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Unlocking the Technology Potential for Universal Access to Clean Energy in Developing Countries

Boucar Diouf [1,2,*] and Ekra Miezan [2,3,*]

1 Department of Information Display, Kyung Hee University, 26 Kyungheedae-ro, Dongdaemun-gu, Seoul 02447, Republic of Korea
2 Nopalu Institute of Science and Technology, 72 Nord Foire Azur, Dakar BP 29044, Senegal
3 Graduate School of International and Area Studies, Hankuk University of Foreign Studies, 107 Imun-ro, Dongdaemun-gu, Seoul 02450, Republic of Korea
* Correspondence: diouf@khu.ac.kr (B.D.); ekra@hufs.ac.kr (E.M.)

Abstract: Access to clean energy remains a major issue in developing countries, particularly Sub-Saharan Africa, despite successive policies and the assistance of international institutions or organizations. The United Nations (UN) launched some of the most ambitious initiatives with the Millennium Development Goals and, more recently, the Sustainable Development Goals and Power Africa, a United States (US) government initiative. Sub-Saharan Africa has an important potential in renewable energy for both biogas and solar photovoltaic energy, but they remain underexploited. This paper presents the challenges of access to clean energy in developing countries and the failure of remedial policies mostly based on public–private partnerships (PPPs) in the context of endemic poverty of rural populations. In addition, the development of modern energy technologies remains very limited. Appropriate reforms should be carried out to change the paradigm and allow universal access to clean energy. This paper also addresses the different structural barriers that hinder access to technology in Sub-Saharan Africa and the consequences of access to clean energy in the context of poverty.

Keywords: clean energy; public–private partnership; technology; developing countries; Sub-Saharan Africa

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1. Introduction

Access to clean energy is still a luxury in some parts of the planet. Over 750 million people live without electricity throughout the world, and at least 2.6 billion people use biomass as their main cooking fuel [1–4]. Biomass remains the largest proportion of energy used as primary cooking fuel in rural areas of developing countries [5,6]. "The African continent accounts for about 50% of the solid biofuels consumed worldwide, with 82% of its inhabitants—or around 900 million people—relying on it for heating and cooking. In sub-Saharan Africa alone, roughly 95% of the population depends on biomass in the form of fuelwood, charcoal and residues" [7]. Populations without access to clean energy, for both electricity and cooking fuel, are mostly in Sub-Saharan Africa and Southeast Asia [8]. Governments have adopted different clean energy policies in rural areas, mainly agency-based or public utility-oriented programs. In the first case, an independent agency oversees the management and access to clean energy sold to populations by private entrepreneurs as any consumer good. In the case of access to electricity, private companies are given a geographic region called a concession, where they have the exclusivity of electricity service; this is a form of PPP. In the second model, the public utility is in charge of rural electrification, generally through grid expansion. This model has shown more success so far. In Morocco, for example, almost 100% rural electrification was achieved within about a decade [9], and very good progress was also made in Ghana and South Africa [10]. Besides the policy, the delay in electrification is partly related to the poverty that prevails in rural areas. In fact, rural populations in developing countries are generally poor, particularly in Sub-Saharan Africa. Consequently, when electricity service is treated just as a commercial good, as in the agency model, poor populations will continue to use candles and kerosene lamps for lighting, and they will walk miles to recharge their mobile phones. In addition to poverty, another characteristic of rural areas in Sub-Saharan Africa is the small size of most villages and the high dispersion of an important number of rural settlements.

Solar home systems (SHSs) could be an ideal solution, but their cost is one of the main hurdles to their successful dissemination. Rural populations are, in general, the least affluent; they have meager income and limited or no savings. In addition, mainstream financial institutions do not grant loans to people without solid guarantees. Clean energy for the rural market is not an attractive business for private investors. The investment per kWh or joule produced is high, the return is slow, and the risk of default payment from poor rural populations is important.

It is necessary to find an alternative to deliver a minimum of clean energy to rural areas of developing countries. Both electricity and clean cooking fuel face the same challenges despite numerous national programs and different external initiatives from non-governmental organizations. It is expected that PPP and subsidies could be enough to fill the gap, but Sub-Saharan Africa is still lagging behind, and biomass remains the main cooking fuel. There is a real technology deficit combined with the poverty of populations.

An alternative is needed to guarantee the expansion of electrification and access to clean cooking fuel in poverty-stricken rural regions of Sub-Saharan Africa and Southeast Asia.

Poverty links the problems of access to electricity and clean cooking fuel. This paper attempts to show that despite the different government policies and the support from the international community, universal access to clean energy remains a huge challenge in rural areas of developing countries. It is hindered by poverty, a lack of research and development to propose the most adequate products at an affordable price, and some other major structural factors such as the size and dispersion of rural settlements. These factors do not attract the private sector, given the clean energy market of poor rural populations.

This paper proposes a global approach to understand the problem of access to clean energy in rural areas of developing countries, with a focus on economic activities and structural characteristics of rural settlements in Sub-Saharan Africa. The economic activities of farmers do not allow them to access clean energy upfront; the financial institutions do not grant loans to poor populations; and some governments have established PPPs to bridge the clean energy gap. This paper also presents the need to pursue strong research and development programs to increase human resources and favor access to adequate and affordable products.

2. The Challenge of Clean Energy in Developing Countries: The Context

Access to clean energy is a basic commodity in the developed world. In some other parts of the world, largely situated in Sub-Saharan Africa, millions of people still use candles and kerosene lamps; charging a mobile phone takes miles to work and fees to pay (Figure 1). Less than 50% of the population in Sub-Saharan Africa has access to electricity [11]. In rural Sub-Saharan Africa, biomass is almost the only available cooking fuel. The preparation of meals exposes people to smoke and related diseases. Exposure to toxic chemicals kills hundreds of thousands of people every year [12]. It is estimated that 1.3 million people die prematurely every year in developing countries due to these toxic fumes [13]. Deforestation is another consequence of the massive usage of biomass [14].

Electricity and gas, considered clean energy, remain long-term targets in rural areas of developing countries. There is a need for adequate policies and better financial conditions for farmers to make them available and affordable to all users.

In fact, the problem of access to clean energy in rural areas of developing countries can have different origins. It can be of institutional origin, have financial sources, or be related to some more structural matters, such as the size and high dispersion of rural settlements. Each one of these issues can be generally studied under the scope of a "more or less successful" PPP program.

Economic empowerment of rural populations would be the first solution to allow farmers to afford their own source of modern energy. Presently, revenues from farming are the bottleneck of living conditions in rural regions of developing countries, particularly in Sub-Saharan Africa.

Sub-Saharan Africa and Southeast Asia are the most energy poverty-stricken regions of the world, even if clean cooking fuels and technologies are more and more widely used, particularly liquefied petroleum gas (LPG) and biogas. As an indicator, in Sub-Saharan Africa, the population increased by 2.7% between 2010 and 2022; this change was much higher than the 0.45% increase in the proportion of the population that has access to clean cooking energy [15]. It will be necessary to have an annual growth of at least 3% to achieve universal access to cooking fuel by 2030 and outpace the demographic growth [16]. If the current trend does not change, about 2.2 billion people will be without clean cooking fuel by 2030.

The above world maps (Figures 1–3) of access to electricity, access to clean cooking fuels, and poverty, respectively, show a perfect overlap. These figures, along with Table 1, give a first indication that the lack of clean energy is first and foremost related to poverty.

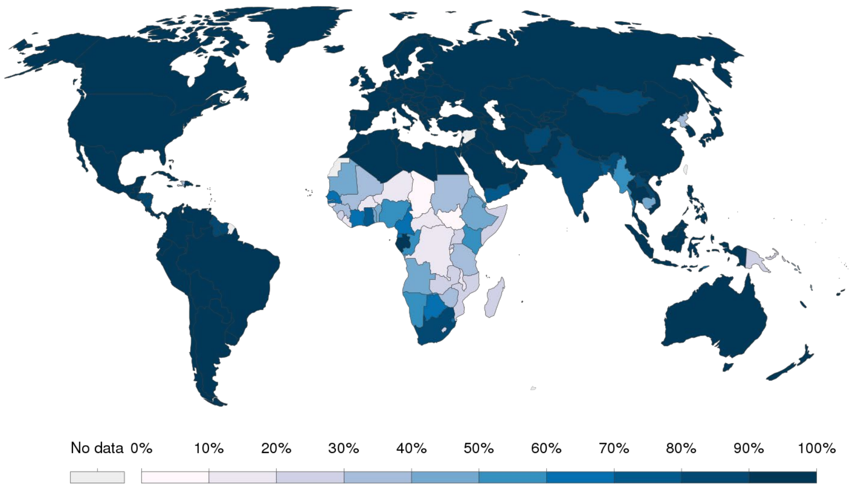

Figure 1. World electricity map [17].

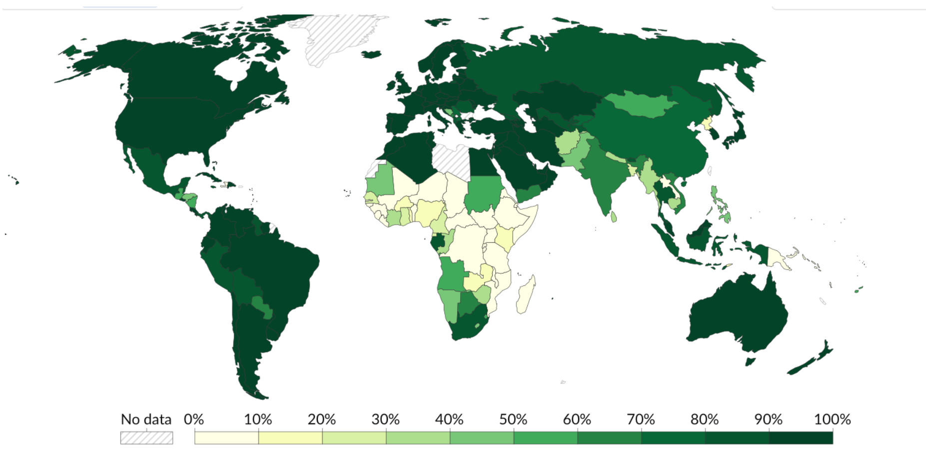

Figure 2. World population access to clean cooking energy [18].

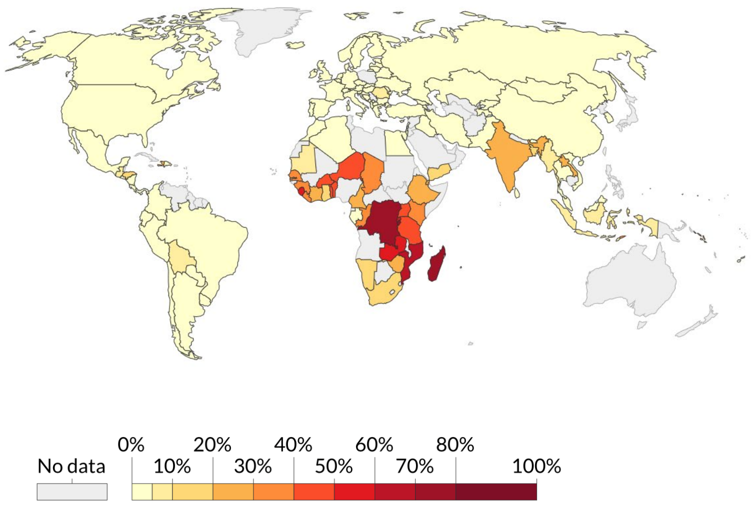

Figure 3. Share of the population living in extreme poverty [19].

Table 1. GDP per capita for different economic zones [20].

Zone	GDP per Capita (USD)	Rate of Rural Electrification
World	12,236.6	84.5
European Union	38,411.1	100
North America	68,369.7	100
Sub-Saharan Africa	1633.2	30.4

Sub-Saharan Africa has the lowest Gross Domestic Product (GDP) per capita in the world (Table 1), corresponding to the world population that can afford less than the population of any other economic zone.

Many international institutions, organizations, and governments have been at the front lines in the fight against extreme poverty in developing countries. The World Bank, the International Monetary Fund, the African Development Bank, the African Union, the European Union, and the United States are some of the most notorious organizations involved in that problematic. The World Bank defines extreme poverty as the condition of those living with less than USD 1.9 a day [21]. Families of 10 with a yearly revenue under USD 1000 are a common reality for farmers in some developing countries; this is the case for Senegal [22]. USD 1000 a year corresponds to less than USD 0.28 per person per day for a family of 10. Despite the efforts of the international community, poverty remains well anchored in the rural areas of developing countries. Some of the most prestigious initiatives are from the United Nations: the Millennium Development Goals [23] were set in the year 2000 for 15 years. This was a list of eight goals, the first being the elimination of extreme poverty and the seventh being environmental sustainability. During this period, important progress was made, as was the case with economic growth. Unfortunately, this growth was not always inclusive, particularly in Sub-Saharan Africa; consequently, the reduction of extreme poverty was not as effective as it could have been expected, even if a United Nations' report states that extreme poverty significantly decreased in the world. Based on this report, extreme poverty dropped from nearly half of the population in the developing world in 1990, 1.9 billion people, to 14% of the same population in 2015, 836 million people, with the most progress made since the year 2000 [24]. The economic growth was clearly biased, driven mostly by services; the primary sector did not change much, and farmers' living conditions even worsened in some situations. In 2015, the Sustainable Development Goals were adopted with a set of 17 goals for the period 2015–2030; the first goal remained the elimination of extreme poverty, and the seventh goal was "access to clean and affordable energy to all", another form of sustainability. According to the International Energy Agency, it will require a yearly investment of USD 31 billion per year to achieve universal access to clean energy by 2030 [25]. Goal number 7 is broken down into targets and indicators, summarized in the five points below:

- Universal access to modern energy;
- Increase the global percentage of renewable energy;
- Double the improvement in energy efficiency;
- Promote access to research, technology, and investment in clean energy;
- Expand and upgrade energy services for developing countries.

These five fundamental points should be translated and fit within local energy, trade, and industrial policies. As an example, research and development budgets are really modest, if not absent, in most developing countries. Trade policies need to comply with international organizations such as the World Trade Organization (WTO), where laws may not always be favorable to the industrialization of developing countries. These countries have many other priorities that should be covered before any other investment that would be seen as a luxury.

The Millennium Development Goals in Sub-Saharan Africa, particularly goal number 1, which was "elimination of extreme poverty", were hindered by, among other factors, rapid population growth and conflicts; this is more pronounced in the central African region. Goal number 7 is very complex, as the primary reason why rural populations in non-electrified regions do not have access to electricity may be poverty, but there are many other related issues, such as an inappropriate industrial policy to put on the market adequate and affordable products. Developing countries are generally negatively affected by some international agreements, as members of international organizations would assist them on the one hand and, on the other, allow their markets to be flooded with inadequate or not durable products that seem at first sight to be affordable but expensive in the long run.

3. PPP in Access to Clean Energy

PPP is a tool that governments and international organizations or institutions use to speed up access to clean energy in developing countries.

PPP faces a context of poverty, and the products proposed in the case of stand-alone SHSs are expensive, regarding the income of farmers, and they have a short lifespan. In the case of concessions in rural areas, the return on investment is slow and the risks are high as the demand is limited to basic appliances such as lights, mobile phones, maybe a television, and rarely a refrigerator. Private investors are not very attracted, despite the incentives offered by governments or sometimes international institutions.

Obviously, grid extension is the ideal tool for universal access to electricity, as observed in developed countries. Most developing countries face scarcity in their governments' resources and need to find alternatives as concessions in partnership with international organizations such as the World Bank to solve the problem of access to clean energy. The problem of concessions has proven that SHSs are the best alternative to achieve universal access to electricity in the near future [26,27]. This was the approach in Morocco, where universal access to electricity was achieved within a decade [26]. For SHSs to be successful with an adequate financial scheme, either populations should be able to afford imported products or poor populations should have access to lower cost but quality products; this may be possible only if local manufacturing is successfully achieved.

3.1. Rural Electrification in Sub-Saharan Africa

3.1.1. Context of Electrification in Sub-Saharan Africa

The proportion of the Sub-Saharan population without access to electricity increased from 33% in 2010 to about 45% in 2022. This drop in the rate of access to electricity is due to fast population growth. Demographic growth, about 2.5% a year, outpaces the rate of access to electricity. There has been slow progress toward universal access to electricity in Sub-Saharan Africa; the rate is generally less than 1% a year. At the current pace, more than half a century will be needed to achieve universal access to electricity in Sub-Saharan Africa.

In Sub-Saharan Africa, limited access to electricity is a major issue, and rural areas are the most underserved. In fact, the average rate of access to electricity hides the large gap between urban and rural areas. The electricity demand in rural areas is low; farmers can only afford a limited number of low power appliances. In addition to the low power demand in rural areas, there is a high dispersion of habitats. Such a situation results in a high cost of production and distribution per kWh. In poverty-stricken regions, this combination of factors is not attractive to private investors.

The evolution of access to electricity in Sub-Saharan Africa has been slow, as shown in Figure 4 below. In urban areas, it changed from about 68% in 2010 to 80.7% in 2021, versus 17% in rural areas in 2010 to 30% in 2021.

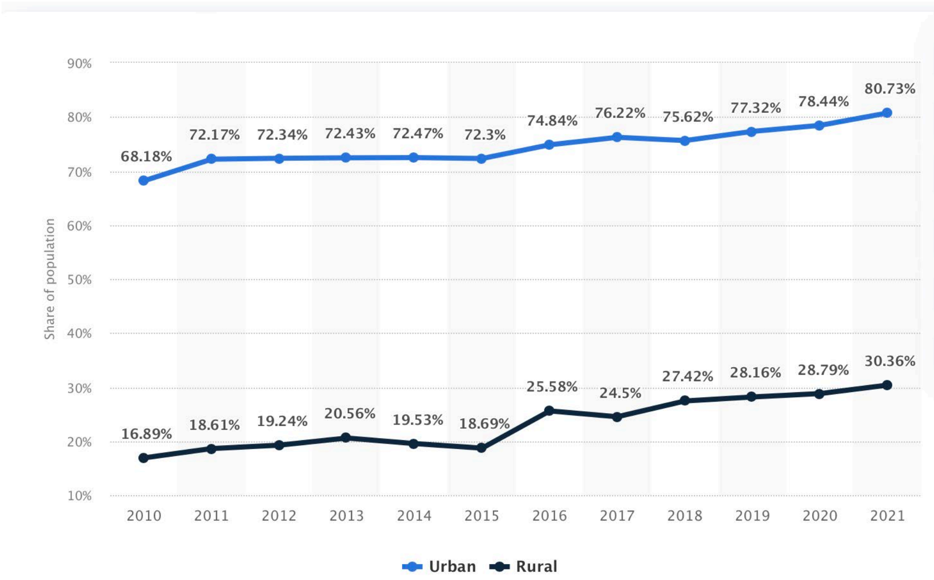

Figure 4. Share of the population with Access to electricity in Sub-Saharan Africa from 2010 to 2021, by area of residence [28].

Installed capacity in Sub-Saharan Africa (excluding South Africa) is 44 MW per million population; in comparison, it is 192 MW in India and 815 MW per million in China [29,30]. One of the main issues limiting access to electricity originates from the insufficient distribution system; such a problem requires important investment. Currently, on average, between 1 and 2 GW of power generation capacity are added yearly, against the 8 GW recommended by the World Bank to match demographic and economic growth [31].

3.1.2. Power Africa Initiative: A Model of PPP

Power Africa is a typical PPP project that targets universal access to electricity in Africa. Power Africa is an initiative launched in 2013 by the US government to leverage partnerships to increase access to electricity in Sub-Saharan Africa. Its objective is to encourage experts, the private sector, financial institutions, decision makers, and governments to work in synergy to find a solution to the African energy crisis and allow more populations to have access to electricity by overcoming institutional, technical, and financial hurdles. Its explicit objective was to add 30 GW of reliable electric power generation capacity and allow 60 million new connections by 2030 [32]. Such an objective is not likely to be achieved.

Despite difficulties, the Power Africa initiative has made major achievements at the continent level since it was launched in 2013 [33]:

○ 978 MW of new electricity to the grid was installed;
○ Quality electricity service for 37.7 million people;
○ Access to USD 234 million in investment to assist off-grid solar companies in gaining access to finance;
○ U.S.-Africa Clean Tech Energy Network (CTEN) initiative was established;

- Health Electrification and Telecommunications Alliance initiative that aims at connecting 10,000 health facilities;
- 7.7 million tons of CO_2 emissions were avoided.

Power Africa identifies the most important barriers for each partner country. On the top of the list are utilities: about 95% of national utilities are chronically indebted; they are mostly state-owned and have the monopoly of power transmission and distribution. The second problem is related to governance and regulatory constraints. Due to the poverty of populations, utility companies are almost under the obligation to play the role of social welfare by keeping their prices sometimes lower than the cost of production. As a result, private capital is not attracted, leaving the financial burden to poor states, eventually leading to underinvestment.

The main issues faced in the Power Africa initiative are related to national utilities, technical aspects, or legal aspects. It could be inadequate energy sources, poor production, transmission, or distribution systems, limited security, debt, monopoly, a lack of access to capital and investment, etc.

Power Africa, like other initiatives, faces the problem of poverty, even if it is indirect. The grid problems faced by partner countries are nothing else but a translation of the poverty of the populations, as the tariffication cannot reflect the real cost of power production. Governments must provide electricity at subsidized costs; it is a form of welfare. Consequently, even if the financial and technical partners are ready to put their efforts together, governments still need to keep energy prices low. Electricity prices and availability can even be a political argument in some countries. Obviously, in such a context, it turns out to be a problem for investors; it is contrary to one of the main goals of Power Africa, which is to commit financiers to projects.

Power Africa, as the other main initiative to improve access to electricity in developing countries, particularly Sub-Saharan Africa, focuses exclusively on PPP. PPP can obviously be leveraged to allow a wide range of possibilities to access electricity, but it turns out to be more of a tool that targets the symptoms of poverty than poverty itself. A major point missing in Power Africa is a strong objective in technology transfer and local manufacturing that could create jobs and have better control of cost and service, which is mostly missing in Sub-Saharan Africa, particularly for off-grid power systems.

3.2. Access to Biogas and PPP in Rural Areas

In most Sub-Saharan African countries, biomass with firewood is the cooking fuel in households, followed by charcoal and then LPG. Electricity and kerosene are not much used; solar stoves remain marginal, mostly because they are not practical.

As for rural electrification, access to biogas in rural areas of Sub-Saharan Africa is achieved in the form of PPP, where households order their digester directly from private entrepreneurs. There have been different attempts to expand the development of biogas in rural areas without much success [34], despite its good potential. For example, for a family of 10, the technical potential corresponds to the possibility for households to collect 30 kg of cow dung daily and enough water.

Technically, to replace the biomass consumption of a standard family of 10 people, 7.5 kg of charcoal, equivalent to 13 kg of firewood (USD 30 of monthly expenses), daily corresponds to a 10 m^3 digester producing 2.5 m^3 of gas.

PPP in access to clean cooking fuel in Sub-Saharan African countries such as Senegal is clearly a failure, almost exclusively due to the low revenue of farmers compared to the cost of digesters (Table 2) [35]. Even though a much smaller percentage of responsibility can be attributed to organizational issues and other problems related to human resources.

Table 2. Costs of biogas digesters for volumes from 4 m^3 to 18 m^3 in the PNB-SN program in Senegal [36] (based on USD 1 = 600 FCFA).

Volume	**4 m^3**	**6 m^3**	**8 m^3**	**10 m^3**	**12 m^3**	**14 m^3**	**16 m^3**	**18 m^3**
Cost (USD)	600	680	760	865	990	1085	1170	1230
Government subsidy (USD)	270	270	270	270	270	270	270	270
Payment after subsidy (USD)	330	410	490	595	720	815	900	960

The PPP that aimed at solving the problem of access to clean cooking fuel in rural areas of Sub-Saharan Africa was essentially limited by the cost of installations compared to the revenue of farmers. Despite subsidies and their technical potential, biodigesters were commercialized as any other commercial good for poverty-stricken populations. As presented in Table 2, in the biogas program in Senegal, the installation of a 10 m^3 digester, for the cost of USD 865, would correspond to almost the entire yearly revenue of farmers. This cost can even be higher than average yearly revenue in some rural regions of Sub-Saharan Africa [37].

If we take the case of Senegal as an example, cooking fuel expenses, particularly wood fuel, corresponding to USD 360 [38] a year, are cumulatively more expensive than the construction of a biodigester, but the financial situation makes the day-to-day expenses more bearable than the long-term investment.

The financial challenge for farmers is not restricted to the construction of a digester. In fact, even if such a construction were to be 100% subsidized, families would still be left with the construction cost of a concrete kitchen for a minimum of USD 300, which is an important proportion of their yearly income.

As presented in Figure 5 below, for a 10 m^3 digester, a biogas digester, including the construction of a kitchen, is much more affordable than fuelwood in the long run. The break-even point is barely after 3 years of operation.

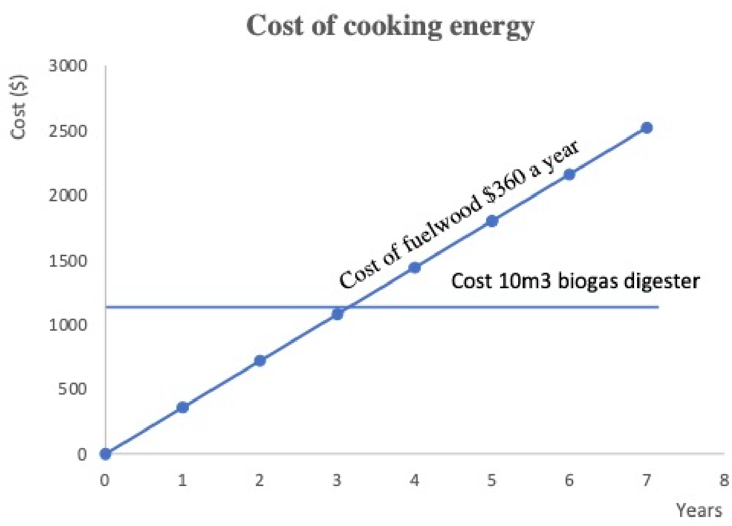

Figure 5. Comparative cost between a 10 m^3 digester and fuelwood.

4. The Way Forward: Need for Technology Transition

Generally, the major missing component in energy policies in developing countries, particularly those in Sub-Saharan Africa, is access to technology for lower-cost but quality products and services, particularly after-sales service. Access to technology could be a game changer that would lead to important cost reductions in energy related goods, as illustrated further in this paper.

Access to electricity through concessions has reached some structural limits [26,39]. It is the same for the large biodigesters [40], which at first glance look like ideal solutions through PPP.

SHSs seem to be natural solutions, as the concept of concessions is not successful, grid expansion is limited due to government resources. There is another structural reason for the lack of success in concessions: rural settlements are generally small and isolated. The organization of villages in general, as represented in Table 3 in the case of Senegal, with 14,000 villages [39] with modest populations, makes them small markets not attractive enough to investors who are looking for large profits. Table 3 below shows the statistics of villages with, respectively, less than 250, 500, and 1000 inhabitants.

Table 3. Repartition of the 14,000 villages in Senegal by number of inhabitants [39].

Village Category	Population	Proportion (%)
Very small	Pop < 250	58
Small	250 < Pop < 500	22
Medium	500 < Pop < 1000	12
Large	Pop > 1000	8
Total		100

As presented in Table 3 above, more than 80% of rural settlements in Senegal have a population under 500 residents, and for 60% of them, the population is under 250 inhabitants, which represents quite a low number of customers to attract investors. Beyond their small size, these villages are in remote locations with generally poor road connections. These characteristics alone make operation costs very high for any external investor. Moreover, these poor populations have a very low energy demand.

For a return on investment of 3 years, in installments, USD 100 per family per year should be paid, corresponding to about USD 8.5 a month. A margin of USD 60 for a USD 300 investment will correspond to a monthly payment of USD 10 per family, as they cannot pay up front. Three years correspond to the theoretical lifespan of lead-acid batteries in a SHS, but it can be much shorter. It seems obvious that such a model will not be attractive to a private investor.

In fact, SHSs may be more adequate when there is no grid electricity available, but the technology and lifespan should be sustainable for a business model to be adopted. It is the same for smaller digesters for the generation of biogas. Such solutions may only be successful if the right technology is available at an affordable price, which may require local manufacturing.

Some of the devices can be assembled locally with reasonable investment, particularly when considering the market size, which can be very attractive, provided there is enough research and development to put on the market the right and affordable products and adequate human resources in number. It is the case for solar panels, lithium-ion (Li-ion) battery packs, simple plastic drum-made biodigesters, or convection dryers for fruits or vegetables, as illustrated in this manuscript. Assembling products locally is associated with savings in labor wages, import tax, shipping fees, and the availability of after-sales service that is generally missing when products are imported, in addition to the creation of jobs. Poverty, high costs, and cheap quality products are some of the main reasons why populations in non-electrified regions do not have their own SHS.

Some important structural barriers hinder access to technology and sufficient skilled human resources in Sub-Saharan Africa. A new approach is urgently needed to respond to the present demand to guarantee access to technology, as carried out around the world. Universal grid electricity is presently a challenge in Sub-Saharan Africa. Fortunately, the sub-continent has huge potential for solar photovoltaic energy, up to 3000 h a year, but off-grid technology remains largely underexploited; the investment in human resources, technology research, development, and production in this field remains very modest. The proportion of GDP allocated to research and development (R&D) is low: 0.44% in 2023 versus the world average of 2.7% (Table 4). There are not enough vocational schools or institutions of higher education, particularly for technical training, to get the required human resources in quality and quantity. A very small number of patents (Figure 6) are generated in Sub-Saharan Africa compared to the rest of the world as a symptom of insufficient research activities. Meanwhile, for example, in the field of renewable energy, solutions could be found for an affordable cost if the technology was available.

Table 4. World Intellectual Property Indicators—2020 [42].

IP Right Applications	2020
Patents	3,276,700
Trademarks	17,198,300
Industrial designs	1,387,800
Plant variety	22,520

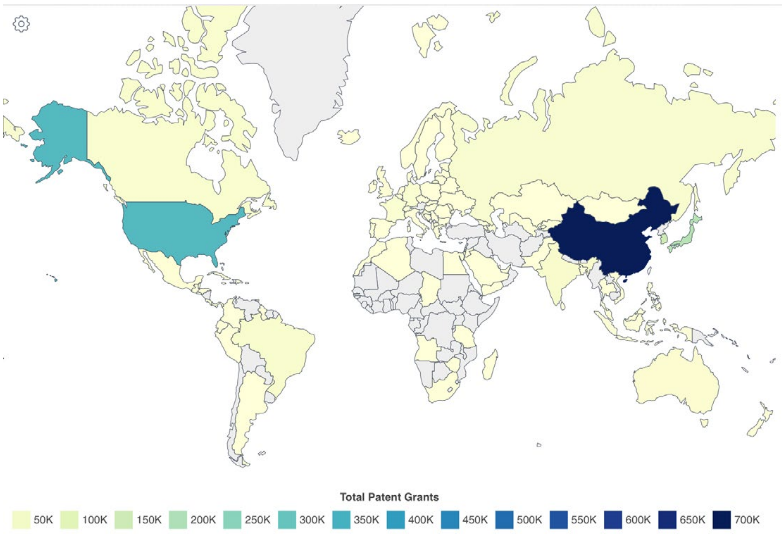

Figure 6. Number of patents per country in 2023 [41].

For the problem of access to energy in developing countries to be solved, an adequate technology penetration policy should be considered, as universal grid extension is out of reach for now and the concession approach is not successful.

Sub-Saharan Africa totalizes a very small proportion of total intellectual property, for instance, only 1834 patents in 2020, equivalent to less than 0.1% of the global number of patents (Table 4).

Sub-Saharan Africa has a much lower proportion of people enrolled in tertiary education as a percentage of the total population compared to any other region or economic zone in the world (Figure 6), about 10% presently versus almost 90% in North America (Figure 7). This situation obviously leads to fewer human resources.

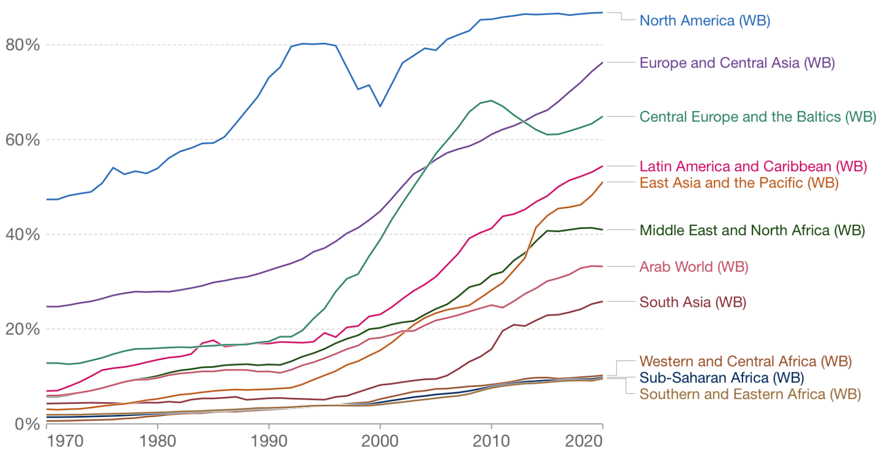

Figure 7. Number of people of any age group who are enrolled in tertiary education expressed as a percentage of the total population of the five-year age group following on from secondary school leaving [43].

Sub-Saharan Africa presents the lowest rate of electrification in the world, with barely half of its population having access to electricity. Yet, Sub-Saharan Africa is the zone in the world with the lowest investment in R&D, as shown in Table 5.

Table 5. Investment in R&D and level of electrification in different zones around the world [44,45].

Location	R&D Expenditure % GDP	Electrification (%Population)
World	2.71	91.4
Arab World	0.71	90.8
Central Europe and the Baltics	1.33	100
East Asia and Pacific	2.71	98.2
East Asia and Pacific (excluding high income)	2.38	98
Euro area	2.31	100
Europe and Central Asia	2.3	100
Europe and Central Asia (excluding high income)	0.99	100
European Union	2.28	100
North America	3.32	100
OECD members	3.01	100
South Asia	0.63	98.8
Sub-Saharan Africa	0.44	50.6

The sections below present the basic technology to assemble Li-ion battery packs, photovoltaic solar panels, plastic drum-made biodigesters, a model of circular economy for sustainable agriculture and livestock production, and convection dryers. These products can certainly contribute to poverty alleviation, the creation of jobs, increased technology penetration, and other benefits for development and population well-being.

The question to solve is how to encourage governments, investors, or the private sector, as those already involved in the field of energy, to bring the leverage necessary to put on the market adequate products at an affordable cost. Such a change of paradigm will require governments to change their policies, including the more efficient management of subsidies.

The way forward will include strategies to increase human resources and technology. The example of Barefoot College International [46], in India, is certainly a great illustration of the real potential to train local populations without technical background to get them more and better involved in solving their own issues as lack of access to clean energy. Some of the programs they establish aim at training local populations, not subjected to migration, to acquire the proper training and serve the community. Such institutes could be reproduced elsewhere in developing countries where they are needed, particularly to serve the basic demand to install photovoltaic systems, build simple plastic drum-made biogas digesters, convection dryers, etc.

The choice of energy sources in stand-alone systems for lighting or cooking fuel is obviously determined by short-term cost and availability, long-term cost (even if it is much lower) and social benefits or environmental consequences are not the first concerns of poor rural populations. Government policy can reverse the paradigm and make long-term affordability as well as environmental and social benefits priorities for populations. Social benefits include jobs from local manufacturing.

Table 6 below summarizes the basic energy sources in a classical rural Sub-Saharan African household and their characteristics. The three levels of advantages H, M, and L stand, respectively, for high, moderate, and low.

Table 6. Quality table of energy sources.

		Safety	Short-Term Cost	Long-Term Cost	Efficiency	Availability	Social Benefits	Issues
Light	Candles/Kerosene lamps	L	H	L	L	H	L	H
	Lead-acid SHS	H	L	M	H	L	M	M
	Li-ion SHS	H	L	H	H	L	H	L
Cooking fuel	Wood	L	H	L	L	H	L	H
	LPG	H	M	M	H	M	L	M
	Biogas	H	L	H	H	H	H	L

4.1. Energy Storage: Lithium-Ion Battery Packs

Li-ion batteries seem to be the future of solar energy storage, particularly in SHSs; they will allow universal access to a minimum of electricity at a lower cost and with more durable systems [47,48]. Li-ion battery cells are manufactured by a few hi-tech companies, generally in Asia, but assembling battery cells in packs is an affordable technology provided the necessary investment is made, particularly for small-size battery packs. It is a great opportunity to close the technology gap and improve affordability for local rural populations. It is a real and credible alternative to classic lead-acid batteries [49].

More investment and better management are needed in renewable energy; the potential is high. The cost of SHSs can be consistently cut down, particularly the cost of batteries. In a lead-acid SHS, batteries represent, on average, 60% of the total price. Common lead-acid batteries have a short lifespan, generally between 3 and 5 years. Li-ion technology opens new opportunities [50]. Li-ion batteries have a lifespan of over 2000 cycles, compared to 300 to 500 cycles for valve-regulated lead-acid (VRLA) batteries [32]. In a pilot project the authors conducted in 2012 in Senegal [39], over 80% of VRLA batteries were out of use after the first 18 months of operation due partly to bad environmental conditions.

To better present the advantage of Li-ion batteries over VRLA batteries, VRLA batteries used in the pilot project are compared to equivalent-capacity Li-ion battery packs assembled locally in Senegal.

The retail price of such battery packs is estimated at around USD 80 for the 7.2 Ah systems and USD 160 for the 14.4 Ah systems.

Operation cost in kWh is compared between the assembled 14.4 Ah Li-ion battery packs and the USD 45 commercial 14 Ah VRLA batteries in the pilot project [46–48].

Table 7 below presents a comparison of the kWh cost for the commercial VRLA and our Li-ion-based systems. The cost of the kWh is USD 0.92 for Li-ion batteries versus USD 1.1 to USD 1.78 for VRLA batteries.

Table 7. Cost comparison between lead-acid and Li-ion batteries in small solar home systems.

	Lead-Acid	**Li-Ion**
Installed capacity	7 Ah	7.2 Ah
Lifespan	300–500 cycles	2000 cycles
Battery retail price	$25	$80
Cost per kWh	$1.25/kWh–$1.56/kWh	$0.92/kWh

Table 7 clearly shows the cost advantage of Li-ion battery packs versus the commercial VRLA batteries for the small systems considered in this paper for SHSs. This shows the possibility of improving accessibility to clean energy if research and development is set as a priority to find proper solutions for rural areas of developing countries.

Presently, the cost of Li-ion cells is even (Figure 8) lower, about USD 100 per kWh against more than USD 1000 in 2010, making these battery packs more affordable to end users. The price is supposed to continue dropping; it is expected to be as low as USD 50 by 2030 (Figure 8). Such a low price would even make local assembly of battery packs more trivial. The price of a current Li-ion battery pack can be expected to drop by half by 2030. Meanwhile, the cost of lead-acid batteries is not likely to decrease much.

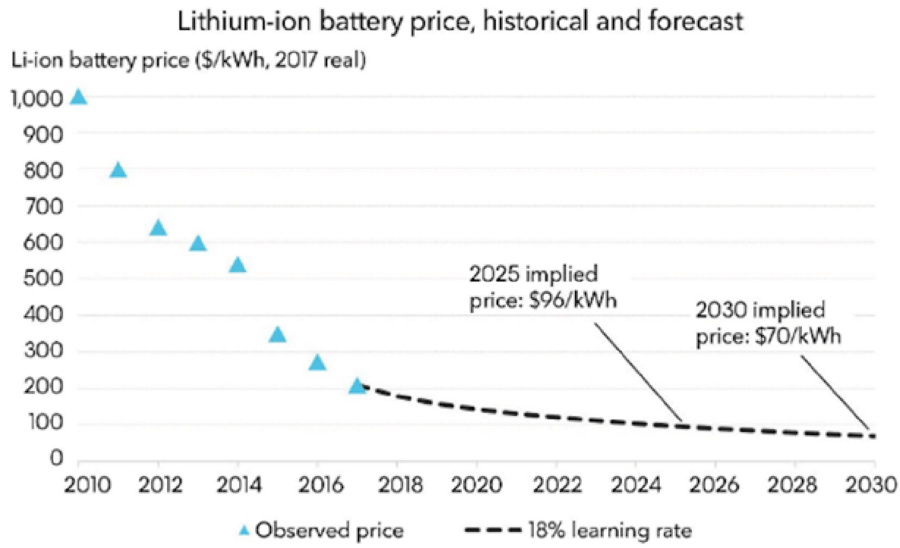

Figure 8. Lithium-ion battery price history and forecast [50].

More investment is needed in renewable energy; the potential is high. One of the main directions to cut down on the cost of solar home systems is through batteries.

Below (Figure 9) is presented a full Li-ion-based SHS kit developed by the authors. The 14.4 Ah system powers two LED lamps and can recharge mobile phones and a laptop computer.

Figure 9. Typical 12 V/14.4 Ah Li-ion SHS.

The 14.4 Ah Li-ion-based SHSs have two 12 V outputs for lights, a 5 V USB output to charge mobile phones, and a 19 V output for laptops. These systems, designed by the authors, were assembled in Senegal with a team of local technicians.

Figure 10 below shows a comparison between a household using candles (for example, in the context of Senegal, USD 0.24 daily) as a lighting source and a household using locally made Li-ion-assembled SHS (7.2 Ah system for USD 150) with a 2000-cycle lifespan for the battery, or about 5 and a half years.

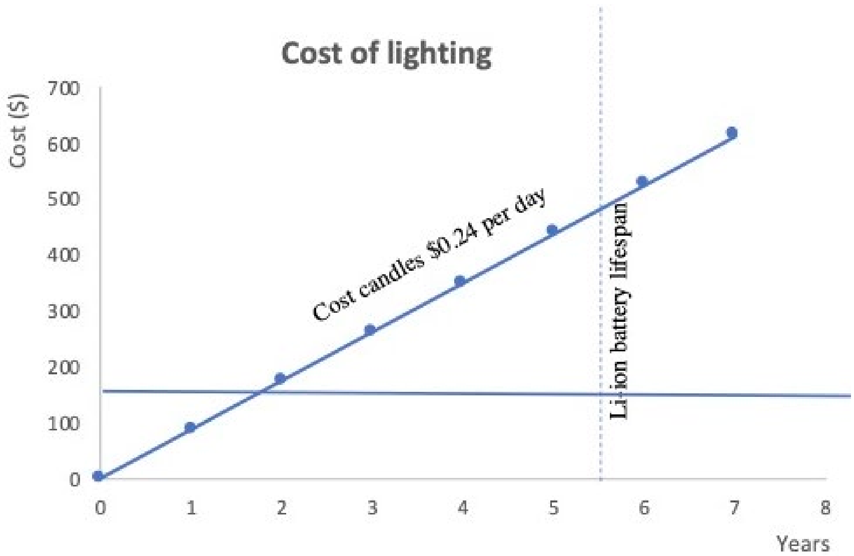

Figure 10. Comparative cost between candles and locally assembled 7.2 Ah Li-ion SHS.

The cost P of a SHS in the long run can be represented by Equation (1) below:

$$P = P_{sys} + n\frac{(365 * n_d)}{n_c}P_{bat} \tag{1}$$

P_{sys} is the cost of the initial SHS;
n_c is the lifespan of the battery in number of cycles;
n_d is the average number of days per cycle;
P_{bat} is the cost of the battery pack (replacement);
In the graph, Figure 10 above, n_c = 2000, n_d = 1, P_{sys} = USD 150.

4.2. Solar Photovoltaic Panels

The same analysis applies to the assembly of solar photovoltaic panels. In fact, few companies manufacture solar cells. Assembling photovoltaic solar modules from solar cells remains an affordable technology. Import and tax policies also need to be reviewed. Investors should have better guarantees for their production and make their investment fruitful.

It remains absolutely challenging to translate Sustainable Development Goals into local policies, particularly goal number 7 in question in this paper. In fact, research, technology, and investment are the central points of access to clean and affordable energy for all.

Reliability of products on the market is another key point, as poor families invest an important proportion of their resources in a power solution that would not last long. This obviously discourages other farmers from investing in such products.

Presently, the cost of a 1-watt equivalent peak solar panel is less than USD 0.4, which opens up the perspective of local manufacturing with many other benefits, such as employment.

A basic 100 W solar panel is sold between USD 60 and USD 80 in most Sub-Saharan African countries, while they could be under USD 40.

The market is important. In fact, about 600 million people do not have access to electricity, corresponding to 60 million families when counting 10 people per household. If each of those families installed only a 100 W solar panel, it would correspond to 60 GW of solar panels. A 100 W solar panel is barely enough to have light, charge mobile phones, a radio, and a small TV. At least a 1000 W equivalent solar panels should be considered when a standard household has basic equipment.

Presently, a standard photovoltaic solar panel is sold at USD 0.4 per watt in China and at least at USD 0.6 per watt in Sub-Saharan Africa; for 60 GW, there will be at least a difference of 12 billion dollars. This shows the gain in local manufacturing and the necessity of including a solid program of industrialization in the energy policy of Sub-Saharan Africa.

The same logic applies to batteries. If a 70 Ah/12 V Li-ion battery is associated with the 100 W solar panel, it will correspond to a total of 50.4 GWh of storage capacity needed.

The International Energy Agency, in partnership with the African Development Bank, reported, as stated above, that universal access to clean energy in Africa would require an investment of USD 31 billion a year for the next 6 years, which corresponds to a total of USD 186 billion [51]. When considering the kits presented above (Figure 9), at USD 260 each, if manufactured locally, a total of "only" USD 15.6 billion would grant each of the 60 million households light and capacity to charge mobile phones.

The same logic can apply to light-emitting diode (LED) lamps for quality products at lower cost, particularly when there is no problem of labor or need for high qualifications.

4.3. Biogas Digesters and Circular Economy

Regarding access to clean cooking fuel, there is a large biogas potential in the majority of rural Sub-Saharan Africa when livestock and water are available. Biogas is less sensitive to investment in research and development than battery technology. But when the agricultural sector does not perform well, farmers' low revenues would not permit them to invest in a large family-sized biodigester, as in most biogas national programs.

Research and development in biogas and poverty alleviation or improvement of farmers' income in rural areas of developing countries may be addressed in terms of market-oriented management and the chain of production. As an illustration, a pilot project was developed in Cambodia with a production model involving livestock farming, agriculture, and biogas. A pig farm was created in collaboration with a local farmer in Batheay, a village in Kampong Cham province. It was with an objective of livestock farming for commercial purposes, agricultural production destined partly to family needs and partly to commercial purposes, and biogas production for clean cooking fuel and lower energy expenses. The whole concept is to reduce life expenditures and generate a higher income. The pigs are raised for a period of about half a year. During this period, they grow from about 5 kg to between 100 kg and 130 kg, from three weeks of age to 5–6 months. The farm is organized in such a way that there are permanently two groups of twenty pigs, 5 months apart in age. This guarantees a continuous production of dejection for biogas and natural fertilizer that can be used in agriculture. This pig farm can guarantee the production of biogas, natural fertilizer, and access to clean cooking energy, which is a challenge in rural areas of Cambodia. This model farm substantially contributes to the improvement of living conditions with a comfortable income from the pig business. Such a model creates direct contact between producers and markets as local populations do their transactions with the farmer without any intermediaries.

In fact, to overcome the low income of farmers and lack of access to clean energy in developing countries, the concept of a circular economy, as described above and presented in Figure 11, appears to be an adequate solution. It connects naturally to livestock, agriculture, and biogas. Agriculture and livestock will be marketed and generate income, while biogas can be the source of cooking fuel and electricity generation when a matching generator is available. As a result, there will be an important reduction in poverty as there will be fewer expenses for energy, or maybe no expenses, as well as for fertilizers. For such a model to be generalized in regions with high biogas potential, there should be a focus on relevant training for technicians to construct digesters and a financial system that would lead farmers to a successful transition from their classical mode of production to a circular model.

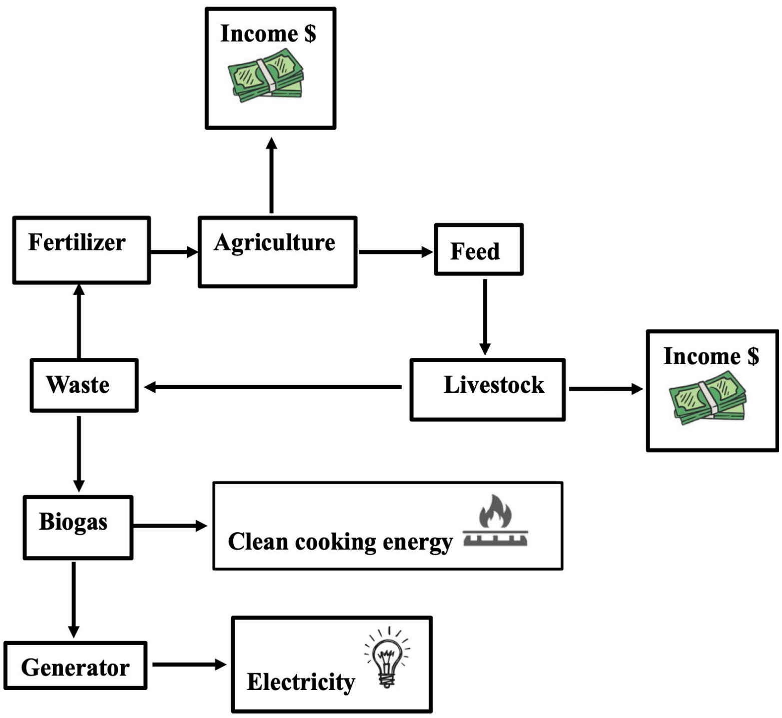

Figure 11. Schematic of a circular economy.

This model applies to other livestock, such as cows or even poultry [40].

Using energy in agriculture is necessary at all stages: production, conservation, or transformation. Farmers in sub-Saharan Africa often lose part of their production of fresh fruits or vegetables due to problems related to inadequate conservation, such as access to cold rooms. Drying fresh products as a mode of conservation is undertaken around the world, particularly when high temperatures accelerate product deterioration and there is no alternative. Fabrication of convection dryers is an affordable technology requiring accessible skills with a minimum of training.

5. Conclusions

Access to clean energy remains a challenge in developing countries, particularly in rural areas, despite successive policies that have shown very modest success. Electricity and clean cooking fuel are still a luxury available only to those in better financial conditions. Committed governments, under the rule of social justice, adopted policies that allow better access to clean energy compared to those where clean energy is taken as just any commodity sold to poor populations. Endemic poverty among rural populations finds its source in the economic activities of farmers: agriculture and livestock farming. These activities, traditionally managed, are of poor yield and are not enough to support rural workers. Successive policies essentially targeted access to energy without taking much into consideration the root causes of poverty in rural areas.

Adequate reforms are needed to improve the revenues of farmers through the management and modernization of farming activities for a better yield. The potential is huge, particularly concerning livestock farming. Mainstream financial institutions need to be reformed, or a new approach of financial institutions needs to be created to match the financial reality in rural areas. Governments could be the guarantors for farmers to be granted loans, as they do not have any solid guarantees or savings.

More incentives should be directed toward investors in technology to put on the market more adequate and affordable products, particularly in solar energy, where the totality of components making a SHS are presently imported.

Endemic poverty is the main barrier impeding access to clean energy in rural areas of developing countries. In this paper, it is defended that the way to go about it is by tackling the root causes of poverty and promoting technology to make available affordable and quality products. Lack of access to clean energy is only one of the many symptoms of poverty and should be treated accordingly.

Obviously, this study cannot be sufficient to respond to all issues of access to clean energy in developing countries, but it remains certain that lack of technology and poverty are important parts of the reasons. An important focus should also be placed on policy and socio-cultural determinants to find adequate solutions.

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References

1. Falcone, P.M. Sustainable Energy Policies in Developing Countries: A Review of Challenges and Opportunities. *Energies* **2023**, *16*, 6682. [CrossRef]
2. Babayomi, O.O.; Dahoro, D.A.; Zhang, Z. Affordable clean energy transition in developing countries: Pathways and technologies. *iScience* **2022**, *25*, 104178. [CrossRef] [PubMed]
3. United Nation. Available online: https://unctad.org/topic/least-developed-countries/chart-july-2021 (accessed on 2 February 2024).

4. Rao, N.D.; Pachauri, S. Energy access and living standards: Some observations on recent trends. *Environ. Res. Lett.* **2017**, *12*, 025011. [CrossRef]
5. Jahanshahi, A.; Lopes, M.; Brandão, M.; De Castro, E.A. Development of bioenergy technologies: A scientometric analysis. *Heliyon* **2023**, *9*, e20000. [CrossRef] [PubMed]
6. Mukhtar, M.; Adun, H.; Cai, D.; Obiora, S.; Taiwo, M.; Ni, T.; Ozsahin, D.U.; Bamisile, O. Juxtaposing Sub-Saharan Africa's energy poverty and renewable energy potential. *Sci. Rep.* **2023**, *13*, 11643. [CrossRef] [PubMed]
7. IEA. Solid Biofuels Consumption Estimation Model. Available online: https://www.iea.org/data-and-statistics/data-product/solid-biofuels-consumption-estimation-model (accessed on 2 February 2024).
8. Center for Strategic and International Studies (CIS). The Role of Renewables in Achieving Universal Access to Electricity in Southeast Asia. Available online: https://www.csis.org/analysis/role-renewables-achieving-universal-access-electricity-southeast-asia (accessed on 2 February 2024).
9. Office National de l'Électricité et de l'Eau Potable (ONE). Available online: http://www.one.org.ma (accessed on 2 February 2024).
10. Nygaard, I.; Dafrallah, T. Utility led rural electrification in Morocco: Combining grid extension, mini-grids, and solar home systems. *Wiley Interdiscip. Rev Energy Environ.* **2016**, *5*, 155–168. [CrossRef]
11. World Bank. Available online: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ZG (accessed on 2 February 2024).
12. Thakur, A.K.; Sameer Patel, S. Indoor Air Quality in Urban India: Current Status, Research Gap, and the Way Forward. *Environ. Sci. Technol. Lett.* **2023**, *10*, 1146–1158. [CrossRef]
13. World Health Organization. Available online: https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health (accessed on 2 February 2024).
14. Gonzalez-Eguino, M. Energy poverty: An overview. *Renew. Sustain. Energy Rev.* **2015**, *47*, 377–385. [CrossRef]
15. Access to Clean Fuels and Technologies for Cooking. Available online: https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2022-ch2-access_to_clean_cooking.pdf (accessed on 2 February 2024).
16. Universal Access to Clean Cooking Energy. Available online: https://sustainabledevelopment.un.org/content/documents/17465PB2.pdf (accessed on 2 February 2024).
17. World Electricity Map. Available online: https://en.wikipedia.org/wiki/File:Share_of_the_population_with_access_to_electricity,_OWID.svg (accessed on 2 February 2024).
18. World Population Access to Clean Cooking Energy. Available online: https://ourworldindata.org/energy-access (accessed on 2 February 2024).
19. Share of the Population Living in Extreme Poverty. Available online: https://ourworldindata.org/grapher/share-of-the-population-living-in-extreme-poverty (accessed on 2 February 2024).
20. World Bank. Available online: https://data.worldbank.org/indicator/NY.GDP.PCAP.CD (accessed on 2 February 2024).
21. Definition Extreme Poverty World Bank. Available online: https://www.worldbank.org/en/news/feature/2016/06/08/ending-extreme-poverty (accessed on 2 February 2024).
22. Average Family Size Senegal. Available online: https://www.prb.org/international/indicator/hh-size-av/map/country/ (accessed on 2 February 2024).
23. UN Millennium Development Goals. Available online: https://www.un.org/millenniumgoals/ (accessed on 2 February 2024).
24. Extreme Poverty Drop. Available online: https://www.un.org/millenniumgoals/poverty.shtml (accessed on 2 February 2024).
25. Requirement Universal Access to Electricity. Available online: https://www.iea.org/news/universal-energy-access-by-2030-is-now-within-reach-thanks-to-growing-political-will-and-falling-costs (accessed on 2 February 2024).
26. Diouf, B.; Miezan, E. The limits of the concession-led model in rural electrification policy: The case study of Senegal. *Renew. Energy* **2021**, *117*, 626–635. [CrossRef]
27. Rate Rural Electrification in Senegal. Available online: https://gestoenergy.com/wp-content/uploads/2019/04/Gesto_Senegal_EN.pdf (accessed on 2 February 2024).
28. Share of Population with Access to Electricity in Sub-Saharan Africa. Available online: https://www.statista.com/statistics/1276907/share-of-population-with-electricity-in-sub-saharan-africa-by-area/ (accessed on 2 February 2024).
29. EIA. Available online: https://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf (accessed on 2 February 2024).
30. IEA. Available online: https://iea.blob.core.windows.net/assets/cc401107-a401-40cb-b6ce-c9832bb88d85/WorldEnergyOutlook2011.pdf (accessed on 2 February 2024).
31. Eberhard, A. *Africa's Power Infrastructure: Investment, Integration, Efficiency*; The World Bank: Washington, DC, USA, 2011.
32. Some Objectives of Power Africa. Available online: https://www.usaid.gov/powerafrica/aboutus (accessed on 2 February 2024).
33. Some Achievements of Power Africa. Available online: https://www.usaid.gov/sites/default/files/2023-02/PowerAfrica-Annual-Report-2022_1.pdf (accessed on 2 February 2024).
34. Akouegnonhou, O.; Demirbas, N. Factors Affecting the Income of Farmers Participating in Traditional and Modern Livestock Markets: Case Study from Benin Republic. *Selcuk. J. Agric. Food Sci.* **2021**, *35*, 210–217. [CrossRef]
35. Alobo, S.; Bignebat, C. Patterns and determinants of household income diversification in rural Senegal and Kenya. *J. Poverty Alleviation Int. Dev.* **2017**, *8*, 93–126.

36. The Potential of Small-Scale Biogas Digesters to Alleviate Poverty and Improve Long Term Sustainability of Ecosystem Services in Sub-Saharan Africa. Available online: https://assets.publishing.service.gov.uk/media/57a08ad9e5274a31e00007ec/FinalReport_Biogas-Digesters-in-Sub-Saharan-Africa.pdf (accessed on 2 February 2024).
37. Senegalese Ministry of Agriculture. Available online: https://www.agriculture.gouv.sn (accessed on 2 February 2024).
38. Authors' Investigation in Senegal, in the Natural Region Bassin Arachidier. January 2022.
39. Diouf, B.; Pode, R.; Osei, R. Initiative for 100% rural electrification in developing countries: Case study of Senegal. *Energy Policy* **2013**, *59*, 926–930. [CrossRef]
40. Diouf, B.; Miezan, E. The biogas initiative in developing countries: From technical potential to failure: The case study of Senegal. *Renew. Sustain. Energy Rev.* **2019**, *101*, 248–254. [CrossRef]
41. Number of Patents per Country. Available online: https://worldpopulationreview.com/country-rankings/patents-by-country (accessed on 2 February 2024).
42. World Intellectual Property Indicators. 2020. Available online: https://www.wipo.int/pressroom/en/articles/2021/article_0011.html (accessed on 2 February 2024).
43. Rate of Enrollment in Higher Education. Available online: https://ourworldindata.org/global-education (accessed on 2 February 2024).
44. Expenditure in R&D. Available online: https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS (accessed on 2 February 2024).
45. Rate of Rural Electrification. Available online: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS (accessed on 2 February 2024).
46. Barefoot College International. Available online: https://www.barefootcollege.org (accessed on 2 February 2024).
47. Diouf, B.; Pode, R. Potential of lithium-ion batteries in renewable energy. *Renew. Energy* **2015**, *76*, 375–380. [CrossRef]
48. Li-ion vs Lead-Acid Batteries. Available online: https://www.energysage.com/energy-storage/types-of-batteries/lithium-ion-vs-lead-acid-batteries/ (accessed on 2 February 2024).
49. Diouf, B.; Avis, C. The potential of Li-ion batteries in ECOWAS solar home systems. *J. Energy Storage* **2019**, *22*, 295–301. [CrossRef]
50. Bloomberg. Electric Vehicle Outlook. 2018. Available online: https://about.bnef.com/electric-vehicle-outlook/ (accessed on 2 February 2024).
51. Financing Energy in Sub-Saharan Africa. Available online: https://www.iea.org/news/doubling-energy-investment-in-africa-requires-urgent-action-to-bring-down-financing-costs-and-boost-access-to-capital (accessed on 2 February 2024).