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Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: Reducing the gap between current business models and on-site experience

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ABSTRACT

The absence of publicly available up-to-date costs breakdown data on photovoltaic (PV)/hybrid mini-grids in Sub-Saharan Africa (SSA) is a barrier that needs to be resolved in order to overcome challenges in rural electrification planning, regulation, life-cycle operation, financing, and funding. The primary aim of this research is to provide better understanding of the cost structures of PV/hybrid mini-grid projects in Sub-Saharan Africa. The review on existing literature reveals significant lack of transparency and inconsistencies in PV/hybrid mini-grid costs. This paper aims to support the fact that there still remains a strong need to reduce the gap between current business model concepts and successfully implemented scale-up electrification models. Based on the experience of PV/hybrid mini-grids projects implemented in various rural communities of SSA, we propose a multi-dimensional cost analysis with a standardised break-down of the real costs of installed projects. Subsequently, we assess the main social and environmental implications and we identify barriers that appear to hinder successful PV mini-grid planning and subsequent implementation in SSA. Africa has the unique opportunity to utilize renewable energy as a primary energy source. Indeed, the continent has the potential to bring electricity especially to its rural population by means of PV/hybrid mini-grids. However, the capability of public and private sector investors to pre-evaluate projects is limited by the lack of locally available information on PV/hybrid mini-grid costs or the reliability of data (when available). Multi-dimensional cost analysis of social and environmental impacts from this study highlight that PV/hybrid mini-grids offer a unique opportunity to create a standardised framework for quantifying costs of PV/hybrid mini-grids in SSA, that can support decision-making processes for designing viable business models. Findings show that there is a strong need to minimise the data quality gap between current business model and that of successfully implemented PV/hybrid mini-grids electrification projects. This gap could be mitigated through studying the issues that influence mini-grid costs (both hardware and software). In addition to understanding other factors that can influence project costs such as the market maturity and remoteness of the site, organisation capability, development approach, and level of community involvement. Regarding policy considerations, stronger political will coupled with proactive rural electrification strategies and targeted renewable energy regulatory framework would be essential in order to establish viable dynamic domestic market for off grid renewables. In the presented benchmarking analysis, the experiences of public and private development organisations are synchronized to contribute to the furthest extent possible to facilitate the assessment. Those include the disaggregation of component costs according to their unit in order to make comparison more accurate and include site-specific parameters in the discussion of costs.

1. Introduction

Sub-Saharan Africa (SSA) though rich in energy resources yet has the least electrification rate globally. The region, with a population of 915 million people, has only 290 million of its citizenry having access to modern energy services [1]. Even though considerable gains have been made in recent years in the provision of energy access services in SSA, population growth appears to be a significant limiting factor. Lack of modern energy services in rural SSA is a pressing challenge in the region, with nearly 80% of rural populace living in the dark. The electrified areas in SSA are typically found in the urban areas, however, as argued by Broto et.al. [2], there nevertheless, remain a growing

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problem in informal settlements in urban areas on the lack of modern energy services due to increased rural-urban migration.

The International Energy Agency (IEA) reports that the average residential electricity consumption per capita is 317 kWh per year in SSA (less than 1 kWh per day) and notably the least energy consumption rate per person in the world [1]. Primary energy demand in SSA stood at 570 Mtoe (2012) and constituted only 4% of the total, globally [1]. The economy of SSA recorded a 2.5% decrease in energy intensity per year since year 2000 [1]. The falling costs of solar photovoltaics (PV) panels and battery systems as well as the available huge potential of the renewable resource makes it imperative for SSA to explore the technology in its energy portfolio for economic growth.

Despite the large technical potential for solar PV in SSA due to the unlimited resource, only limited use of solar PV electricity generation has been implemented to date. Since the early nineties, the main PV use in Africa was stand-alone systems with however untraceable market records [3,4]. However, during the last decade rapid cost reductions are being achieved for solar PV, due to technological developments, improving learning rate and economies of scale. Since 2012, the number of utility-scale PV projects are rapidly increasing due to the establishment of regulatory frameworks and institutions for renewable energy [5]. Overall, the installed PV capacity has grown more than forty times from 2008 to 2016 [3] with a total capacity of 2.5 GW by the end of 2016. IRENA published in 2015 a renewable technology roadmap study for African countries across the different sectors [6]. According to the roadmap, PV solar power could contribute 4% of total final energy consumption by 2030 produced from 31 GW of installed PV (which is more than a four-fold increase compared to the 2013 level of 5%).

There is a need to accelerate the pace of rural electrification in order to achieve full access to electricity by 2030, especially rural areas in Sub-Saharan Africa (see Fig. 1). Mini-grids offer a modular and competitive solution to accelerate the electrification in rural areas, characterised by remoteness and sparse population density [7]. Under this rationale, this paper focus its attention to the status of PV/hybrid mini-grids in rural areas in SSA.

Further penetration of solar energy to the energy mix of Sub-Saharan Africa has been achieved through the establishment of PV/hybrid mini-grids for rural electrification as an alternative to grid extension [7]. Different autonomous mini-grid sizes and architectures can offer a lower or higher tier of service [8] depending on the quality and duration of electricity provision. Thus, enabling energy access to remote population at a lower cost. Nonetheless, rapid deployment and replication of successful projects would be achieved via deep understanding and reduction in costs structures of related hardware and software costs. This paper presents and thoroughly explains the costs of installed PV/hybrid mini-grid projects, through a joint collaboration between the private and public sectors.

Table 1
Summary of literature coverage for PV/hybrid mini-grids in Africa.

Region covered	Technology	Framework covered	Selected references (cited in main text)
Global	PV	Costs (breakdown)	[13–20]
Global	Mini-grid	General status and barriers	[24–26,29,41,42]
Global	Mini-grid	Costs (general)	[7,22,27–31]
Africa	PV	Costs (general)	[4,7,21]
Africa	Mini-grid	General status and barriers	[26,37,43]
Africa	PV mini-grid	Costs (model)	[32–36]
Africa	PV mini-grid	Costs (breakdown)s	[21,31,38–40]

1.1. Overview of PV/hybrid mini-grids in Sub-Saharan Africa

The renewable energy (RE) based mini-grid sector is growing and attracting interest from public and private sector investors [9,10]. The latest report from the Africa Progress Panel calls for a diverse energy mix with immediate deployment of off grid solar systems that can be deployed in tandem with the improvement of grid infrastructure [7]. Nevertheless, comparative studies of PV/hybrid mini-grid installation costs in Sub-Saharan Africa are scarce. The capability of private and public investors to assess rural electrification options is restricted by the lack of consistent data, for example of disgreggated PV/hybrid mini-grid cost factors.

Table 1 summarises the regional, technological and specific coverage of the exisiting literature not only specific for PV/hybrid mini-grids but as general overview of relevant literature. At the international level a number of leading institutions and networks have provided relevant literature on PV costs, as examples the work done by REN 21 [11], the Joint Research Centre (JRC) [3], and Latin American Energy Organisation (OLADE) [12]. The International Renewable Energy Agency (IRENA) [13], JRC [14] and IEA [15] have examined PV system pricing by disaggregating costs and technologies including survey reports and PV breakdown costs. Bazilian et al. [16] analysed the

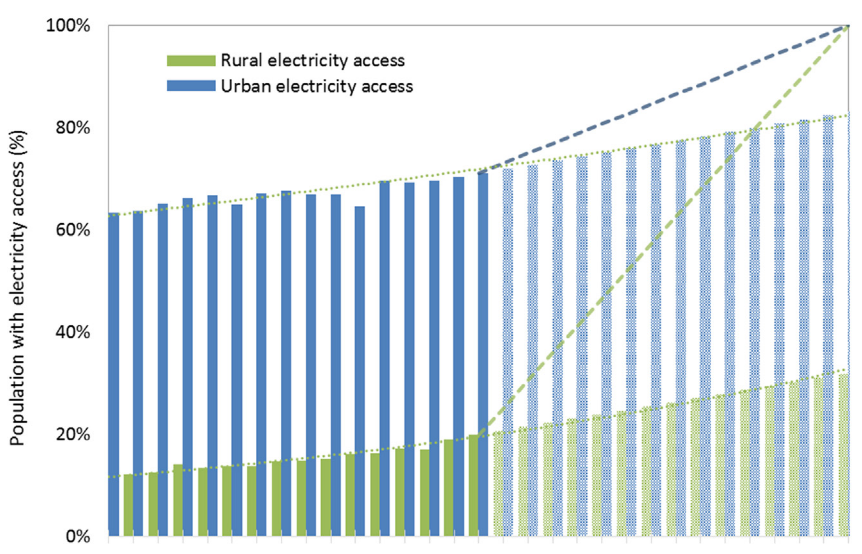

Fig. 1. Evolution of fraction of population with electricity access in SSA (linear increase needed to reach 100% electricity access in 2030).
Source: Based on [1] and JRC calculation

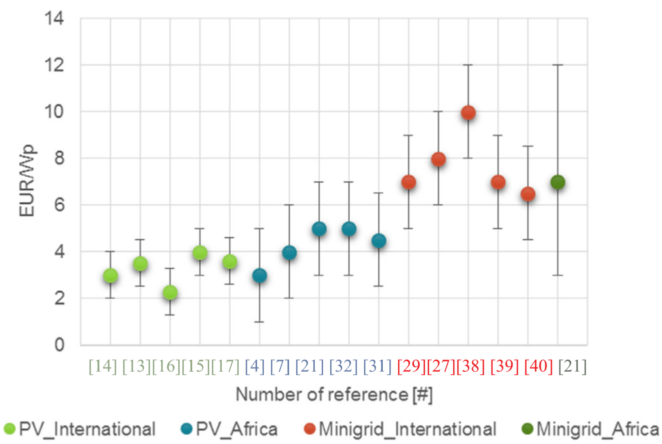

Fig. 2. Distributed PV technology costs in the selected literature.

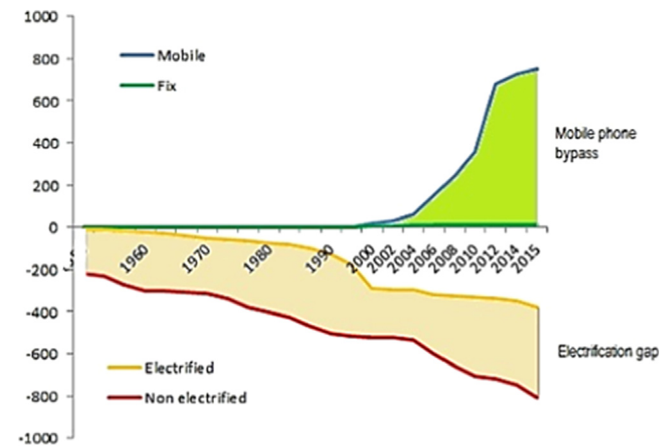

Fig. 3. Distributed energy technologies business trends in Africa could follow the successful example of the communication sector.
Source: JRC complied with data from: [18,19].

dramatic reductions in costs and market prices of PV. While, the National Renewable Energy Laboratory (NREL)/ Lawrence Berkeley National Laboratory (LBNL) have studied the historical evolution of PV prices in the United States of America and the specific breakdown of hardware costs and soft costs [17–20].

In contrast, there are few studies on specific PV installation costs in Africa. IRENA published in 2016 a general overview for PV in Africa focusing on costs and markets [21], while the IRENA mini-grid Outlook [22] publication focuses on the cost evolution of PV/hybrid mini-grid components by disaggregating them according to their functionalities and types (Fig. 2).

There are several studies specifically for mini-grids PV/hybrid mini-grid, most notably on the general status of off-grid systems, i.e. the Climatescope's off-grid data hub [23], the Energy Sector Management Assistance Program (ESMAP) report of the World Bank group [24], the Hybrid Mini-Grids for Rural Electrification report commissioned by the Department for International Development (DFID) [25] and the Off-Grid Renewable Energy Systems working paper from IRENA [26]. There are a number of publications analaysing the main barriers to the deployment of mini-grids [22,25,27], and studies containing general information on mini-grids costs [22,28,29,30]. For example, Thwaites et al. [31] presented a preliminary cost framework for PV based mini-grids. Szabo et al. [32–34], Cader et al. [35] and Mendis et al. [36] have published on decentralised energy planning models in Africa, but have not focused on authenticated field costs of PV/hybrid mini-grid. The African Progress Panel published in 2017 an overview of the electrification process in Africa including global cost of electricity generated by mini-grid and stand-alone systems [7]. Recent studies from IRENA provide new insights into PV/hybrid mini-grids in Africa [21]. In addition to these reviews, isolated case studies and applications related to hybrid mini-grids in Sub-Saharan Africa are presented in detail [37–40]. To the best of the knowledge of the authors, there have not been any study that undertake detailed analysis of the cost breakdown for installed PV/hybrid mini-grids in Sub-Saharan Africa (Figs. 2–6).

2. Framework conditions to off-grid implementation in SSA

2.1. Need to strengthen market design

Today, electricity from renewable technologies is vital to development; it is a common resource that delivers economic growth, is abundant and indigenous, has an immense job creation potential, and has lowered environmental impact compared to traditional fossil fuel and large hydroelectric generation. There is a clear link between distributed energy systems and share of renewables in the electricity mix [44]. The strong penetration of renewable energy in, for example, some of the European Union (EU) countries has been linked to its increasing price competitiveness with conventional sources. For instance, from 2008 to 2012, the solar photovoltaic module prices were decreased five fold [45]. A new IRENA report published in 2018 also highlights that solar PV costs are expected to halve by 2020 [46]. Unfortunately, this tendency is not reflected in the SSA markets due to other factors that are not technology-related. There is a strong need to work on national support schemes and to remove extensive taxes in order to accelerate high share of renewables in the SSA market. Additionally, streamlining and enhancing the stability of the regulatory and business frameworks to attract investors' confidence and protect consumers are paramount. Furthermore, the long-term sustainability should be supported through inclusive engagement with the communities [47]. Worldwide, many national electrification plans profoundly rely on grid extension without taking alternative options into consideration regarding their electrification portfolio [48].

The lack of documented experiences, information, knowledge, and open source quality data on renewable mini-grids in SSA has an impact on energy planners who must rely on traditional grid-extension projects for the electrification of rural communities. Similarly, it tend to make policy-makers less likely to promote and enable policies that promote the use of mini-grids in rural electrification due to misperceptions on technology costs and risks. These considerations drive costs up indirectly since the lack of adequate conditions makes investments riskier and hence costlier. There is a strong need to increase the awareness of national rural electrification decision-makers on the technical characteristics and installed costs of renewable energy (RE) mini-grids as an alternative to the grid extension.

Despite the growing popularity of RE mini-grids, it is still a challenge to define a generic scale-up implementation approach [49]. Distributed energy technology business trends in Africa could follow the most successful example of market expansion in the continent, that is the telecommunication sector (Fig. 3). However, some critics postulate that the mobile phone market cannot be compared to distributed energy, as their relative costs to the household budgets are very different. They also claim that the service level that the distributed electricity system could provide is also lower compared to the centralised grid. However, despite the fact that the household electricity expenses exceed those for mobile phones, distributed RE generation could be an important part in reaching electrification goals as a cost-effective, low-carbon solution.

Electrification portfolio decisions have to be based on comparisons among possible alternative options, supported by real case studies of lifetime costs of distributed energy versus the grid extension option. PV module costs have fallen over 50% in real terms over the past five years [15,45,50,51]. Energy storage technology prices have also dropped significantly and further reductions appear promising for the off-grid market [22]. Together the falling prices of PV module and storage

would contribute to reducing the gap between grid extension and PV/hybrid mini-grids.

2.2. Key questions and aim of the research: attracting PV/hybrid mini-grids investments in Africa

International development organisations, governments and donors are in the process of changing their investment models to support direct development activities. The new vision is to move away from grant/aid investments towards the use of public sources as seed capital for the pre-investment phase, which are supplemented by private equity. This new financing approach enhances the feasibility and the overall sustainability (from financial, political, environmental point of view) of supported projects. By this, public money can attract further public or private investors so the investment flows could be scaled-up. If these multiplicative effects should take place, not only would both the public and private sector gain but the biggest winner would be the un-electrified population in SSA as they would receive relatively prompt access to modern energy. However there are some questions to be answered in this changing development finance regime. For example, are the projects mature enough to be attractive to private investors? Are the perceived risks reduced enough by the public sector interventions and control mechanisms? Is there evidence of actual costs of PV/hybrid mini-grids in SSA? This paper seeks to illustrate and assess real costs of PV/hybrid mini-grids in areas which are not connected to the main grid in Africa. These autonomous PV/hybrid systems at present appear to be key environmental friendly option that could be scaled-up faster compared to longer-span large power plants and grid extension.

This paper aims to identify how to establish a more robust cost model, followed by a multi-dimensional cost factor analysis (Section 2.1), and to pinpoint how identify the most significant cost factors that hinder the dissemination of PV/hybrid mini-grids in SSA.

3. Methods

In scaling up off-grid rural electrification projects, international development organisations rely on private engineering companies (or through NGOs) to implement projects. The public procurement processes documentation has to be formulated in a way that both stakeholders (policy makers and implementers) understand the requirements in the same way. The private sector can compete in public tendering calls that more closely reflect the requested infrastructure, as more details (technical, service, costs ceilings) are defined in the tender documentation. Quite often in the past, these stakeholder expectations were not met in former development programs as the service to be provided, the range of technologies and associated costs were not defined and understood in the same way by all stakeholders. This quite often lead to situations where the companies did not compete on the same level of playing-field and the delivered system did not meet the expected outcome of the donors. An unusual approach of this paper is that the methodology used brings together the experiences from project implementers and public support organisations for common agreement on both cost structures and technical aspects, and benchmark them in a way that can be used in future tender documents. The innovative approach in cost structuring presented in this paper defines a new way of comparing mini-grid costs and makes it a useful tool for project developers, policy makers and other interested stakeholders.

In this section, we summarise the data gathering procedure employed in this study and we provide the classification of hardware and non-hardware ('soft') costs for each PV/hybrid mini-grid component. The results are based on a bottom-up data collection process and the analysis of PV/hybrid mini-grids implemented in various rural communities of SSA.

From September 2013 through September 2015, we disseminated a comprehensive survey to commercial mini-grid installers in SSA. The survey was divided into three major sections, i) technical and economic information for each mini-grid component (Section 2.1), ii) impacts on users, and iii) environmental impacts (Section 2.2). For the first component, the survey collected up-to-date data and benchmarked the current costs of the PV rural mini-grids installed between 2009 and 2015. Total expenditure data were collected for all mini-grid components (hardware costs) and annual operation and maintenance (O&M). The annual expenditures used to calculate the levelised cost of electricity were translated into euros per kilowatt-peak [EUR/kWp] of installed PV capacity for most cost factor group (PV array, balance of systems (BOS), inverter and other equipment), [EUR/kWh] for storage costs, [EUR/number of connections] for the distribution grid, and [EUR/kVA] for the diesel generator (see Table 2).

Section 2.2 describes the methodology used for the calculation of the social and environmental impacts of PV/hybrid mini-grids.

In Section 3 we describe the methodology for the cost comparison of implemented PV/hybrid mini-grid projects with the costs information obtained from our continental least-cost option methodology [32,33].

3.1. Cost factor groups

We use a bottom-up gathering methodology to benchmark the installation costs of the selected PV/hybrid mini-grids in Sub-Saharan Africa. We group them in five main factor groups for the hardware components and one additional factor for the soft costs. The six factor groups consist of (1) PV array, (2) BOS (balance of system), (3) Storage and Monitoring, (4) Distribution, Metering and End-users, (5) Backup generator, and (6) Soft costs. Table 2 shows the aggregated mini-grid components for each factor group and Fig. 4 shows an example of aggregation of cost factor groups and break-down for total softcosts for one of the studied cases.

In addition, Table 2 includes the unit for each component group so that project costs can be analysed according to the more significant costing factors, e.g. EUR/kWp or EUR/kWh, and make cost comparison more accurate. In most of the literature, PV and PV/hybrid mini-grid costs are usually only presented in terms of EUR/kWp; however to further analyse the effect of the sizing of the factor groups on the PV/hybrid mini-grid costs, we distinguish the corresponding constructive units of each factor group. For instance, a mini-grid with larger storage autonomy will be more expensive than a similar one with smaller batteries, resulting to the same cost per kWh of storage but higher costs per kWp and, thus, an unfair comparison.

In the case of PV array [kWp], Storage [kWh], Back-up generator [kVA], Distribution and Metering and End-users [# connections] the constructive unit used is straightforward. In other cases the allocation is less straightforward; monitoring and control equipment are allocated to the kW [AC] units of the power inverter. The BOS and charge controller's size depends directly on the capacity of the PV array [kWp], rather than the battery inverter or storage's size. The soft costs were

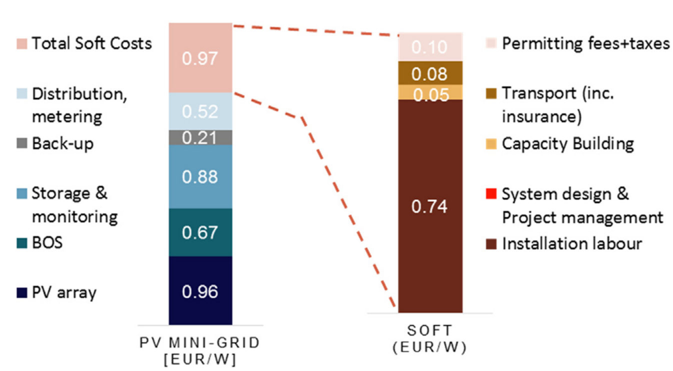

Fig. 4. Example of aggregation of cost factor groups (left) and break-down for total soft costs (right). Note: In this example System design and project management are not included.

collected as lump sums, even though in most of bibliography, soft costs are pegged to the kW_p as a reference to the plant capacity [19,20].

Section 3.4 contains the analysis of the components associated with their basic unit. The investment that should be set aside to run its operations' working capital is included in the section 2.3 and used to calculate the LCOE on a 20 years' lifetime. The installed costs are expressed in real 2016 euros [EUR]. To allow comparison with previous studies and other sources of information, the total hardware costs are defined by the upfront financial investment normalised by the installed PV capacity in watt-peak [EUR/W_p].

Soft costs were further broken down to identify the most influential coefficients in the case of remote mini-grids (i.e. remoteness and maturity of the local market). Soft costs were divided in five sub-categories: (6.1) Installation, civil works and material, (6.2) System design and project management, (6.3) Capacity building, (6.4) Permitting fees, Taxes and Financing, (6.5) Transport and Insurance.

3.2. Methodology to calculate the social and environmental impacts of PV/hybrid mini-grids

Data on hardware and soft costs for 27 installed PV/hybrid mini-grids in Sub-Saharan Africa were analysed in order to benchmark direct impacts (avoided CO2 emissions, number of beneficiaries and sectors involved).

Various previous studies assessed PV/hybrid mini-grids impacts on the social-economic factors of rural population [30,37,52–55]. One of the key advantages of mini-grids compared to single topology is the extent of the coverage of energy services to social and productive uses. In this study, we assess the social and environmental impacts in terms of increase of electricity access for each community before and after PV/hybrid mini-grid installation. We measure the social impacts of introducing PV/hybrid mini-grids in each community by the number of social (such as hospitals and schools), productive (such as powering commercial applications) and individual beneficiaries. Table 3 provides a range of consumption and number of beneficiaries for each type of energy service category and Fig. 5 shows the specific electricity load profile used in the calculations of one of the studied mini-grids.

A simple methodology for estimating the carbon mitigation potential of implemented PV/hybrid mini-grids in Sub-Saharan Africa was used by calculating the avoided greenhouse gas emissions (GHG) for each community.

The total amount of avoided GHG emissions by a PV/hybrid mini-grid were calculated by taking into account the load profiles and the PV output for each location [57]. The PV output is estimated in each location by PVGIS [56], which includes the PV energy curtailed and not captured due to deviation between production and demand. The avoided GHG emissions were calculated by comparing the GHG emissions of the PV/hybrid mini-grid with the emissions of a stand-alone diesel-genset generator covering the same electricity demand over the lifetime of the PV/hybrid mini-grid as shown in Eq. (1).

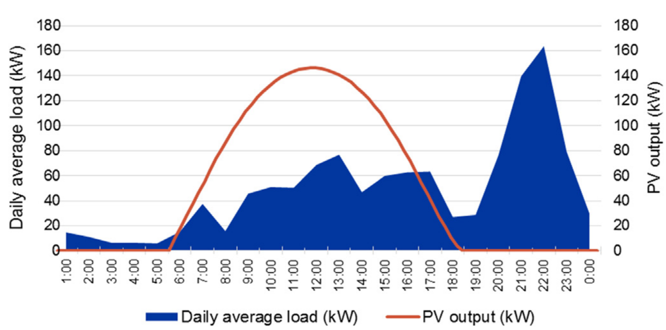

Fig. 5. Example of electricity load profile and PV output for a specific PV/hybrid mini-grid location [56].

$$\mathrm{GHGavoided} = \sum_{t=0}^{T}\left[[CO2eq_{diesel}]_t - \left[\sum_{i=1}^{n}(CO2eq_{PVmini})_i\right]_t\right] \quad (1)$$

Where:

- GHG_avoided: avoided GHG emissions by a PV/hybrid mini-grid over lifetime T
- t: time in years (t = 0 is the installation year)
- T: lifetime of the PV/hybrid mini-grid project (in years)
- 'n' is number of components of the PV/hybrid mini-grid (PV module, inverter, batteries and genset back-up)
- $CO2eq_{PVminii,t}$: GHG emissions of component i for specific electricity load at year t [kgCO2/year]
- $CO_2eq_{diesel_t}$: GHG emissions of diesel genset to cover same specific electricity demand as mini-grid at year t [kgCO_2/year]

3.3. Methods for cost comparison. LCOE model and uniform input values

In this study, we extend our analysis from capital costs (distinguished by cost factor and corresponding unit) to the levelised cost of electricity (LCOE) [58]. Thus enabling the comparison of the actual mini-grid costs of the six case studies in SSA with the costs of the modelled PV/hybrid mini-grids obtained in previous studies at continental level [32,33,56]. We calculate the LCOE for each community PV/hybrid mini-grid using the following equation:

$$\mathrm{LCOE}_n = \frac{\mathrm{CAPEX}_0 + \sum_{t=1}^{T}\{(R_t + O_t)/(1+r_n)^t\}}{\sum_{t=1}^{T}\{(Eg_n + ES_n)/(1+r_n)^t\}} \quad (2)$$

where:

- n: community
- $LCOE_n$: Levelised cost of electricity in community n [EUR/kWh]
- $CAPEX_0$: Initial mini-grid investment cost at t = 0 [EUR]
- t: Time in years (t = 0 is the installation year)
- T: Economic lifetime of the mini-grid project [years]
- Ot: Operation and maintenance cost in year t [EUR]
- Rt: Replacement cost in year t [EUR]
- Egn: Average genset electricity production per year [kWh]
- ESn : Average solar electricity production per year depending on solar radiation in location n [kWh]
- rn: Discount rate in community n

The estimation of LCOE per installation made use of field-specific data for the cost of capital, installation, O&M, as well as local techno-economic assumptions, including daily data of solar resource, and lifetime of components, etc. The annual energy output [kWh/year] was calculated for each location and mini-grid capacity using PVGIS Africa

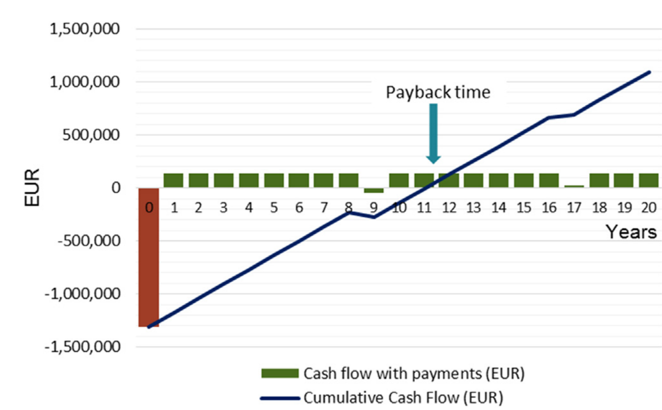

Fig. 6. Example of cumulative cash flow for one of the analysed PV/hybrid mini-grids.

Table 2
Summary of cost factor groups for rural PV/hybrid mini-grids.

#	Factor group	Components	Cost Unit	
1	PV array	PV modules	EUR/kWp	Only silicon PV panel technology is considered
		PV mounting structure		
2	BOS	PV cabling	EUR/kWp	
		PV earthing	EUR/kWp	
		Charge controller	EUR/kWp	
		DC protections board	EUR/kWp	
		Inverter	EUR/kW (AC)	Battery inverter and grid-tied inverter (AC bus)[a]
		AC protections	EUR/kW (AC)	General board and surge discharge protections
		AC cabling	EUR/kW (AC)	Inverters AC cabling, AC cabling to main switchboard
3	Storage and Monitoring	Battery bank and battery rack	EUR/kWh	Only lead-acid batteries considered as benchmark. Capacity differentiation,
		DC battery protections	EUR/kWh	from 1 to 3 days of autonomy.
		DC battery cabling	EUR/kWh	The Depth of Discharge (DOD) designed at 70%.
		Control and battery room	EUR/kWh	Main building for batteries, control equipment and others
		Monitoring board and Software	EUR/kW (AC)	Plant measuring operating conditions and monitoring equipment. Data gathering capacities can vary
4	Distribution and Metering and End-users	Street lighting (poles, lights…)	EUR/# connections	LV or MV
		Distribution lines (including cabling and connection boxes)	EUR/# connections	In some mini-grids, there is a distribution grid in place but need refurbishment, usually where a genset is already used to provide the
		Earthing lines and electronic protections	EUR/# connections	electricity.
		End user indoor wiring	EUR/# connections	
		End user metering and protections	EUR/# connections	Metering equipment (equipment installed depends on business model): Fee for service, pre-paid, flat rate, etc.
		End-user devices and household internal devices	EUR/# connections	Includes sockets, light bulbs, radio, TV, refrigerator, etc. Considering energy efficient appliances
5	Back-up generation	Diesel generator and cabling	EUR/kVA	Usually already available on-site, might need refurbishment or replacement
6	Soft costs	Installation, civil works and material	Lump sum	Labour installation: Buildings, land clearing and preparation, fences, etc
		System design and project management	Lump sum	Management, commissioning and engineering
		Capacity building	Lump sum	Strengthening skills, competencies and abilities of community
		Permitting fees, taxes and financing	Lump sum	Administrative and financial aspects
		Transport	Accessibility factor [EUR/km]	Shipping and land transportation
	Other equipment (for O&M)	Spare parts and storage	kWp	Some mini-grids are contracted with a minimum stock of materials

[a] Either AC-bus projects with grid-tied inverters, or DC-bus with charge controllers or hybrid AC/DC.

[56]. We assumed uniform values for discount rate (4%) and lifetime for PV modules (20 years) and lead-acid batteries (5 years). Fig. 6 shows as example a particular cumulative cash flow for one of the analysed PV/hybrid mini-grids.

3.3.1. Grid extension versus PV/hybrid mini-grid electricity costs

This section describes the methodology used to calculate grid extension cost in order to be able to compare the 'field' PV/hybrid mini-grid implementation costs with the grid extension electricity cost. Grid extension is likely to be a viable alternative compared to PV/hybrid mini-grid in each community n when:

$$(Cost_{\text{mini-grid}})_n {*} (\#Conn_{mini-grid})_n > \quad (Cost_{grid})_n {*} D_n \tag{3}$$

n: Community with PV hybrid/mini-grid
$Cost_{mini-grid}$: Cost of PV hybrid/mini-grid per connection $[\frac{EUR}{connection}]$
$\#Conn_{mini-grid}$: Number of connections per mini − grid
$Cost_{grid}$: Estimated cost of grid extension per kilometre $[EUR/km]$
D: Distance from the settlement to the main grid $[km]$

Grid extension costs in Sub-Saharan Africa can reach 30,000 EUR/km or more [59]. In addition, as most countries experience constant capacity shortage in the transmission grid and power shortage in generation, the grid extension may trigger investments in the centralised power system that may be more than double its costs [61]. In this study, the unit cost for grid extension is relatively high (40,000 EUR/km), which is comparable to the field data [61,62].

4. Results

One-dimensional capacity cost analysis [per kWp] can only be relevant when comparing similar mini-grids that have been designed with similar storage autonomy, PV energy fraction, and radiation resource. In our methodology, we have kept in mind that depending on the solar radiation conditions at each site, similar capacity PV generators will yield different daily energy plant outputs. When we proceed with a more granular factor analysis (using different dimensions), it is possible to establish a more robust costing model of mini-grids in accordance to the specific characteristics of the project. Commonly the full project costs are depicted in EUR/kW_p following the approach of grid-tied projects; nonetheless, off-grid plants have more functionalities and cost factors, many of which do not directly correlate to PV Standard Test Conditions (STC) capacity. Each of the main factor groups is measured by a different *unit* according to the embodied component (see Table 2).

Table 3
Ranges of consumption and number of beneficiaries for each category.

Unit	Average Consumption [kWh/day/connection]	Direct beneficiaries # beneficiaries	Indirect beneficiaries # beneficiaries	Comments
Social infrastructure	0.5–9.5	–	20–8000	Depending on social service offered
Productive use	0.5–4.4	–	10–60	Depending on type of productive use
Residential	0.5–2.8	5–7	–	–

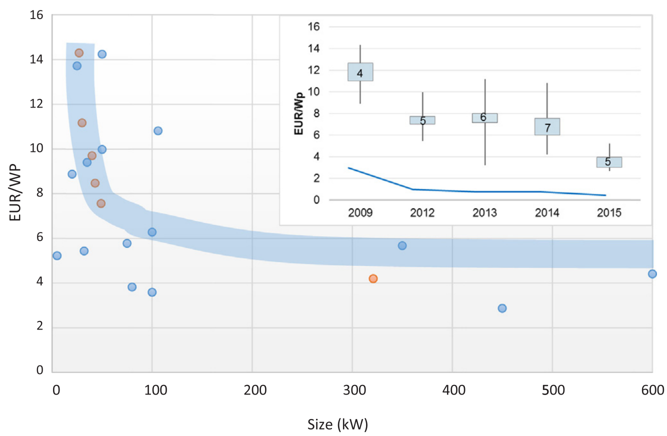

Fig. 7. Full project investment cost variation by PV generator capacity size of the mini-grid (selected samples in red for harmonized study). In box - Full project investment cost variation (number of samples, max and min) by year of procurement. Blue line: corresponding PV module cost for the year of procurement.

4.1. *Effect on cost dependent on mini-grid size, module market prices and global market maturity*

The techno-economic data for 27 installed PV/hybrid mini-grids in Sub-Saharan Africa have been compared and analysed. Several steps were taken to clean and standardise the format of the data. Evaluating the PV/hybrid mini-grid samples one by one PV/hybrid mini-grid, we selected a sample of six PV/hybrid mini-grids according to the quality, reliability, and harmonization of the data collected (in red in Fig. 7). In Fig. 7, the red points represent the dataset for which we could harmonise the component costs, while those in the blue represent the samples for which access to the cost per component [21] were not available. Projects were removed from the data sample when the reported installed price was deemed likely to be an appraised value. For a consistent comparison, all PV/hybrid mini-grids assessed were autonomous with battery storage, diesel genset as a back-up, and low voltage (LV) distribution grid.

There is a size-cost trend, for example a larger PV generator size correlates positively with lower per-unit costs. Larger scale PV/hybrid mini-grids of > 150kWp have capital costs in the value range of 4 – 6 EUR/Wp, meanwhile the smaller size PV/hybrid mini-grids of < 50kWp have capital costs of 8 – 14 EUR/Wp. The range of PV/hybrid mini-grids' costs is highly dispersed because the offered services by the mini-grids are different, ranging from low quality of services–meaning mini-grids supplying electricity for 6 h per day and without energy management systems – to high PV penetration rates offering 24 h service. The market maturity level can explain the high disparity of total costs and strongly influences the cost-sharing of services.

From the larger range of PV/hybrid mini-grids in Fig. 7 [21], we selected a group of PV-hybrid mini-grids with reliable energy characteristics (red dots in Fig. 7). The selected PV/hybrid mini-grids under study (Fig. 8) offer high quality service (service 24 h) with high PV penetration, battery storage with autonomy of 1–3 days and with small genset as backup.

The main tendencies are a general decrease in costs due to global maturity of the market (in this case from the first installations in 2009 to the latest in 2015). From Fig. 8(A), it is visible that the cost of the system components was much higher for the 2009 project than for the subsequent ones. However this cost decrease is less pronounced in the last years as the costs of various components are saturated after 2013.

As it is visible from Fig. 8(A), the size of the PV/hybrid mini-grid has also a positive effect on the project costs: the bigger the project's PV capacity, the cheaper the unit cost of the electricity produced by the off-grid system. This economy of scale effect is experienced by the donor organisations as well; where once donors focused on micro projects of 10

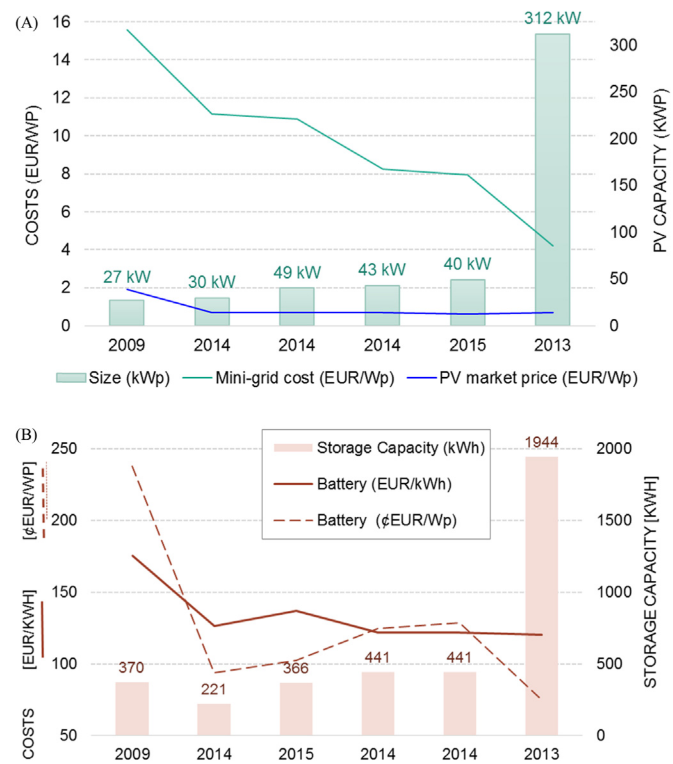

Fig. 8. (A) Variation of PV/hybrid mini-grids' full project investment cost [EUR/kW$_p$] with PV generator size and year of installation (B) comparison of battery storage costs versus battery size in [EUR/kW$_p$] and [EUR/kWh].

kWp or less in size, their priority is shifted towards medium-scale projects. This has multiple advantages: not only that the number of beneficiaries is multiplied, but they deliver the electricity at much lower costs.

When evaluating storage costs (Fig. 8B), it is important to consider the impact of the load profile and the demand during night hours, as well as the autonomy of the battery. In this study, the mini-grids selected are all designed with lead-acid batteries of a maximum operating Depth of Discharge (DOD) set to 60% with 1–3 days of autonomy. To analyse the storage costs it is important to use the appropriate units (Fig. 8B). While the storage costs show homogeneity in all case studies (in a range from 120 to 175 EUR/kWh) the use of EUR/kW$_p$ [21] may erroneously point to storage costs which do not reflect the design of the capacity storage of the mini-grid. Storage costs for larger mini-grids measured by the total PV capacity (kW$_p$) were lower, but should be compared to the capacity of the batteries (kWh). When using the appropriate units the cost reduction due to economies of scale is not significant but it reflects the variation of storage configuration when offering different electricity services (i.e. higher use during night-time). There has been some price variation in lead-acid batteries from 2009 to 2015, namely that the price per kWh went down from 175 EUR/kWh to 120 EUR/kWh in the selected case-studies, i.e. around 30% cost reduction.

4.2. *Costs breakdown*

Fig. 9 compares the PV/hybrid mini-grids' cost shares of each factor group. The share of total capital costs of the PV/hybrid mini-grids is 14% (± 2 deviation from mean) in average for PV modules and mounting structure, 14% (± 5) for BOS, 21% (± 6) for storage and monitoring, 21% (± 7) for distribution, metering and end-user devices, 3% for the diesel genset and 27% (± 4) for the soft costs.

Fig. 10 breaks down the costs of the PV/hybrid mini-grids for each of the cost factor group. The PV generation part has very similar costs of PV module per kW$_p$ in almost all the case studies, at around 0.85 EUR/W$_p$, with a range of a maximum value of 1.3 EUR/W$_p$ and minimum of

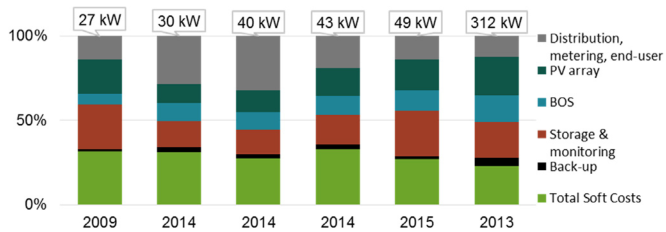

Fig. 9. Distribution of component costs for the selected PV/hybrid mini-grids.

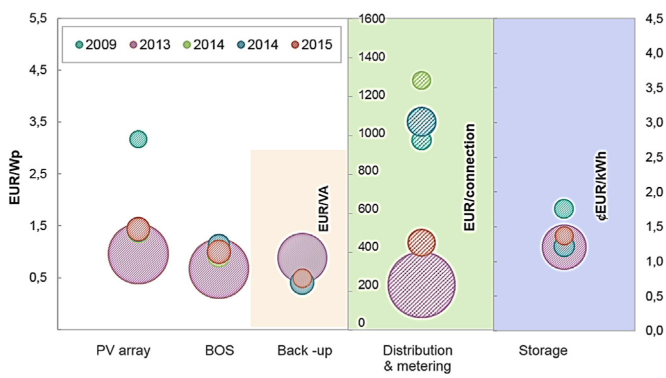

Fig. 10. Comparison of PV/hybrid mini-grids component costs for each group depending on year of installation. Bubble size: PV STC capacity for PV array, BOS and back-up, energy capacity for storage and number of connections for distribution and metering.

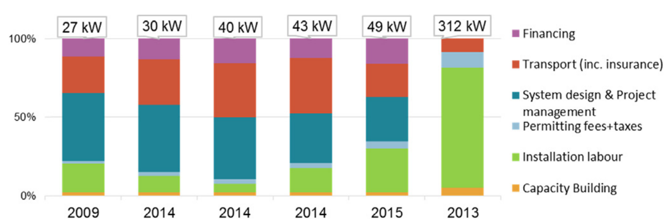

Fig. 11. Distribution of soft cost components. Note: In the 312 kWp mini-grid the financing and system design is not included as was covered by an NGO.

0.67 EUR/W_p. However the PV costs of module have fallen over 50% in real terms over the past five years [15,45,50,51], from 1.9 EUR/W_p in the earlier project (2009) to 0.7 EUR/Wp in the 2015 project. The lower PV cost of the latest project (2015) reflects the grade of PV market maturity in the global market.

Fig. 10 compares the costs of the PV array and BOS in relation to the capacity of the PV generator (bubble size in Wp) and the year of installation. The back-up systems are compared in relation to the size of the diesel genset (bubble size in VA). The battery costs are compared depending on the year of installation and capacity of the battery (bubble size in kWh). The differences in storage costs per unit are more homogenised. The variation in cost of storage depends on the load profile and autonomy as it influences the required size of the battery (i.e. when productive use is dominant then the load profile peaks during the day reducing battery size compared to a load profile peaking at night). For two communities with the same daily demand and solar resources, the one with the highest autonomy will require the larger size of batteries. BOS costs (charge controller, inverter, protection board, cabling and earthing) are consistent with an average cost of 1.0 EUR/W_p ranging from 0.67 to 1.3 EUR/W_p.

4.3. Breakdown soft cost components

This section presents the results from bottom-up data collection of non-hardware or *soft* costs for the selected PV/hybrid mini-grids. According to our analysis, the soft costs accounted for a significant portion (from 25% to 35%) of total installed PV/hybrid mini-grid costs PV/hybrid mini-grid. This fraction of cost is lower than, for instance, US PV systems costs for residential market [19,20] where, in general, soft costs are about 60% of the overall proportion of PV system costs. The main reason of this difference is that the soft cost in United States (US) market study includes a number of components linked to the developer or installer profits and supply chain costs, not included in the present mini-grid study. Moreover, in the residential market of the US, the impact of the PV prices' plunge is reflected to the total project cost, whereas soft costs are not decreasing at the same pace. On the contrary, the mini-grids consist of more components which makes the share of soft costs lower (Fig. 11).

The case presented hereafter is that the transportation costs are related to the accessibility factor of each site (Fig. 12). The travel time from the PV/hybrid mini-grid to the major city (accessibility factor) has been extracted from the accessibility map in Nelson et al. [63].

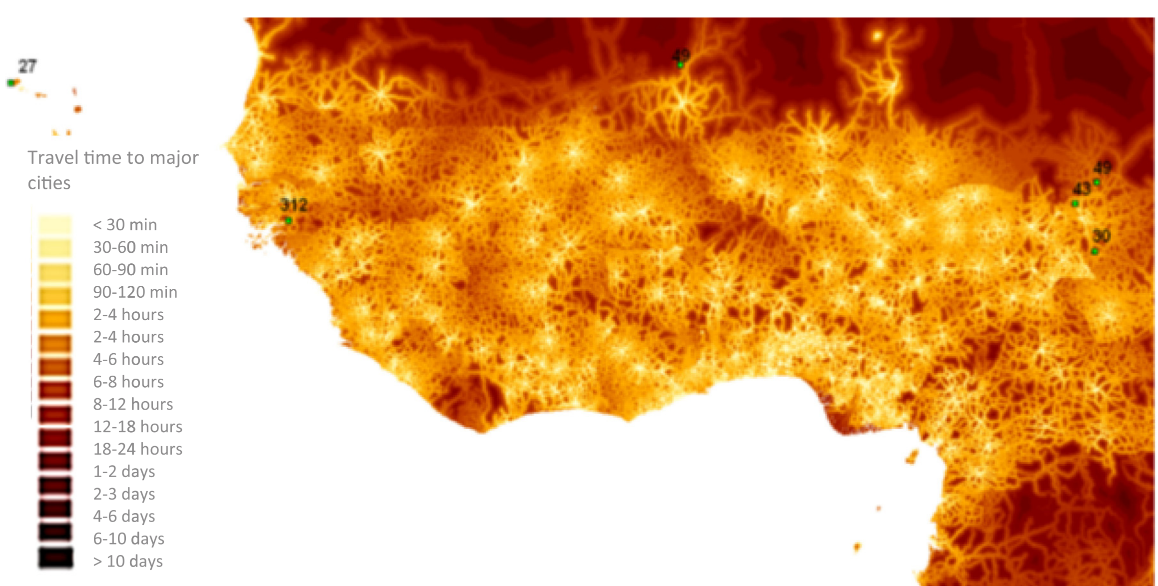

Fig. 12. Extracting accessibility factor from travel time to major cities [63].

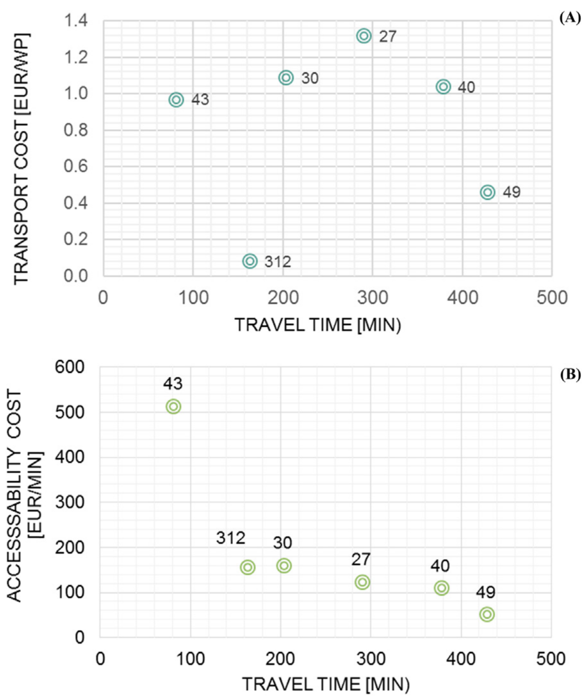

Fig. 13. Transportation costs (A) and accessibility costs (B) versus travel time.

Fig. 13 analyses the transportation costs of the installed PV/hybrid mini-grids based on the field studies' data (transportation costs) and accessibility costs related to the travel time.

This assessment shows that the transportation costs counteract the accessibility factor with the factor of economies of scale: anecdotal evidence reported by the developers show that installing several mini-grid in the same region simultaneously leads to decreased transportation costs per mini-grid. Moreover, servicing several mini-grids in a same remote area will help spread costs and make O&M activities more efficient. Likewise, local market maturity will reduce soft costs as more installers and service providers are available, whereas familiarity and a business-friendly environment facilitates project delivery.

4.4. Time span of soft components

In Sub-Saharan Africa, regulatory requirements and permitting processes for off-grid mini-grid installations are often difficult and costly [64]. Installers reported labour-hour requirements for permitting in an average of 200 h of labour for 30–50 kWp PV/hybrid mini-grids, substantially longer process than the time consumed when compared to US market for connected PV systems which is in the range of 8–22 h per PV installation [19] and fewer than 10 h of labour required in Germany [65]. The regulatory framework for off-grid project in SSA countries presents a large variety of approaches [66] and in many cases PV/hybrid mini-grids may need more permitting process or/and extended environmental impact assessment, etc.

The largest PV/hybrid mini-grid (312 kW_p) shows longer installation on-site process (480 labour-hours) than smaller PV/hybrid mini-grids (between 150 and 200 labour-hours). Also, the 312 kWp mini-grid was the first of its kind in the country, which means that the lack of similar experiences made the installation longer and, thus, more costly than in the other cases. The results of survey are in line with the expectations compared to PV-connected systems in US and Germany (range of 40–75 labour hours for on-site installation of connected PV system) [65]. Obviously, differences in the time requirements for the installation is partly a result of the complexity of PV/hybrid mini-grids that involves installation of batteries, distribution grid, individual meters, etc. compared to a standardised connected PV system.

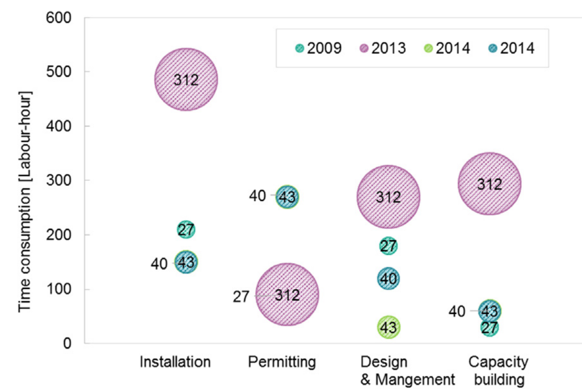

Fig. 14. Time consumption (in labour hours) for each soft cost component depending on mini-grid size and year of installation. Bubble size is the PV/hybrid mini-grid size.

Fig. 14 points out the role of the long permitting process on the soft cost components. The long permit procedures increase the cost of most of the project development phases. This highlights the significance of the institutional strengthening, mitigating and/or elimination of permitting bottlenecks. As private investors cannot influence this, public sector capacity building of the central and local governments thus become important cost mitigation factors in the private development of these projects. Shorter permitting periods can decrease costs for private investors.

4.5. Evaluating impacts

In this section, we evaluate the main impacts of the selected group of distributed energy generation projects in SSA. In doing so, we focus on researching a number of key areas that is: calculating and modelling the financial viability compared to conventional technologies (see section 3.6); and estimating the social costs and benefits of PV/hybrid mini-grids, including environmental benefits and increase of access to electricity.

4.5.1. Impact on access to electricity and number of beneficiaries depending on energy services

The impact of rural electrification has been assessed in terms of increase of electricity access in the community before and after the PV/hybrid mini-grid implementation (Fig. 15). As electricity access, it is referred the existence of some electricity source even for lighting, such as an electric lantern. According to the surveys, in five out of six communities, the access to electricity increased significantly by at least tripling their electrification rate. In one of the communities, the electrification rate remained the same (already at 95%) but the quality of electricity service increased from 8 to 24 h, climbing the tiers of service.

Fig. 16 shows the distribution of energy services for each PV/hybrid mini-grid. The total number of beneficiaries from the six PV/hybrid mini-grids installed in SSA are 1400 new household connections (11,000 direct beneficiaries) and around 100,000 inhabitants would be direct beneficiaries to electricity access for social well-being or

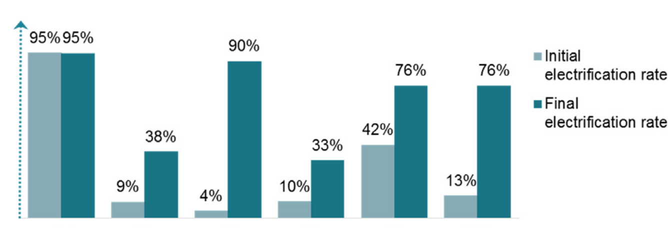

Fig. 15. Impact of PV minigrid implementation on the rate of access to electricity for each settlement.

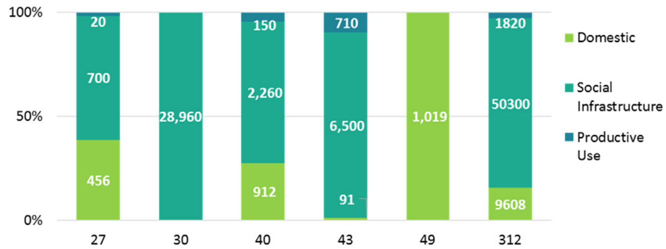

Fig. 16. Distribution of type of energy services offered in each PV/hybrid mini-grid (productive use, social infrastructure or domestic use) and total number of beneficiaries classified on type of services (white numbers).

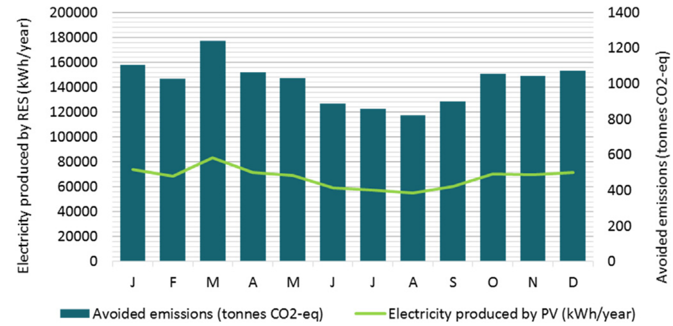

Fig. 17. Total electricity produced by PV and embedded avoided CO_2 emissions in 20 years.

Table 4
Summary of total social and environmental impacts for the 6 selected PV/hybrid mini-grids in Africa.

		# infrastructure	# users
Social Impact	Education centres	23	14,300
	Health centres	5	2700
	Administrative and religion centres	37	35,000
	Public Lighting and water supply	16	37,000
Productive Impact	Business, shops, workshops	141	2700
Domestic use	Households	1400	11,000
			102,700
Environmental impact	CO_2 emissions avoided in 20 years	12,000 t	

productive uses (i.e. improved educational and health services). Table 4 summerises the total social and environmental impacts for the selected PV/hybrid mini-grids.

4.5.2. Mitigation Cost Analysis: Avoided tons of CO_2 emissions

The Paris Agreement, secured in December 2015 during the 21st Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) is a landmark agreement by 195 countries that set the basis for the first universal, legally-binding climate deal. Under the Paris Agreement, a common framework that commits parties to submit their ambitious efforts with regards to climate change mitigation and on their resilience to the impacts of climate change was achieved. These are inscribed in the intended Nationally Determined Contributions (iNDC) that countries submitted to the UNFCCC as part of the Paris Agreement. The iNDCs currently appear to be the backbone for possibly establishing future carbon markets since there is inactivity in carbon trading in the Clean Development Mechanism (CDM). How such future markets would be established based on iNDCs is rather uncertain at this stage. However, the knowledge and experience gained from the CDM would be invaluable in establishing future carbon markets. For this reason, we present a mitigation cost analysis based on the proven CDM.

In the CDM, projects can earn saleable certified emission reduction (CER) credits—each equivalent to one ton of CO_2. Despite the great potential of RES in Sub Saharan Africa only 2.1% of CDM projects for renewable energy are located in sub-Saharan Africa [67]. Under the CDM, PV mini grids can be registered under the AMS-III.BL methodology “Integrated methodology for electrification of communities” [68]. We calculate the CER corresponding to the total amount of PV capacity installed (0.8 MW) that fall under microscale project criteria (i.e. aggregated installed capacity below 5 MW). We calculated the emission reduction costs by calculating the baseline emissions (t CO_{2eq}) of diesel genset (see Table 5 with baseline emission factors) with a CER price of 0.6 EUR/CER [69], that would represent around 0.2% of the total investment costs. The 2013 EU Reference scenario [70] projects CER prices of between 35 EUR/tCO2 in 2030 and 100 EUR/tCO2 in 2050. When the costs of carbon emissions are assumed at the long-term assumption of 40 EUR/tCO_2 then the cost of the whole project would sum up to 0.5 million EUR (15% of total investment). Carbon emissions depend on the efficiency degree of diesel generators; the average for existing generators at the selected sites was calculated at 1.7 tCO_2/MWh diesel electricity. The estimated emission factor of 1.7 tCO_2/MWh is derived based on a 30 kW diesel generator working with 0.25 of its load, which generates 0.0075MWh electricity in one hour and emits 13.1 kgCO_2. This calculation is based on the IPCC emissions factor of diesel (74,100 kg/TJ), Net Calorific Value of 43 TJ/Gg, engine's fuel consumption rate of 4.83 l/h [71] and diesel density of 0.83 kg/l [72]. It should be noted that this baseline emission factor is solely based on the above-mentioned assumptions. Surveys on off-grid diesel generation in Sub-Saharan Africa may give other figures. Fig. 17 shows the total electricity produced by PV in all mini-grids and their embedded avoided CO2 emissions in 20 years.

Table 5
Baseline emission factor.

Range of power consumption [kWh/year]	Baseline emission factor [tCO_2/MWh]
< 55	6.8
Between 55 and 250	1.3
> 250	1.0

4.6. Leapfrogging energy technologies

Despite the growing popularity of PV/hybrid mini-grids, it is still a challenge to define a generic scale-up implementation approach [49]. From the implemented PV/hybrid mini-grids in this study we can observe that the service provided by off grid systems in SSA can exceed the main grid in terms of reliability (not only the black out durations but the average lifetime of network and their inadequate maintenance) [59]. On top of it, at longer term PV/hybrid mini-grids are amenable to be eventually connected to the main grid [73].

For grid extension levelized electricity costs [EUR/kWh], we calculate the investment costs for specific distance to an existing MV line [5000 EUR/km] and the respective distance [km], connection costs [100 EUR/connection], the production cost from the current main grid for each country and the specific electricity demand of each community.

In previous work, the Joint Research Centre (JRC) carried out a geospatial analysis assessing least-cost rural electrification options in Africa (Fig. 18) [32,33,74]. Three rural electrification technologies i.e. PV/hybrid mini-grids, mini-hydro and diesel generators were compared with the grid extension options and were visualised in GIS based maps.

Table 6 highlights that PV/hybrid mini-grids are already the least-cost option for most of the selected locations. PV/hybrid mini-grids show a 20–70% lower cost compared to diesel genset options. The

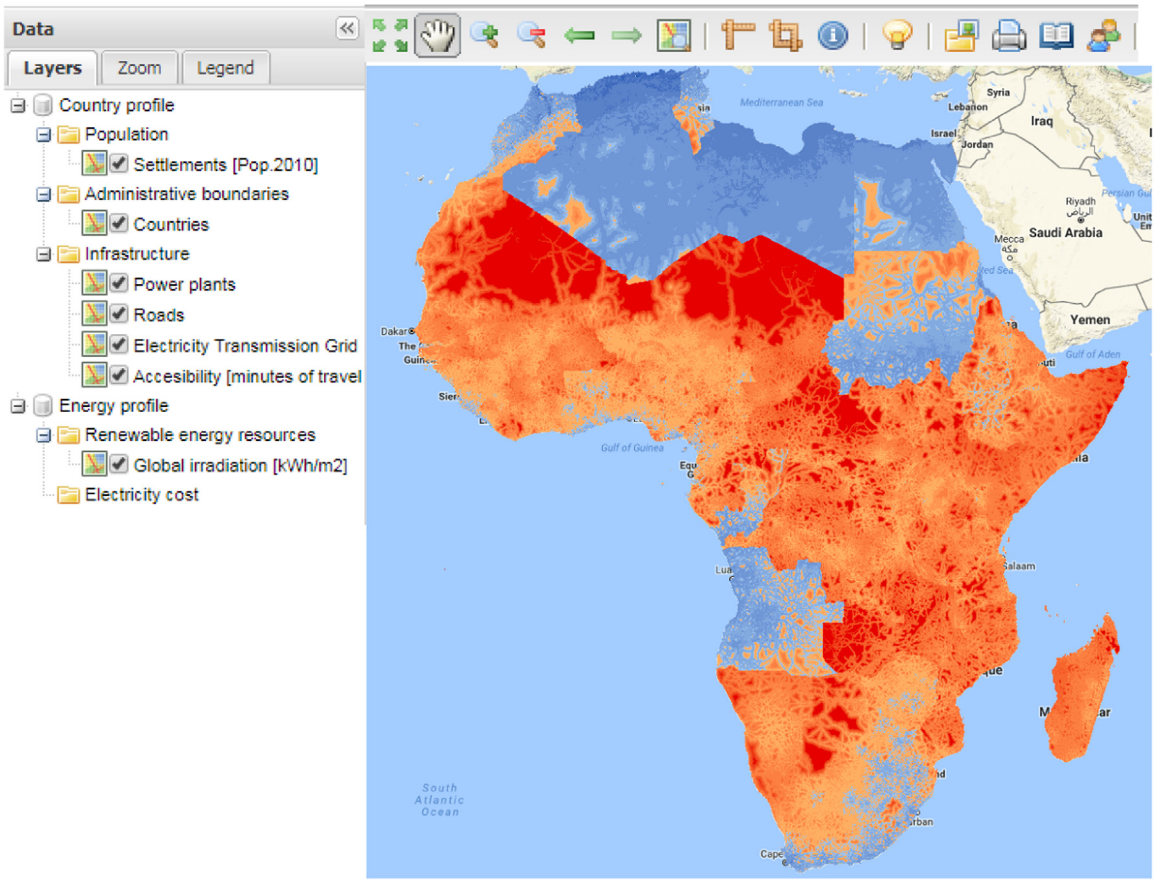

Fig. 18. RE2nAF snapshot of the geospatial interactive tool comparing of PV/hybrid mini-grid generation costs with diesel genset generation costs.

Table 6
Cost of field PV/hybrid mini-grids installation in Sub-Sahara Africa versus modelled cost, diesel genset cost and grid extension cost for selected locations.

Size of PV/hybrid mini-grid [kWp]	LCOE based on implemented PV/hybrid mini-grids [EUR/kWh]	LCOE implemented PV/ hybrid mini-grids[a] [EUR/kWh]	LCOE Generation Modelled[b] [EUR/kWh]	Diesel genset [EUR/kWh]	Grid extension [EUR/kWh]
27	0.41	0.34	0.22	0.53	0,38
30	0.33	0.21	0.20	0.88	0,77
40	0.30	0.18	0.20	1.07	0,88
43	0.22	0.16	0.20	0.47	0.43
49	0.25	0.21	0.25	0.32	0.14
312	0.25	0.25	0.25	0.31	0.13

Note: Discount factor used for modelled LCOE: 4%. Softcosts not included. Distribution not included. Genset generation included with diesel prices 2015 [75,76].
[a] Soft and distribution excluded.
[b] PV module costs assumed to 0.75 EUR/Wp.

model used at the continental level tool and additionally collected site specific cost component data to assess the cost (LCOE modelled) of the main *generation* components of mini-grid technologies in rural electrification projects (the softcosts are not included). The underlying assumption in the model is that the cost of the generation components is the main factor that determines the most competitive electricity option. Therefore, the rest of the local grid lines and the transaction costs were assumed uniform for all the rural electrification options; it did not take into account the costs of e.g. local (low or medium voltage) distribution lines – assuming that the grid is a competition neutral element that in many countries is provided by the national grid operator. To allow a direct comparison we compared with the LCOE deriving from the generation costs of implemented mini-grids (LCOE generation), that exclude software costs and distribution costs. The differences of LCOE modelled at continental level and the LCOE calculated with the implemented mini-grids range between 0% and 30%.

While the core analysis focused on the hardware costs, the collected cost components highlights the importance of soft costs on the LCOE. The soft costs were affected by conditions such as transport costs which also strongly depend on road infrastructure etc. Soft costs were affected by the local market maturity in complex ways (cost of labour, average duration of work phases, availability of local experts, payment modalities etc.) that is out of the scope of the model and the tool used. The general tendency of reduced soft costs over time and between the least and more developed market can still be clearly observed from the cost component data. The falling cost of PV modules and battery storage may bring even lower the PV/hybrid mini-grid costs allowing rural Africa to bypass the carbon-intensive technologies. The main reason for a successful implementation of mini-grids in rural Africa is not anymore a cost-effective reason but relies on robust institutional and regulatory framework [66] for rural electrification. A robust institutional and regulatory framework that would strengthen the market maturity of

any particular country and initiatives that support mitigating the higher risks of investments.

5. Conclusions

Project developers increasingly rely on remote data collections in order to explore new markets. In this remote data mining, existing GIS-based tools for energy data have become increasingly valuable. At the same time, site specific real data are important to validate the information contained in the GIS-based tools. The present study collects and presents such site specific data that serve multiple purposes. Such findings help calibrate existing tools in order to better serve the information request from investors, energy planners, and the policy makers, including:

- Quality of data
  - o Data derived from on-site experience for the installation of PV/hybrid mini-grid show a strong variability (range of costs) depending of the quality of the collected data.
  - o Data harmonization was processed including only successful implemented PV/hybrid mini-grids and excluding non-reliable data. These values have been analysed to assess the factors that influence (the most) the total costs and their variation.
- Breakdown of costs.
  - o The total installation costs of the PV/hybrid mini-grids in Africa (average 8.33 EUR/Wp) is high relative to the price of modules (0.83 EUR/Wp). Initial capital expenditure related to cost of components comprise approximately 14% of PV array (1.19 EUR/Wp) and 14% of BOS.
  - o Cost analyses is not unidimensional. It is crucial to use the correct dimension for each aggregated component group to better understand the cost contribution of each factor. This allows for more accurate analysis of the factors that influence the variation of the PV/hybrid mini-grid costs.
  - o The decline from year 2008 through year 2014 in installed PV/hybrid mini-grid prices is largely attributed to falling module prices and increase on the global market maturity. The fall in module prices represents roughly 80% of the drop in total hybrid PV/hybrid mini-grids prices for ≤ 100 kW over the same period (that is from 2008 to 2014). Dynamism in global module prices, however, is not linearly reflected into the overall PV/hybrid mini-grid price because there are many other aspects involved in mini grid design and construction.
  - o The current soft costs for PV/hybrid mini-grids have significant implications on both profitability and scalability for their implementation in the SSA market. The market maturity and existence of a clear institutional framework in any particular country can provide a significant opportunity to reduce total costs. For example, soft costs for ≤ 100 kWp mini-grids declined by approximately (2.5 EUR/Wp) from 2009 to 2015, constituting almost 40% of the reduction in total installed mini-grid costs over that period. In recent years, however costs of BOS and distribution lines have remained relatively constant while PV module prices fell rapidly, and as a result the respective share of non-module costs have grown significantly.
  - o Another key challenge is the rapid change of cost of PV modules and storage technologies. This is particularly challenging for researchers as their published studies become outdated in prices within a few months of publication.
  - o The distribution of installed prices across the 27 installed projects is wide (including IRENA projects published in [21]). For example, among ≤ 500 kWp mini-grids installed in Africa, roughly 20% of systems had an installed cost of less than 5 EUR/Wp, while a similar percentage (i.e. 20%) had an installed cost above 12 EUR/Wp. When proceeding to the data harmonization, the costs' distribution was narrowed by analysing PV/hybrid systems with high penetration of PV and high quality of services with an average total costs of 8.33 EUR/W_p.
  - o Total installed costs show significant economies of scale, with a median installed price of 9.5 EUR/Wp for PV/hybrid mini-grids < 50 kWp completed in 2013–2015 compared to 4.5 EUR/Wp for commercial systems > 150 kWp. In addition to the economies of scale from larger PV arrays there are other scale benefits of having a single monitoring room. Taken together these improvements can provide better service with higher energy service's quality and longer battery life [49].
  - o Installed prices vary widely across countries and it is recommended that a careful, detailed analysis be undertaken (especially as privacy restrictions does not allow the publishing of these data). The price disparity across countries is a possible reflection of a number of differences in country and local factors (e.g. market size and level of market maturity in each country, permitting requirements, competitiveness of the installer market, labour rates, tax exemptions, and incentive levels). Light handed regulation on mini-grids can boost innovation and drive soft costs down [64] while concurrently making it more attractive to project developers and mini-grid operators to operate in the country. A mature renewable energy market is more likely to have locally available trained staff and more local installers than a non-mature market. This directly decreases the soft costs related to labour and capacity building but also the hard costs as it is more probable to find replacement material locally. This buttress our position that PV/hybrid mini-grid costs cannot be compared on a per kW-peak solar capacity basis, without considering project and site-specific parameters such as the load profile and solar resource, level of service provided, regulatory framework and market maturity or site accessibility.
- Important aspects for decision-maker/private investor to select the site includes:
  - o Solar resources, optimal inclination and orientation, and variability of solar resources (important for battery sizing). All these criteria has been taken into account in our calculations by PVGIS [56].
  - o Community size and household distribution (whether highly dispersed or concentrated): more dispersed population requires higher investments in distribution network, monitoring and management (See Section 3.2).
  - o Location and accessibility: influences the transportation costs, logistics and cost of diesel fuel (See Section 3.3).
  - o Market maturity level: in general, total PV/hybrid mini-grid costs are lower when the PV market is more developed, and hence more competitive as well as availability of local expertise (i.e. capacity building aspect) (See Section 3.3). Cost reduction challenges occur at various different levels, from technical O&M and system management complexity to country's political security.
  - o Financial opportunities: a very crucial factor for the reducing the gap between current business models and on-site experience is to emphasise the important role of the 'sum-up' discount factor which in the case of Sub-Sahara African countries could reach unbearable values (e.g. in Kenya increasing from 6% of government discount factor to the final 19%).
  - o The private investors focus on the whole project cycle more completely than the grant type of investments as their longer term reputation is at stake. While there is a pool of information available on the development cost of grant financed projects, there is hardly any information available for their post development performance. The 2009 project of this study was already upgraded in 2014, so not only is it fully functioning, but it has even increased its PV generation and beneficiaries.
- Impacts.
  - o Although from an emissions perspective PV/hybrid mini-grids result in lower carbon emissions than fossil-fuel based generation,

the benefits of emissions savings associated with mini-grids are not reflected in its prices.
- o Besides the direct beneficiaries (Number of domestic, institutional and commercial users), the PV/hybrid mini-grids have an even larger number of indirect beneficiaries which is difficult to be quantified.

- Further developments for the rural electrification continental tool.
  - o Future work could build on this study by strengthening the integration of the effects of:
    - ▪ Policies that stimulate decentralised generation development and certainty of policy support. For example, the integration of the national/regional subsidies/tariffs for renewable energy technologies on the financial cash flows (which vary country by country).
    - ▪ Supporting regulatory and institutional framework (e.g. regulation, tendering, licensing and planning). Transaction costs depends on the legal and regulative framework for rural electrification.
    - ▪ Reporting and social factors (such as leadership, organisation, etc.) at community level.
    - ▪ The internal and external risks predictions on the total costs (for instance integrate a discount factor for each country depending on the national risks).
    - ▪ Socio-economic analysis: consumer attitudes and social acceptance. The load profile determines the configuration of the PV/Hybrid mini-grid. The energy consumption and social patterns (i.e. when and how much electricity is consumed) and distribution of population (highly dense versus highly dispersed population) can be incorporated and evaluated in a tool to be further developed.
  - o The costs in the continental tool are assessed for the main generation components of mini-grid technologies in rural electrification projects. Therefore, it did not take into account the costs of local (low or medium voltage) distribution lines – assuming that the grid is a competition neutral element that is provided by the national grid operator in most countries.
  - o In view of the existing gap between current business models and on-site experience, we provide suggestions for future research which are likely to be highly relevant in order to adequately inform public policy and private sector on distributed generation and its role in the future of the energy supply in rural Africa. Final prices should be integrated, taking into account the existing national subsidies for renewable energy technologies or national and regional distributed generation regulations and incorporated in a visual analysis.
- Leapfrogging in energy technologies

The great potential of renewable energy technologies as shown in this study demonstrate the immense opportunities for most SSA communities without modern energy access to technologically leapfrog to cleaner energy options. Primary enabler for such disruptive sustainability transition would be cost reduction of components and soft costs, reduction in the high risk of such investments, as well as better institutional and regulatory frameworks.

The improvement of the tool will help the international and public donor organisations to plan their interventions in a way to make projects more attractive to private investors (i.e. adding public finance part to the cost components that should be addressed by local authorities like permits, fee structure). This can also define thresholds for qualifying eligible project proposals, so the applications without realistic cost assumptions could be filtered out during the investment decision process. For private investors this could be useful in the project appraisal process to plan their investment costs on a more solid basis. There is still reduction for the implementation of PV/hybrid mini-grid costs to be achieved: in he latest years dynamic reduction of component costs engages to pursue for a reduction on the softcosts. This reduction would be only achievable with the support of a replicable model [40] that strengthen the maturity of the SSA market and decreases investment risks.

Disclaimer

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