, the questions were divided into three main categories: health, education and economy. The aim was to identify the areas that mainly benefit from electrification and to identify obstacles that could prevent further positive development steps. In the health category, the focus was on issues related to health care in local hospitals and the use of fossil fuels for cooking, heating and lighting in private households. Questions on economic aspects related to infrastructure and business opportunities, with a particular focus on electricity costs. The education category addressed the impact of electrification on children's education in the local school. To supplement the questionnaire, respondents had the opportunity to add their own

comments. To reduce barriers to entry, respondents had a choice of two types of media. Either the questions were provided on a traditional paper questionnaire or the survey could be completed independently and interactively on a tablet PC. Initially, several obstacles required adjustments to the prepared survey, which are summarized in Table 1. The first issue was unexpected communication problems. Although basic communication in English was possible, this knowledge was not sufficient to conduct a systematic survey. In addition, there was great distrust of the person asking the questions. On Kibumba, detailed questions about living conditions are uncommon and are generally not answered to strangers. To remove this obstacle, a local translator and the village chief were brought in. This created a more trusting atmosphere so that the locals were more open to participating. Special care was taken to integrate the interview into a daily life session in order to achieve the authentic results. Nevertheless, it was not possible to conduct individual interviews. Instead, questions were answered exclusively in groups of individuals one at a time. In addition, female respondents in mixed groups (male and female) refused to answer questions. For this reason, male and female respondents were interviewed separately. It turned out that the questions, which were developed in advance with the help of scientific methods, were too theoretical, distanced and complex in practice.

A total of ten people were interviewed on-site, representing about 7% of the total population of Kibumba. The people interviewed did not live together, but each represented a household. They were interviewed in gender-segregated groups. The female group consisted of five individuals who were 15, 39, 40, 46 and 48 years old. The ages of the male participants were 25, 36, 36, 50 and 50.

3.2.1 Results

All of the people interviewed stated that health care at the local hospital had improved noticeably after the mini-grid system was installed. In particular, the use of electric equipment, the possibility of treatments without daylight and the fact that medicines could be stored in a refrigerator. None of the respondents replaced fossil fuels with electric-powered solutions for cooking and heating because electricity was too expensive. Households with electricity use it mainly for lighting and charging mobile devices. The women's group added that safety in the dark could be improved by installing street lights. They unanimously called for the installation of public lighting, as lighted streets and roads help prevent possible assaults and rapes. All of the people interviewed said that having electricity would have a positive effect on the economic development of Kibumba. Various business ideas were presented in both groups. The female group suggested buying sewing

Table 1 On-site adjustments due to survey start experiences

Issue	Scope	Measure
Communication	Language	Translator
	Questioning by strangers	Questioning by a person of trust
Methods	Individual interviews	Representative group survey
	Gender-specific inhibitions	Gender-separated interviews
Comprehension	Theoretical and scientific questions	Question adjustment on site
	Multimedia range	Creation of a daily situation

machines to tailor and repair clothes or running refrigerators to offer homemade juices made from avocados and mangoes to people in the village. The male group mainly saw an advantage for local fishermen by installing refrigerators for hygienic storage and electrically operated drying equipment. There is also a high demand for electric grain mills. However, all respondents in both groups indicated that the main obstacle to implementing these ideas is the high price of electricity. The local utility charges 3500 Tanzanian Shillings/kWh (1.39 EUR). In view of the low average income, respondents suggested a target price of 1000 Tanzanian Shillings/kWh (EUR 0.40) to start business activities. The issue of education did not play a major role for the respondents. Electricity connection has had no impact on learning materials and teaching methods in the local school. Table 2 summarizes the results of the individual sections, which are described in more detail starting in Sect. 3.3. All answers must be seen against the background that there was no form of power supply on Kibumba before the mini-grid system was installed, not even, for example, via a generator or similar.

3.3 Socio-economic aspects

High energy consumption can be directly linked to a country's level of development (Rahman 2020). In this section, we analyse this assumption by examining the impact of electricity on development in three different sectors: health, education and economy.

3.3.1 Health

People reported that electrification has had exclusively positive effects on health care. All respondents said that treatments had improved, confirming the assumption that electrically operated medical equipment leads to more comprehensive treatments. The ability to refrigerate medications, thereby extending their life, fundamentally improves medical care and local living conditions (Peters et al. 2016). The survey shows that none of the respondents associate a possible electricity connection with cooking or heating. This means that people continue to rely on fossil fuels for cooking and heating (World Bank 2017). However, this leads to high levels of on-site pollution (Elf et al. 2017). In addition, these energy sources are expensive,

Table 2 Overview results on-site survey

Section	Effects	Reason	Potential
Health	Availability of medicines	Fridge operation	Rapid treatment
	Daylight-independent treatments	Indoor lightning	Continuous operation
	Improved treatment methods	Electrical devices operation	Performing complex treatments
	No effect on emission levels	Electricity too expensive	Replacement of fossil fuel for cooking and heating
Education	No measurable impact	Not yet focused	Street lighting for public security
		So far no use of electrical devices	Acquisition of multimedia devices to improve learning methods
		So far no need for daylight-independent teaching	
Economics	Developed fishery (durability)	Fridge operation	Trade with surroundings
	Entrepreneurial activities	Electricity availability	Textile processing with sewing machines Grain processing electrically powered grain mills

inefficient and the main cause of health risks such as lung and respiratory diseases, heart disease and cancer. Electrically powered alternatives could significantly reduce these risks and thus protect people's health (IEA 2014b).

The main reason people do not use electricity for cooking is the high cost. Since wood can be collected for free, it is understandable that a nearly free resource would be preferred over expensive electricity. However, in addition to the harmful emissions caused by burning wood, a valuable ecological carbon store is gradually being decimated, which has a huge negative impact on the environment and also threatens the health of the local population. Due to the growing population and very inefficient stoves, approximately 763 million tons of wood were consumed in SSA in 2018. This is equivalent to about 2.0 tons per year per household and each ton of wood burned can be estimated to emit 1.8 tons of CO₂ (van Buskirk et al. 2019). In addition, deforestation for fuel purposes promotes soil erosion, which is one of the most serious environmental problems in SSA with enormous ecological consequences (Borrelli et al. 2013). Without systematic reforestation, there is a risk of losing fertile soils and water-holding plants, leading to desertification in the dry season and muddy soils in the wet season (Sivakumar 2007). This permanently alters soil properties and affects the soil's ability to absorb water (Vanani 2017). It also contributes to the pollution of water bodies. Corrosion and sedimentation affect water quality, which in turn impacts water management (Derakhshannia et al. 2020). Therefore, electricity generated by a solar-powered mini-grid system using second-life LIBs can have many positive impacts on the health and environmental conditions of the area of use.

3.3.2 Education

Even though the survey did not provide any direct results on changed conditions in education, the prerequisites for positive developments are in place. New media such as the Internet and computers can be used, which significantly supports and develops teaching. In addition, children in electrified households can also learn independently of the daily routine, especially in the evenings. One potential barrier may be that children are an integral part of the family's work. In particular, they are often used to collect wood as fuel for cooking and heating (Biran et al. 2004). Thus, if wood was replaced as the main energy source with electricity generated by a mini-grid system, children may be less involved in family work and have more time for education. The survey results underscore the assumption that the primary focus of local people is to increase their household income through the use of electricity. Since there is a causal relationship between the level of education and a country's gross domestic product (GDP),

improvements in people's economic situation will increase the importance of education (Islam et al. 2007).

3.3.3 Economics

In addition to already noticeable improvements in health-care, the survey revealed that the greatest potential in the use of electricity lies in the area of business. This is because work can be done independently of daylight and completely new areas of business can be developed with the help of electricity. This leads to an increased number of revenue opportunities through the use of new electrical machines and new media. It should also be considered that the replacement of fossil fuels such as wood will reduce the time required for collection. This time savings can be used to pursue business activities and generate additional income, or if done by children, for school activities. In addition, in areas where wood is not freely available, it must be purchased at a cost of approximately \$0.03 per kg (van Buskirk et al. 2019). This is an additional burden on a household's budget and underscores the causal link between electricity and economic growth at the macroeconomic level (Ohler et al. 2014). Another important aspect is the social cost of carbon (SCC). According to Nordhaus, SCC refers to the economic costs resulting from the emission of carbon dioxide. The so-called DICE model (Dynamic Integrated model of Climate and the Economy) assumes a baseline of \$31 per ton in 2010 with an annual increase of 3% (Nordhaus 2017). Fundamentally, a structural and comprehensive development strategy must recognize that all forms of emissions contribute to climate change. The associated consequences for a variety of natural processes and socio-economic effects are complex (Ostad-Ali-Askar et al. 2018, 2020).

4 Possibilities to influence electricity costs

As described in Sect. 3.2.2, the evaluation of the on-site survey showed that economic development and its positive effects were prevented by the high electricity costs for private households. In the following, different possibilities to influence the electricity price are discussed. Since the mini-grid system generates electricity from renewable energy, emissions trading can be a promising opportunity. If a renewable energy system saves CO₂ emissions in direct comparison with a system that generates electricity from conventional energy sources, the saved emissions can be sold in the form of pollution rights on the world market via the emission trading system (ETS). With the revenues, the price of electricity could be subsidized. Derived from the ETS, the Clean Development Mechanism (CDM) and the Carbon Initiative for Development (Ci-

Table 3 CERs calculation per annum

System	Type	Annual production in kWh	Litre/kWh on-site	kg CO ₂ /litre on-site	kg CO ₂ p.a. on-site	tCO ₂ eq in EUR via CERs
PV mini-grid	Mitigation activity	15,000	–	–	–	–
Diesel Generator	Basic scenario	15,000	0.4	2.8	16,800	5.04

Table 4 Overview of evaluation mechanism and opportunities

Instrument	Actors	Legal basis	Requirements	Assessment	Result for Kibumba project	Outlook
Clean Development Mechanism (CDM)	Community of Nations	Kyoto Protocol	Verified emission reduction	CO ₂ -Comparative scenario	No significant earnings for cross-subsidization	So far no transfer to Paris Climate Agreement
Carbon Initiative for Development (Ci-Dev)	World Bank	Based on CDM architecture	Result-oriented innovative private sector projects	Measurable reduction of emissions by clean energy production in developing countries	Could be particularly suitable	Uncertain future due to the coupling of the trading architecture to CDM
Free Basic Electricity (FBE)	Government initiative	Respective basis of the applying states	Low-income households	Potential for microeconomic development	Achievement of scalable effects depending on scope	Offers the possibility to directly influence socio-economic development

Dev) could be suitable models. The free basic electricity (FBE) Initiative, a certain quota of free monthly electricity, is an additional alternative. A detailed overview of all measures and mechanisms and their effectiveness is presented in Table 4.

Based on the intention to limit the environmental impact of industrial activities, trading in so-called pollution rights is intended to help comply with defined upper limits for certain pollutant emissions such as CO₂ and SO₂. These caps and their validity periods are determined in advance in a political decision-making process. For industrial actors, the amount of pollution allowed is regulated through the use of allowances, which are subject to free trade. Thus, in a perfect market environment, a price for pollution would emerge that represents the value of the abatement cost of one unit of emission reduction (Michaelis 1996). If an actor's emissions exceed the value of the allowances purchased, a penalty must be paid that would motivate the industrial actor to reduce its emissions. The result is a transparent price for harmful emissions. This is particularly the case when the allowed caps are gradually lowered under a cap-and-trade approach, which aims to achieve an overall reduction in harmful emissions. In this framework, the limited availability of allowances leads to higher prices, which in turn can be an incentive for companies to invest in

more environmentally friendly processes if the abatement costs are lower than the purchase of allowances (Feess 2007). Since the introduction of the European Emissions Trading Scheme (EU-ETS) in 2005, several countries and regions, including the USA, Canada, Mexico, Europe, Kazakhstan, China, South Korea, Japan and New Zealand, have developed and implemented emissions trading schemes. The long-term international environmental goal is to link the existing systems into a global and efficient carbon market as a climate change mitigation tool to directly influence global emissions. In the power sector, the ETS has proven to be a suitable instrument for emission reduction. Under the U.S. Regional Greenhouse Gas Initiative (RGGI), CO₂ emissions have been reduced by 47% since 2008. In the UK, the system has also contributed to only 5% of electricity being generated from coal in 2018, down from 39% in 2012 (ICAP 2020). In the approach described here, which has been operational on Kibumba since February 2019, the predominantly CO₂-neutral on-site solar operation opens up opportunities to generate revenue from the emissions saved. These returns could be used to reduce the cost of electricity, thereby facilitating access to electricity for local people.

4.1 Clean Development Mechanism (CDM)

The Clean Development Mechanism (CDM) is a climate policy instrument under the Kyoto Protocol (Article 12). It seeks to help industrialized countries comply with established emission limits and to assist developing countries in implementing sustainable and climate-friendly development. Industrialized countries that finance projects that reduce greenhouse gas emissions in developing countries can use the savings to reduce their carbon credits. These so-called certified emission reductions (CERs) are shown in Fig. 6. The developing countries included in the CDM are explicitly named in Annex B of the Protocol.

The greenhouse gases relevant for CDM projects are also detailed in the Kyoto Protocol and include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). Because these gases contribute to the greenhouse effect in varying degrees, they are weighted differently according to their global warming potential and reported as one metric ton of CO₂ equivalent (tCO₂eq) (UNFCCC 1998). For example, one ton of CH₄ is equivalent to 25 tCO₂eq (UNFCCC 2020). In this way, the CDM attempts to achieve countries' specific reduction targets at the lowest possible cost. Since reduction costs are traditionally higher in industrialized countries, their stakeholders can use the CDM to implement measures to switch to emission-reducing processes in developing countries in order to offset emissions in their own countries. This follows the basic idea that the effort to reduce emissions is easier in developing countries compared to established industrialized countries. This stems from the fact that the industrial sector and infrastructure in developing countries are typically underdeveloped. Therefore,

these sectors can be implemented in a climate-friendly manner from the outset. In industrialized countries, switching to climate-friendly processes involves high costs. Financial and technological contributions to CDM projects therefore promote sustainable development in the target countries. This is a lucrative opportunity and incentive for both developed and developing countries to support such projects. Over the past 15 years, 2 billion CERs have been issued, resulting from 7800 projects worldwide (GIZ 2019). This underlines that the CDM has become a successful instrument for climate-friendly developments. The demand for CERs is mainly generated by trading under the EU-ETS. The reason for this is that CERs can be traded in a fixed framework like emission allowances and private sector actors are mainly responsible for the distribution of emission reduction targets in the EU. Accordingly, companies can use this aspect to expand their scope of action in developing countries. The basis for calculating the reduction performance of a CDM project is a reference scenario. The difference between the emissions of the reference scenario and the emissions of the CDM project results in the reduction performance of the project (Sterk et al. 2014). Since 2013, three factors had a significant impact on the trading value of CERs: First, the specifications of the EU within the framework of phase III (2013–2020) of the ETS, second, the limited use of CERs and, third, the international climate debates about the future policy of pollution reduction. As a result, CERs are now traded at around EUR 0.30 per ton while their price was similar to EU emission allowances (EUA) for a very long time (Wu et al. 2020). Even if the experiences with this approach were positive in the past, one of the biggest challenges at present is the transfer of the CDM system from the Kyoto Protocol to the Paris Climate Agreement. This should bring the price

Fig. 6 Clean Development Mechanism (CDM). Source: Author's construct

of CERs back in line with the value of the EUA. The continuation after 2020 has not yet been conclusively clarified (GIZ 2019). To validate the suitability of using the CDM system to reduce the electricity costs of the mini-grid system operating on Kibumba, the following assumptions were made. The annual production of the system is 15,000 kWh. No CO₂ emissions are generated on site due to the use of a PV system. Thus, the project is an emission reduction measure. A conventional diesel generator is considered as a reference scenario, which should produce a comparable amount of electricity in the same time. As shown in Table 3, in a direct comparison, conventional electricity generation with diesel generators produces about 2.8 kg of CO₂ per litre of diesel. A diesel generator requires about 0.4 L of diesel to produce one kWh, as mentioned in Sect. 2.3. This leads to an annual CO₂ emission of 16.8 t with a possible CERs certificate of EUR 5.04, at a price per ton of EUR 0.30. Thus, the CDM cannot significantly reduce the electricity costs of the mini-grid system. In the next section, we will analyse the World Bank's Carbon Initiative for Development as a possible alternative.

4.1.1 *The World Bank's Carbon Initiative for Development (Ci-Dev)*

The Ci-Dev, a World Bank trust fund, mobilizes financial resources for result-oriented innovative private sector projects aimed at reducing emissions through clean energy generation in developing countries. The initiative has committed to purchase \$76 million in emission reductions, also known as carbon credits, from 12 energy access projects currently underway in SSA. Carbon crediting is the conversion of emission reductions into carbon credits that can be traded through the Emission Reduction Purchase Agreement (ERPA). Similar to the CDM, emission reductions can be achieved if countries promote developments that systematically reduce greenhouse gas emissions. This includes, for example, the generation of energy from renewable sources such as solar power plants. (Labre et al. 2010). These developments can be individual investment projects, entire programs, or policy-based, climate-friendly interventions. This shows that performance-based payments for the purchase of carbon credits can be successfully established as a business model. Current and future carbon market mechanisms can also be influenced to increase the proportionate resulting gains for developing countries and make an additional positive contribution to their development (World Bank 2016). The Ci-Dev may be particularly appropriate for the project presented here as an approach to cross-subsidize the high energy costs of trading emission reductions. However, the construct is essentially based on the architecture of the CDM and uses its

methodology and infrastructure to certify emission reductions from the respective projects. Therefore, the uncertain future of the CDM also affects Ci-Dev, even though alternative solutions are already being discussed (Spalding-Fecher et al. 2016).

4.2 Free basic electricity (FBE)

FBE is a government initiative under the national electrification program (NEP) in South Africa in 2000, which aimed to accelerate electrification of disadvantaged, low-income communities and households by providing a target group with a certain amount of electricity free of charge. Prepaid metres were installed in targeted households to monitor and control the amount of electricity consumed (Ballantyne 2012). During a test period in 2002 and 2003, representative test households were credited with 50 kWh per month. The limit was set since 56% of all affected households consumed less than 50 kWh of electricity. The threshold was set because 56% of all affected households used less than 50 kWh of electricity. Therefore, this value was defined as sufficient to meet basic needs, which includes enough electricity for lighting, boiling drinking water with a kettle or using the radio or television (Department of Minerals and Energy 2003). Although these connections were limited to only 10 amps, it became clear that free electricity had a significant impact on household energy consumption. When households were required to purchase their own electricity, the average energy consumption was 20 kWh and was mainly used for low energy applications (Howells et al. 2005). However, it was also found that the fixed amount of 50 kWh per month was too small to have a significant socio-economic effect: It was not sufficient to replace fossil fuels for energy-intensive activities such as cooking and heating (Ruiters 2011). Moreover, it was observed that the affected households started to use additional electrical appliances, so that the monthly limit was quickly reached. In this respect, 50 kWh FBE per month cannot be considered a general solution to energy poverty. Instead, the level of FBE must be determined on an individual basis (Masekameni et al. 2012). Studies suggest that the rate should be increased to at least 100 kWh per month for sustainable effects. Nevertheless, the FBE approach provides an opportunity to directly influence household energy consumption and thus improve their socio-economic development. Note that the provision of free electricity quotas is not an altruistic measure by the government. Rather, it can be used to stimulate development beyond helping households at the microeconomic level. A free electricity quota makes it easier for start-ups to enter the market. In the long run, the economic success enabled by FBE would reduce reliance on free electricity quotas, create jobs and contribute to

local development. These downstream effects are in the state's interest and underscore the relevance of these activities. Finally, a contemporary FBE limit could also reduce the number of illegal electricity connections in affected areas, decriminalizing affected households and avoiding the associated dangers (Ngeva 2019).

5 Results and discussion

Successful socio-economic development of rural regions in SSA depends on various factors. Generally, it is assumed that sufficient energy supply is a core element for a successful development. In addition, factors such as sustainability and environmental characteristics of energy production also play a major role (Murshed et al. 2020). Mini-grid systems offer great potential to support the electrification of non-urban regions. They are self-sufficient, inexpensive and can be adapted to individual use. Due to the high solar radiation in the regions south of the Sahara, solar systems are particularly promising (Kay et al. 2021). The results of the empirical field study presented in this article show that a PV mini-grid system with second-life battery storage can be a promising approach for the electrification of non-urban areas. In addition, this system is a sensible reuse scenario for batteries, which were primarily used in electric cars. Due to increasing electromobility, batteries with a calculated residual capacity of up to 80% will be available in high numbers after their first use (Kamath et al. 2020). Internationally, a wide variety of approaches is being pursued to find a sustainable solution to the problem of the huge amount of batteries that will be available in the future. In the course of the Circular Economy, the improvement of recycling processes is increasingly in focus (Hu et al. 2020). However, instead of recycling batteries with high residual capacity, second-life use cases should be identified to compensate the high energy production and the emissions associated with it. In this article we demonstrate that a PV mini-grid system with second-life battery storage can be a promising approach.

In addition to purely technical considerations, we analysed the impact of electrification on the living conditions of the local population within the framework of a qualitative on-site survey. The results showed that the provision of electricity is only part of the challenge. For the full development of the socio-economic potential, it is crucial that people can also afford electricity. (Monyei et al. 2018). Hence, an automatism between electrification and local development success cannot be fully proven. The results of the survey illustrate this, as all respondents cited positive impacts of electrification as long as they did not directly pay for it. In particular, positive impacts on local health care were noted. Here, great progress was made in

improving care through the use of electricity. However, in this sector the electricity costs were institutionally supported. Nonetheless, an improved health sector is important for the future of non-urban areas since the regional development crucially depends on the health status of the local population (Ajala et al. 2005). Therefore, both the use of solar energy and institutional financial support is a sensible strategic investment for local development. The advantage of the PV mini-grid system is that the energy can be provided locally in an almost CO₂-neutral way compared to conventional methods. This is another positive health aspect since a sustainable energy infrastructure that generates electricity from renewable energy sources reduces local pollutant emissions and thus contributes to sustainable socio-economic development. In addition, it reduces the dependence on fossil fuels and promotes the sensitivity to climate policy goals (Choudhary et al. 2019).

In addition, the evaluation of the survey demonstrated that no positive effects of electrification were achieved in the field of education, which was contrary to initial assumptions. However, the correlation between electrification and educational success can usually be observed as a long-term effect since it depends on the number of years of schooling and on the downstream effects into the labour market (Kumar et al. 2018). Therefore, this sector should be the focus of future observations.

In general, the economic sector is supposed to have great potential for development due to electrification. The survey showed that the availability of electricity promotes self-employment and can thus improve the economic situation of local people: people were motivated to use the potential of electrification for a variety of entrepreneurial activities. Local textile production can be established with the purchase of electric sewing machines, which in turn may stimulate trade with the mainland and the surrounding area. Local fisheries could preserve the daily catch with appropriate cooling or drying equipment and trade with surrounding areas. In addition, people stated a high demand for electrically operated grain mills and the operation of a supra-regional mill was seen as a valuable business option. The potential economic success associated with these new opportunities would create jobs and help to increase prosperity (IEA 2017). The great economic potential is particularly evident in the context of the resource-based view (RBV), which implies that successful economic development depends on both specific skills and resources (Hunt 1997; Galbreath 2005). Above all, this means that sustainable entrepreneurship requires identifying and using resources and investing in their future (Banabo et al. 2011). Entrepreneurship in rural areas is considered very labour-intensive compared to urban areas. In addition, the focus is often not only on making profit, but also on creating employment opportunities for the local population (Mathur

et al. 2015). This gives people the opportunity to pursue their own visions within the framework of entrepreneurial freedom, which includes the acquisition of additional knowledge for continuous and sustainable development. In addition, more and better opportunities for earning money leads to increased self-esteem, which strengthens the community (Tende et al. 2020).

In a region where the majority of the population lives in poverty with a daily income of 1.90 US dollars per person, the focus on affordable energy is essential (World Bank 2018). In the course of the evaluation, it turned out that the local operator at Kibumba island currently charges 3500 Tanzanian shillings per kWh for private households, which corresponds to approximately EUR 1.39. In comparison with the income of the population these prices are extremely high. The reason is the low connection rate in the private sector, which means that the operation of the mini-grid has to be financed by only a few users. In contrast to other surveys in SSA, our survey revealed a high willingness to pay for the electricity service. All interviewees were willing to pay for electricity within their financial means (Blimpo et al. 2019). In terms of income, the people stated that 1000 Tanzanian Shillings per kWh (0.40 EUR) would be the highest affordable price. Note that this is an above-average value in relation to the local income (Sievert et al. 2020).

At present, the reduction in the electricity price to the indicated level cannot be realized via normal operation. In order to solve this problem, cross-subsidization of the electricity price by trading CO₂ certificates was discussed (Thapa 2017). In our field study on Kibumba the PV mini-grid system saves pollutant emissions of 16,800 kg CO₂ in comparison with conventional reference scenarios for an annual production of approx. 15,000 kWh. These savings can be marketed in industrialized countries through ETS mechanisms such as CDM and CI-Dev. The resulting revenues could be used to reduce the price of electricity (Chen et al. 2021). However, calculations have shown that the current market price is too low to generate significant returns. This is mainly caused by the price drop of certificates from around 28 EUR to 0.30 EUR per ton due to the uncertain future of the aforementioned mechanisms, which were originally invented in the Kyoto Protocol and have to be transferred to the Paris Climate Agreement (GIZ 2019). However, it can be expected that certificate prices will rise significantly in the near future, because industrialized countries are constantly limiting their emissions, which will increase the value of pollution rights. As an example, the prices for emission allowances in the EU emissions trading system increased from 4 EUR- 9 EUR in 2017 to over 25 EUR in 2019 (Menner et al. 2019). In this respect, the development should be closely monitored in

order to re-evaluate this cross-subsidization approach in the future.

In order to bridge this period and further support development on the ground, an institutional socio-economic approach was discussed with FBE. The provision of a quota of free energy (50 kWh per month) has already been successfully applied at household level in South Africa (Ruiters 2009). This government-funded initiative supports access to electricity and thus contributes to increasing wealth and income. Provision can also be hugely important for the development of business activities, which further promotes the development of wealth (Sievert et al. 2020). For the scenario described in this article, this method could be an important approach for the socio-economic development strategy. However, care should be taken to ensure that the quotas cover the individual needs of the region. Usually, packages of 50 kWh per month are offered, which only cover basic needs. These should be adjusted for a significant impact on local development (Bohlmann et al. 2021). This approach could serve as a further impetus for local development on Kibumba and encourage the correlation between electricity consumption and level of development (Ouedraogo 2013).

6 Conclusion

The aim of this research was to evaluate the socio-economic impacts associated with the electrification of Kibumba Island in Lake Victoria, Tanzania (Africa). Twelve months after commissioning, we evaluated the technical efficiency of a photovoltaic (PV) mini-grid system using second-life battery storage and the effectiveness of the electricity supply to the local population. We found that the system produces enough electricity to supply the core infrastructure and offers enough reserves to absorb future increased consumption, as currently only about 44% of the annual electricity production is consumed. In addition to the technical evaluation, we conducted a qualitative survey of the local population. The aim was to understand the impact of the installed system on people's living conditions. The study showed that health care was significantly improved. Positive effects on economic development could also be demonstrated whereas electricity had no measurable influence on the educational sector, yet. The main obstacle that prevented private households from using electricity was the high price of 1.39 USD per kWh. The reason for this is the small percentage of private households connected to the electric grid. As a result, the costs of the system have to be borne by few consumers. In order to overcome this problem, we discussed and analysed different possibilities to reduce the electricity price. Since the system uses renewable resources, emission trading system

(ETS) mechanisms such as the Clean Development Mechanism (CDM) and World Bank's Carbon Initiative for Development (Ci-Dev) could be employed. Compared to fossil fuels, the system saves 16,800 kg of CO₂ emissions per year, which can be sold in the form of pollution certificates and the resulting revenue might be used to reduce electricity costs. Due to the extremely low price of EUR 0.30 per ton of saved CO₂ emissions, this mechanism is not applicable at the moment. However, it can be assumed that the transfer of certified emission reductions (CERs) to the Paris Climate Agreement and the constant limitation of emissions in industrialized countries will increase the demand for emission allowances and revitalize the market price. However, the analysis in this article showed that even a price in line with the EU emission allowances (EUA) of currently 40 EUR per ton cannot generate enough revenue to decrease the price per kWh to about 0.40 EUR, which was the highest affordable price for the local population. Nonetheless, different framework conditions may lead to different results. Therefore, future research should consider ETS mechanisms as promising opportunities to reduce electricity costs. Furthermore, we discussed the provision of a monthly contingent of free electricity via free basic electricity initiative (FBE) as a method to bridge existing problems and support local development. The limited availability of data was the main limitation of the presented study. The specific constellation of the scenario related to the system used and the initial situation currently only maps this location. In order to validate the potential heterogeneity of the results, future research may expand the analysis to include studies of comparable scenarios.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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