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BENCHMARKING STUDY OF SOLAR PV MINI GRIDS INVESTMENT COSTS

PRELIMINARY RESULTS

ESMAP Mission

The Energy Sector Management Assistance Program (ESMAP) is a global knowledge and technical assistance program administered by the World Bank. It provides analytical and advisory services to low- and middle-income countries to increase their know-how and institutional capacity to achieve environmentally sustainable energy solutions for poverty reduction and economic growth. ESMAP is funded by Australia, Austria, Denmark, the European Commission, Finland, France, Germany, Iceland, Italy, Japan, Lithuania, Luxemburg, the Netherlands, Norway, The Rockefeller Foundation, Sweden, Switzerland, and the United Kingdom, as well as the World Bank.

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Energy Sector Management Assistance Program
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1 | INTRODUCTION

Solar photovoltaic (PV) minigrids are a reality. Several pilot projects have demonstrated over the last half decade that these solutions can be a reliable and competitive alternative to grid extension, and have opened the appetite of policy makers and planners to consider ambitious decentralized electrification programmes. However, any vision for a large-scale replication needs to be informed on the current state of minigrid costs, both in terms of cost per power supply capacity and cost per customer.

ESMAP, with the collaboration of Trama Tecnoambiental (TTA) is currently undertaking a PV minigrid costing study with the aim **to provide a benchmark of the on-site (upfront costs only, including hard costs and logistics) of already commissioned PV only or PV-diesel hybrid mini-grids in the African and Asian contexts, that have a proven track record of operation, to enable the pinpointing of opportunities for cost reduction in future projects.**

The cost assessment of any infrastructure needs to adapt to the nature of such infrastructure, most especially if one of the aims of the assessment is to understand where costs are incurred, where they can realistically be managed or reduced and where subsidies could be considered if needed or desired due to the electrification benefits that may accrue.

A first technical standardization of micro-grids was developed by Task 11 of the International Energy Agency PVPS, based on the recommendations of the International Electrotechnical Commission IEC 62257 TS series.[1]

In the case of mini-grids for electricity supply, there are several functions (or subsystems) to consider:

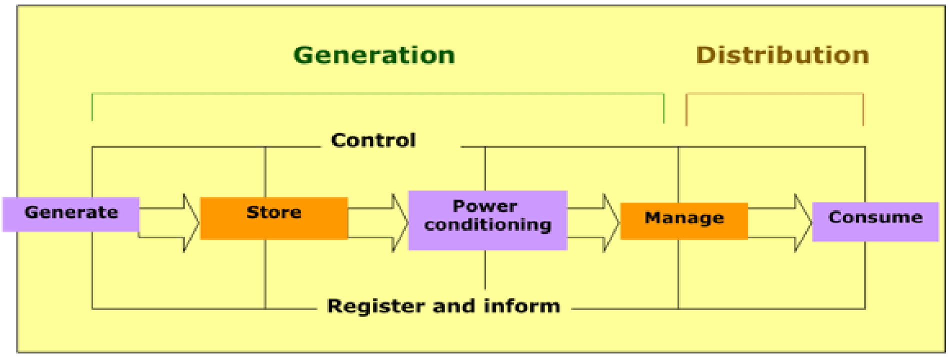


Figure 1: Typical functions in a decentralized electricity delivery scheme

Figure 1 above separates those functions related to generation from those associated with distribution. As was the case with the site characterization, the micro-grid (or mini-grid) business model assumed in the reference cases is a decentralized (or stand-alone or off-grid) system that combines a generation micro-plant feeding a distribution micro-grid that supplies end-users. This covers both the conventional "concession" model and the small "energy cluster" models seen in Africa and Asia.

Depending on the type of electrical coupling (DC or AC) between PV panels generation and storage, there are two main types of minigrid generation subsystem configuration, as shown in Figures 2 and 3.

[1] P Jacquin 2011 - Social, Economic and Organizational Framework for Sustainable Operation of PV Hybrid Systems within Mini-Grids – IEA PVPS Task 11

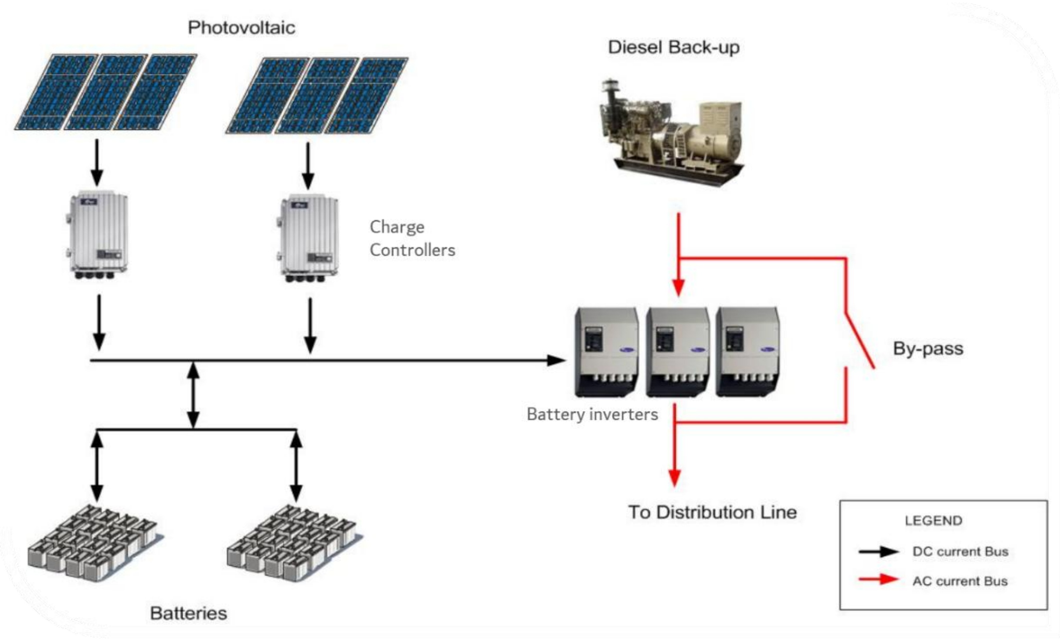


Figure 2. Typical DC coupling architecture in a PV-hybrid minigrid

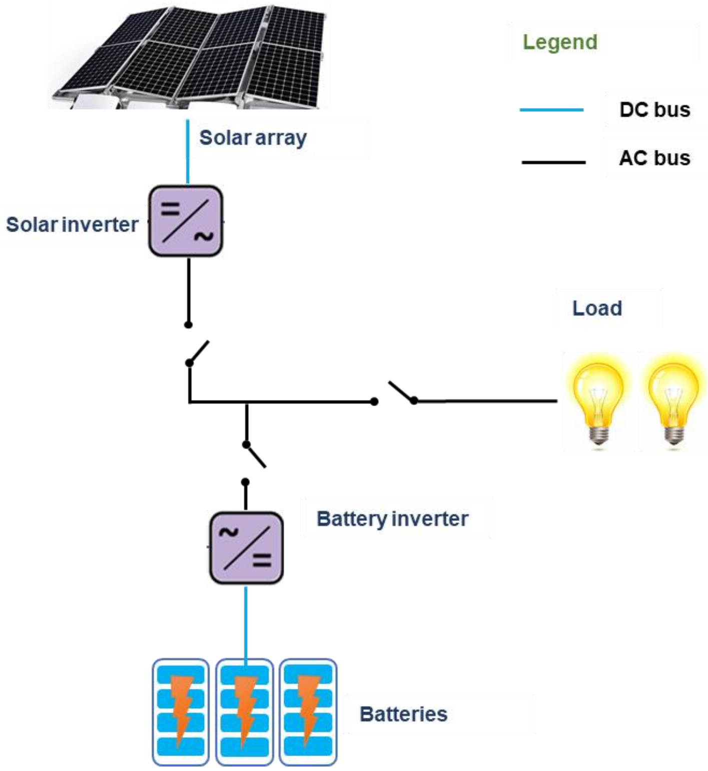


Figure 3. Typical AC coupling architecture in a PV-hybrid minigrid

2 | PV MINIGRIDS COST CATEGORY COMPONENTS

2.1 HARD COST CATEGORY COMPONENTS

Based on the typical functions of a mini-grid as presented in the previous section, this study has investigated the following set of Equipment and Supplies cost categories. Each category includes several cost items and their corresponding unit indicator, listed in the table below:

Table 1 Solar Minigrid Equipment and Supplies HARD Cost categories

Hard cost Category	Unit
1 Generation	
PV modules (including spare parts)	kWp
PV modules Structure	kWp
Charge regulators (MPPT) and protections – DC coupling or Solar Inverter (MPPT) and protection – AC coupling	kWp
2 Storage and powerhouse	
Lead acid (incl. cells, cabling, protection)	kWh
Lithium ion (incl. cells, cabling, protection)	kWh
Monitoring and control system	unit
Powerhouse (building, cabinet, container, incl. fence)	m^2
3 Conversion	
Battery inverter incl. cabling	kVA
EMS Energy Management System	unit
Backup Diesel generator	kVA
4 Distribution and Consumption	
LV grid (incl. poles, cabling and protections)	km
LV distribution poles	km
Street lighting (if applicable)	n. customers or km
Smart meters and service connections	n. customers
5. Customer systems (without installation)	
End user indoor wiring (cabling, sockets and protections) (if applicable)	n. customers
End user appliances (if applicable)	n. customers

The criteria that guided the selection of the above items have been (i) enabling analysis at pre-feasibility and feasibility levels, and (ii) coherence with IFC, GIZ, other donor and available private sector cost breakdown in the feasibility studies, financial models and on-going minigrid projects developed by TTA.

2.2 SOFT COST CATEGORY COMPONENTS

Mini grid soft costs have also been investigated in order to complement the equipment and supplies cost and therefore approach the overall on-site Capital costs in real, operating PV minigrids.

Project development and Logistics are more likely to be region or country specific (e.g. the maturity of PV and minigrid industry in a given country), or even site specific (e.g. the remoteness of an off grid community, like an island, will largely condition the logistics costs). From this point of view, it is not a straightforward issue to select a benchmark unit for these cost categories; this study provides some analysis in this sense. The soft cost categories and corresponding costing unit are:

Table 2 Solar Minigrid Equipment and Supplies SOFT Cost categories

Soft cost Category	Unit
6. Project development	
Management and engineering	% overall hard costs or kW (AC service)
Capacity building and training (of local operators)	
7. Logistics	
International shipping costs (maritime), incl. customs	% overall hard costs or kW (AC service)
Local transportation costs (road)	
Storage of equipment	% overall hard costs or kW (AC service)
Insurance	

Installation costs have also been investigated, as a separate category.

2.3 Level of electricity service supply

Previous studies[2] have shown the relevance of considering costs per customer as well as costs per component unit when assessing the affordability of electricity services from mini-grids. This is because average kWh costs are useful to compare solutions for one application but for different systems in different locations and small demands, transaction costs, local management, etc., may represent a higher fraction of service costs.

At the same time, current energy development visions, such as the UN Sustainable Energy for All, or the Sustainable Development Goals[3] (specifically, SDG 7 “Ensure access to affordable, reliable, sustainable and modern energy for all”) are promoting the practitioner’s debate towards the issue of which levels of access to energy are sufficient to enable residential energy needs as well as to deploy productive uses of energy (commercial, or even industrial).

In rural electrification, ideally, the optimal minigrid would be the one offering the highest level of electricity supply (quantity of electricity served) to customers from the lowest CAPEX possible, bearing in mind that minigrids can offer several levels of supply according to different tariff or service schemes. This study follows the demand segmentation pattern shown in Table 3 has been followed, in order to define reference electricity consumption tiers applicable to all the minigrid cases analysed. This pattern is adapted from the reports Energy Access multitier framework (ESMAP, 2015) and on Quality Assurance for MiniGrids (NREL, 2016), as well as the analysis of TTA database of PV mingrids built since 1998.

The CAPEX per customer is then assessed for each tier, so that a more precise comparison can be done between minigrids that are supplying different levels of service, regardless the number of customers they are serving.

[2] Arranz-Piera P., Vallvé X., González S., Cost effectiveness of PV hybrid village power systems vs. conventional solutions. 3rd European Conference PV-hybrid and mini-grid, 11-12 May 2006 Aix en Provence, France.
[3] http://www.un.org/sustainabledevelopment/energy/

Table 3 Demand segmentation (energy consumption)

Tier 1 - Residential basic (<8kWh/month)
Tier 2 - Residential med (<20kWh/month)
Tier 3 - Residential high (<50kWh/month)
Tier 4 - Productive (<110kWh/month)
Anchor load(s) (110kWh/month and above)

In order to calculate the CAPEX per customer, the Generation costs (cost categories 1-2-3-5-6-7 in Table 1) have been prorated by Tier consumption level, while the Distribution costs (category 4 in Table 1) evenly considered per customer.

3 | PV MINIGRID CASES ASSESSED

The hard cost benchmark study has been based on a selection of currently operational solar mini grid case studies in Africa and Asia, delivering electricity service in the following conditions:

- Service availability 24hour / 7days a week
- Low voltage distribution
- Solar generation as the primary source (minimum solar fraction 60%)

During the period March to November 2017, over 50 minigrid project developers and practitioners in the minigrid space were contacted, in order to identify suitable PV minigrid cases for the Costing analysis that this work pursues. Until October 2017, 16 cases of solar minigrids have been received and completed, after a series of iterations and interviews by the TTA research team and the relevant minigrid developers. All of them started operating within the last 4 years.

Figure 4. Solar PV minigrid cases (16) assessed in the CAPEX benchmarking study

Table 4 Solar Minigrid cases studied

Site, Country	Continent	Operating since	n. Customers	Power (AC) output kW	Service	Solar fraction	Management Model
Manikgonj, Bangladesh	Asia	2017	1099	228	24/7	87,5%	Private utility
Mombou, Chad	Africa	2014	133	40	24/7	100%	Community
Volta Lake, Ghana	Africa	2015	157	50	24/7	93%	Public utility
Talek, Narok, Kenya	Africa	2015	120	40	24/7	94%	Public utility
Tanzania	Africa	2016	63	30	24/7	100%	Private utility
Kutubdia, Bangladesh	Asia	2014	360	100	18/7	85%	Private utility
Tunga Jika, Nigeria	Africa	2017	290	100	24/7	100%	Private utility
Lengbamah, Lofa, Liberia	Africa	2017	156	23	24/7	100%	Private utility
Segbwema, Kailahun, Sierra Leone	Africa	2016	204	128	16-18/7	100%	Private utility
Samfya, Luapula, Zambia	Africa	2014	480	60	24/7	100%	Public utility
Laithway, Myanmar	Asia	2016	130	10	24/7	100%	Public utility
Bihar, India	Asia	2017	95	30	24/7	90%	Private utility
Kakpin, Ivory Coast	Africa	2016	150	36	24/7	100%	Community
Dubung, Tanahun, Nepal	Asia	2015	112	20,4	24/7	100%	PPP-(Private utility)
West Bank, Palestine	Asia	2016	39	29	24/7	100%	Community
Bambadinca, Guinea Bissau	Africa	2015	1421	200	24/7	98%	Community

Table 4 shows the variety of cases analysed, 10 in Africa and 6 in Asia; the power output capacity ranging from 10 to 228 kW, and customers per minigrid ranging from 39 to 1421. In terms of the Management model applied, half of the minigrid cases are being operated by private utilities or PPPs, while the other cases are run by public utilities (4 out of 16), and community organizations (4 out of 16).

4 | OVERALL CAPEX AND CAPEX PER KW

The first result that arises from the minigrid cases analysis is the overall CAPEX; Installation costs are deemed to be very site specific (even inside one same country or state), and they have been disaggregated form the equipment and supplies costs.

Table 5. Overall CAPEX for each PV Minigrid case

Site, Country	In operation since	Power (AC) output kW	Greenfield or Brownfield	CAPEX without Installation USD	CAPEX with Installation Cost USD
Manikgonj, Bangladesh	2017	228	Green	1.050.500	1.090.211
Mombou, Chad	2014	40	Green	276.703	296.529
Volta Lake, Ghana	2015	50	Green	339.111	364.922
Talek, Narok, Kenya	2015	40	Green	293.919	304.409
Tanzania	2016	30	Green	242.256	265.312
Kutubdia, Bangladesh	2014	100	Green	762.238	973.177
Tunga Jika, Nigeria	2017	100	Green	582.298	639.212
Lengbamah, Lofa, Liberia	2017	23	Green	132.434	151.969
Segbwema, Kailahun, Sierra Leone	2016	128	Brown	367.051	400.703
Samfya, Luapula, Zambia	2014	60	Green	551.017	602.757
Laithway, Myanmar	2016	10	Green	85.049	88.591
Bihar, India	2017	30	Green	88.592	96.214
Kakpin, Ivory Coast	2016	36	Green	352.991	385.081
Dubung, Tanahun, Nepal	2015	20,4	Green	144.961	154.166
West Bank, Palestine	2016	29	Brown	157.577	169.524
Bambadinca, Guinea Bissau	2015	200	Green	2.374.954	3.262.754

In order to start a cross comparison of minigrid cases, the CAPEX per power capacity is a first benchmark to be assessed. Figure 5 shows the overall CAPEX per kW, ranging from nearly 12 USD/W to 3USD/W. Potential correlations in terms of minigrid size, number of customers, geographical location, type of management model, project scale, minigrid market maturity and level of service per customer are further investigated in this study, in order to understand the drivers for such a wide range in the CAPEX per kW data.

One first appreciation from Figure 5 is that there are no substantial differences due to the Continent variable; a similar range of values is observed in Asia and in Africa, with the exception of the highest CAPEX per kW score, being roughly 11.8 USD/W in Africa and 8.5 USD/W in Asia.

Figure 6 shows the CAPEX per kW registered in a set of 24 additional cases characterised by ESMAP in Bangladesh and Myanmar, all of them developed in the last 2 years. For the Bangladesh cases (16 PV minigrids, ranging from 100 to 250 kWp), CAPEX per kW levels are found to be between 3.2 and 10.9 USD/W, while in Myanmar (8 PV minigrids, ranging from 17 to 120 kWp), CAPEX per kW are between 2.8 to 6 USD/W, except for one case (1.9USD/W) where the service per customer is very basic. These results are pretty much in line with the Asian cases presented in Figure 5.

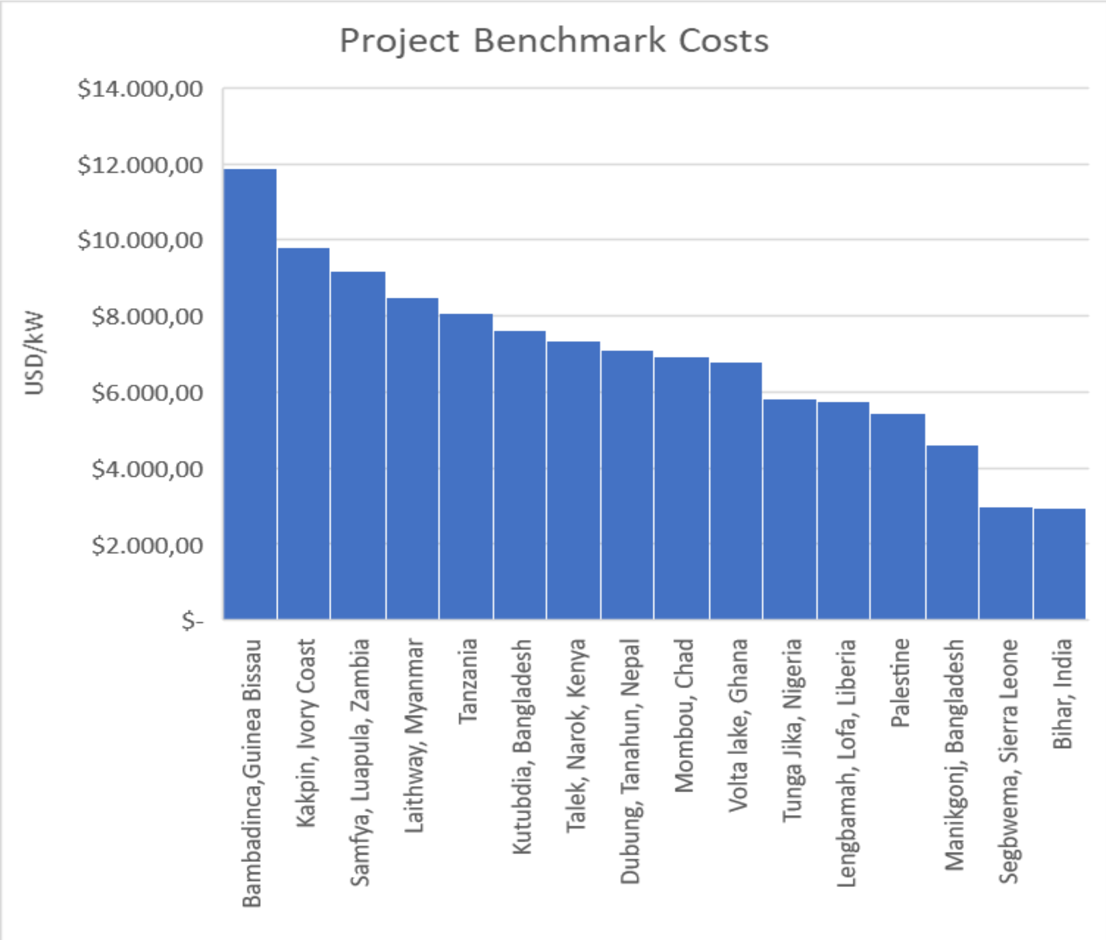


Figure 5. Overall CAPEX per kW (without installation) for each minigrid case study

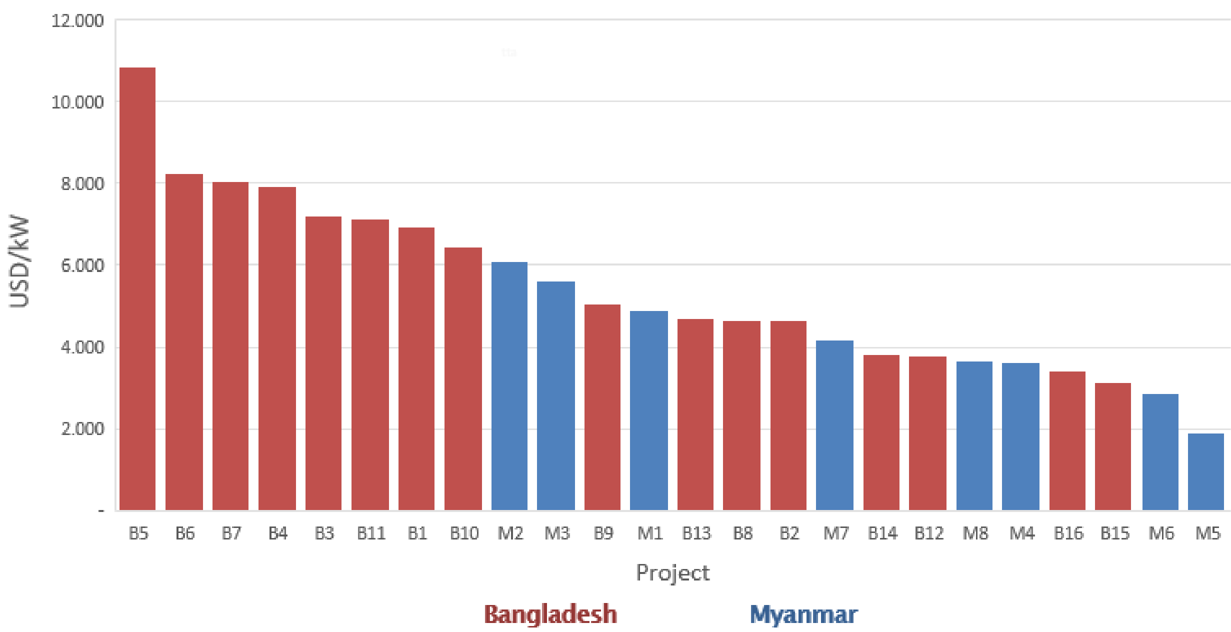


Figure 6. Overall CAPEX per kW (without installation) for additional minigrid cases *(source: ESMAP)*

Results suggest that there is no direct correlation between the number of connections and the overall CAPEX per kW (Figure 7), i.e. it cannot be inferred that the more connected customers a minigrid will have, the lower CAPEX it will incur. Such effect is, in part, explained by the lack of direct correlation between the number of customers and the minigrid power output, due to the differences in the levels of service that each customer has contracted. This is an argument that flags the need for a tiered approach to the CAPEX per customer benchmarks mentioned in section 2.6.

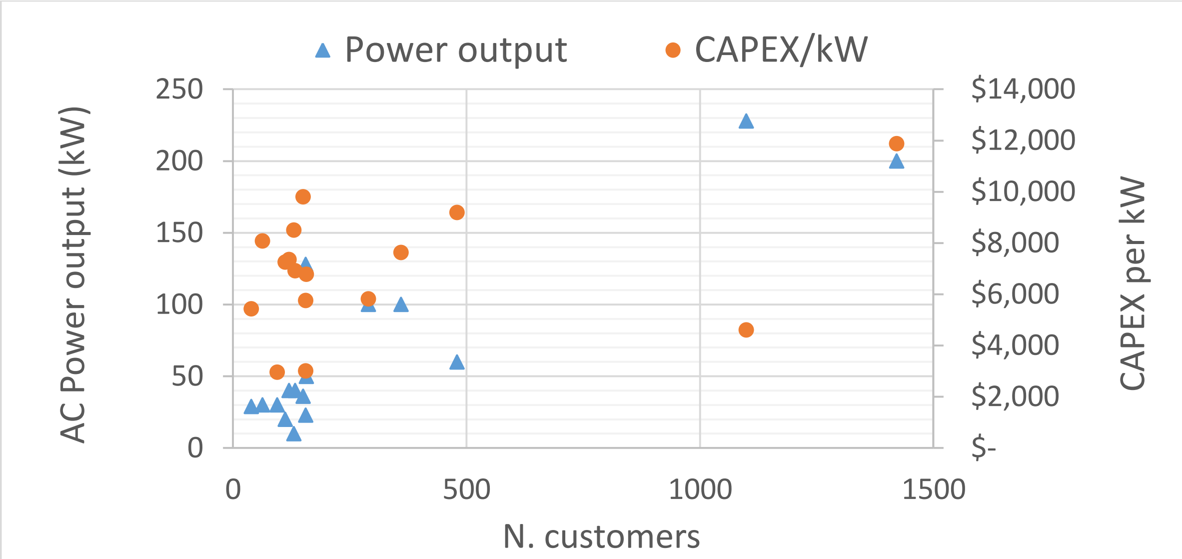


Figure 7. Number of customers vs power output and CAPEX (minigrid capacity range of 10 to 250 kW).

The influence of the electricity service management (or business) model is explored below. It can be noted that minigrids developed and operated under private utility service schemes have relatively lower CAPEX per kW, throughout the whole capacity range spectrum.

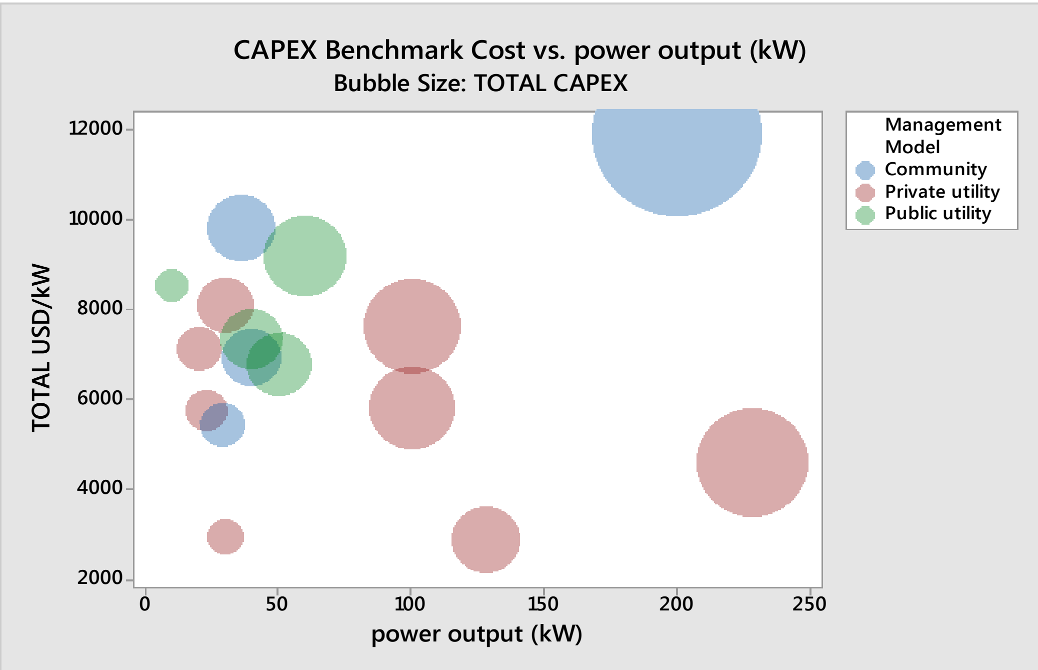


Figure 8. Overall CAPEX per kW (without installation) and by electricity service management model.

Another factor influencing the overall costs is the project scale (or minigrid market maturity), by looking at whether the minigrid cases were developed as a single project, or as part of a multi-minigrid programme. In Figure 9 below, Multi S (small) stands for programmes involving up to 5 minigrids, and multi L (large) stands for programmes involving more than 6 minigrids.

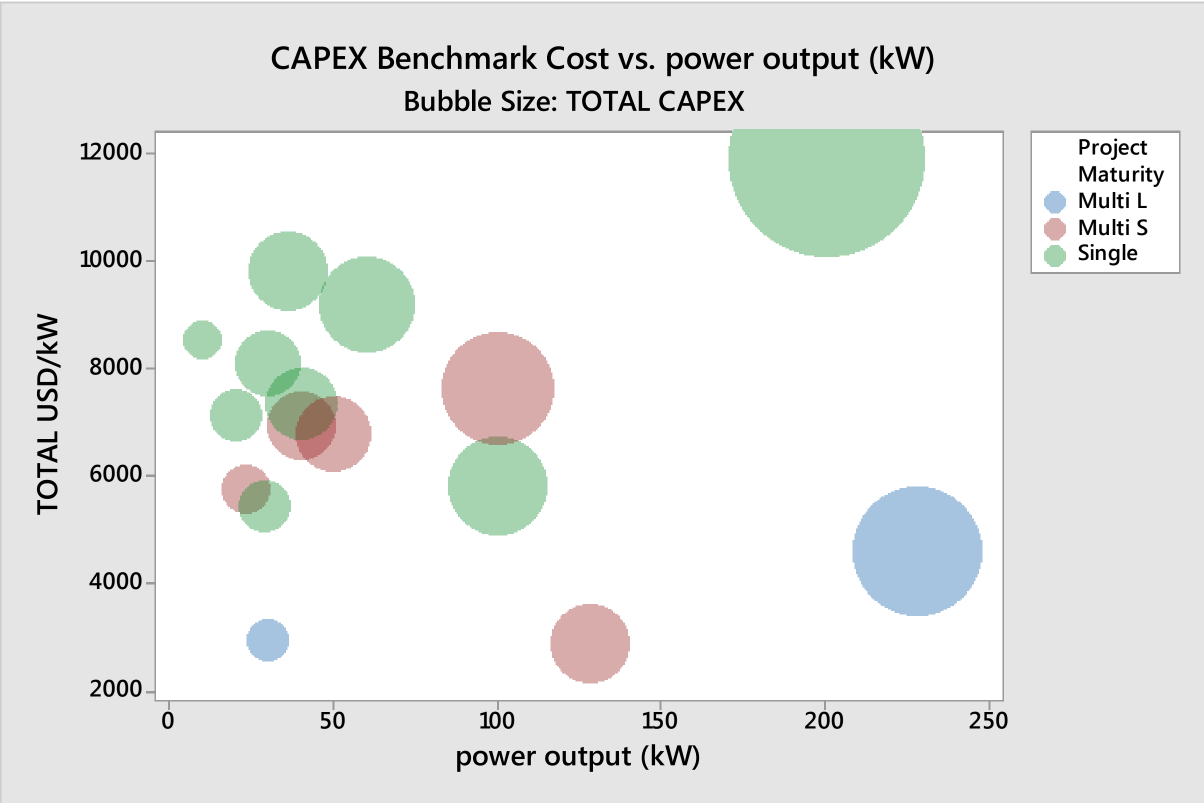


Figure 9. Overall CAPEX per kW (without installation) and by type of project

A clear trend can be observed here, with multi-minigrid cases registering lower CAPEX than single minigrid projects. 20% to 70% reductions on CAPEX per kW can be achieved if multi-minigrid programmes are promoted.

5 | CAPEX BREAKDOWN BY COST CATEGORY

The relative weight of each CAPEX cost category (see sections 2.2 and 2.3) for each case study is presented in the figure below.

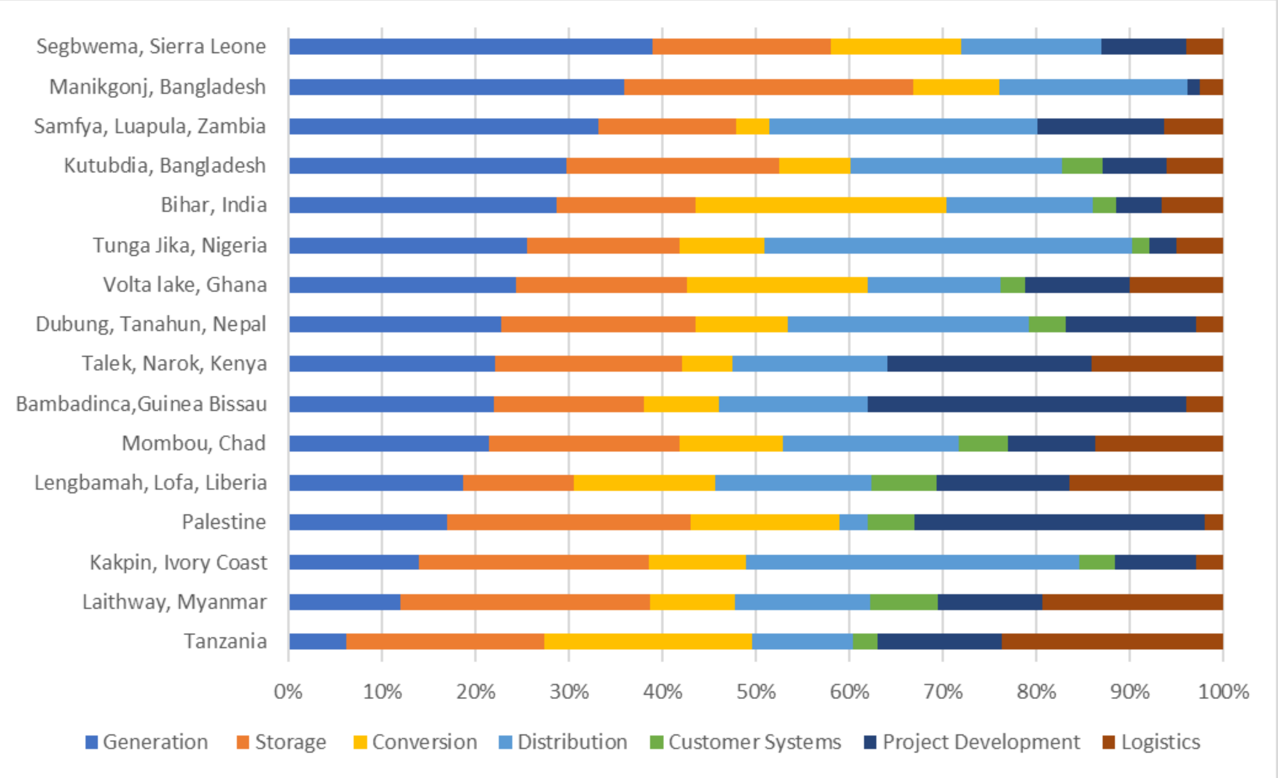


Figure 10. PV Minigrid CAPEX breakdown (%) into Cost categories

The CAPEX per cost category weight differs significantly from case to case, but figure 11 shows the median values of each main component category contribution to the overall CAPEX:

Generation: 23%

Storage and Powerhouse: 20%

Conversion: 10%

Distribution: 17%

Customer Systems: 3%

Project Development: 11%

Logistics: 6%

Figure 12 presents the Cost benchmarks (median values, CAPEX per characteristing sizing Unit) of each category.

Generation: 1485 USD/kWp

Storage and Powerhouse: 220 USD/kWh

Conversion: 844 USD/KVA

Distribution: 331 USD/customer (or 14980 USD/km)

Customer Systems: 47 USD/customer

Project Development: 832 USD/kW

Logistics: 470 USD/kW

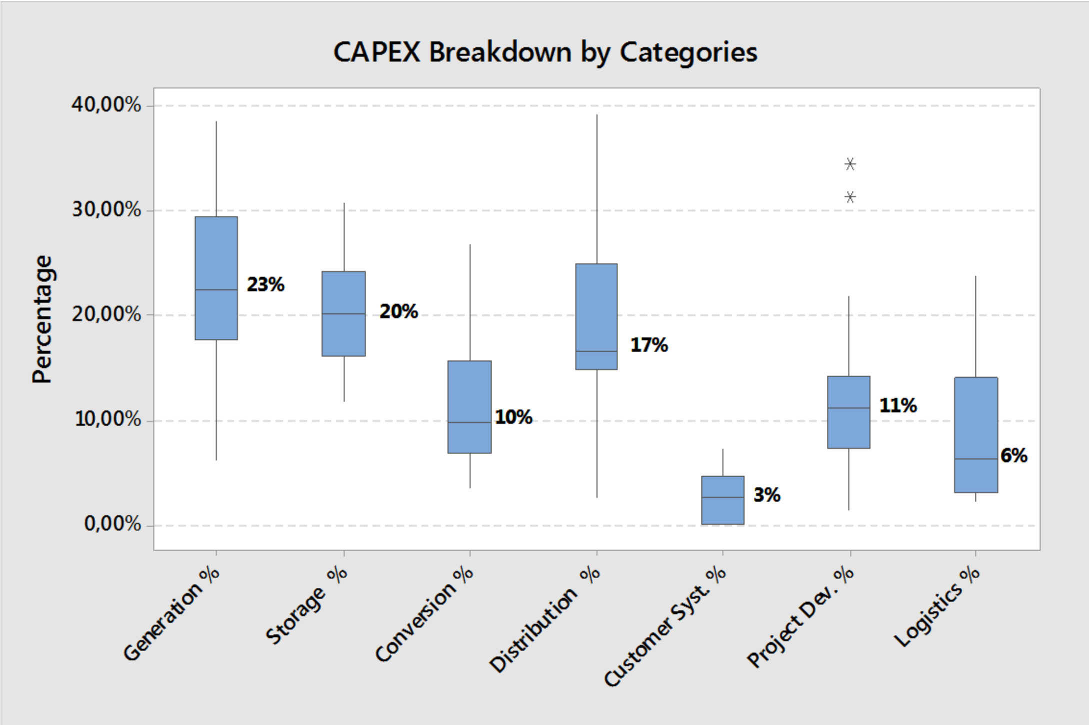


Figure 11. Median values of the CAPEX Cost categories breakdown (sample size: 16 PV minigrids)

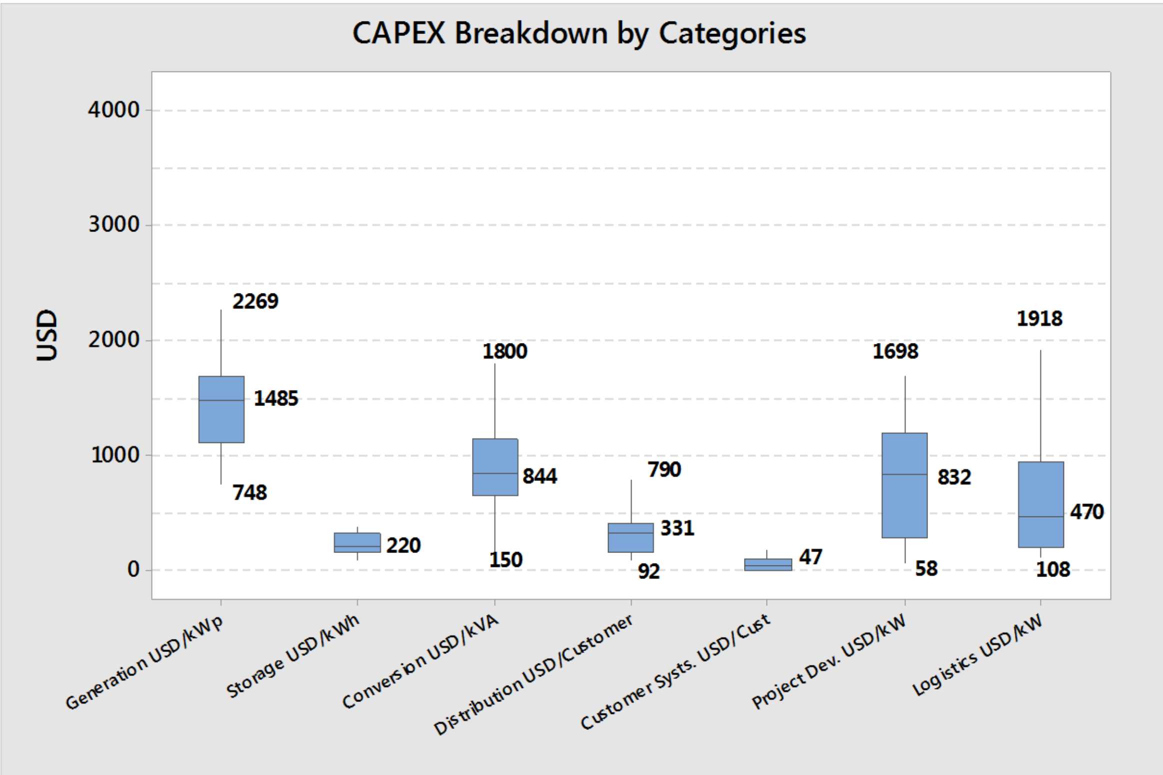


Figure 12. PV minigrid functional category CAPEX median values (sample size: 16 PV minigrids)

An aspect that clearly influences the Project development costs is whether the PV minigrid has been built as a single project, or as part of a multi-project programme. Multi S (small) stands for programmes involving up to 5 minigrids, and multi L (large) stands for programmes involving more than 10 minigrids.

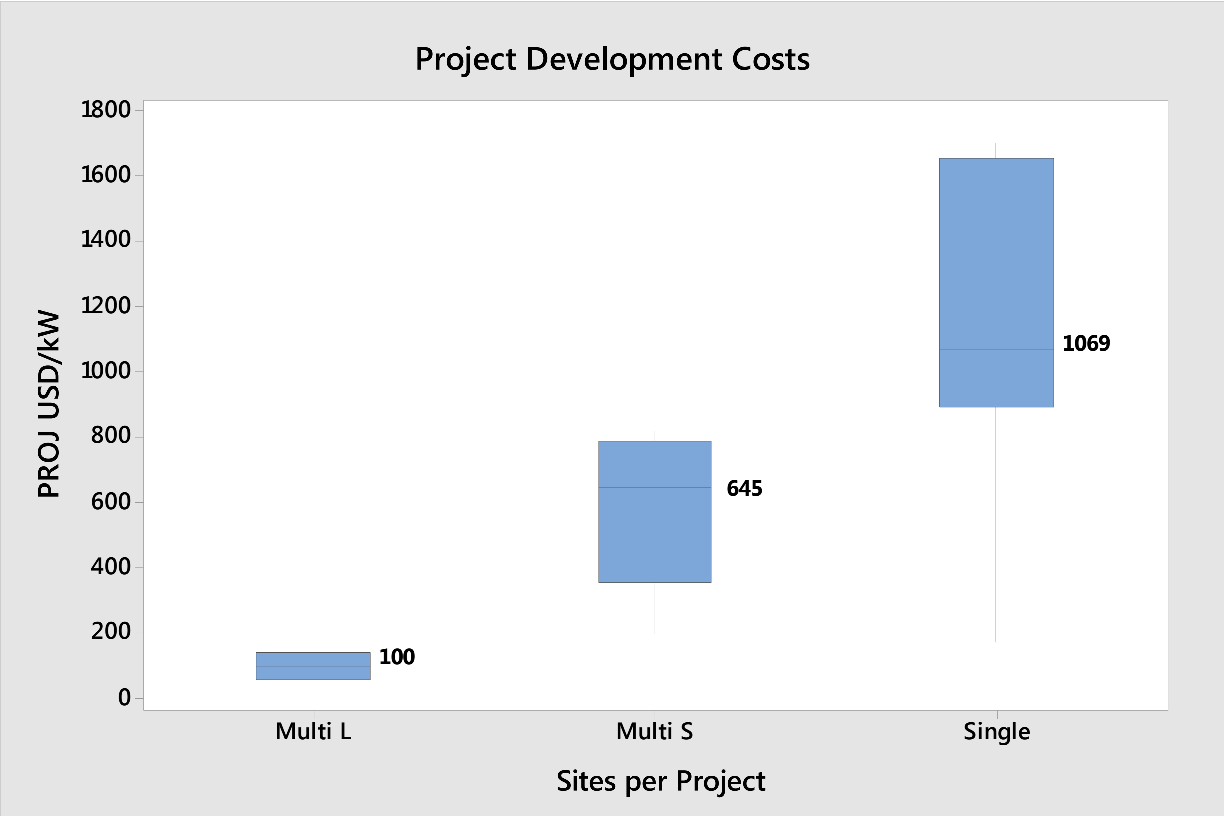


Figure 13. Minigrid project development costs are clearly influences by project multi project scale.

6 | CAPEX BREAKDOWN BY EQUIPMENT

The analysis of specific equipment costs is also interesting in order to approach potential spaces for Cost reduction in PV minigrid deployment. Table 6 shows the main equipment sizing at each of the assessed minigrids.

Figure 14 shows the relative weight of the main equipment costs in the overall CAPEX of the minigrids assessed, and reveals that batteries have nowadays the biggest impact, followed by PV panels, Inverters and the distribution grid cabling. Distribution costs can vary significantly from case to case (widest data range in Figure 14).

Figure 15 presents the Costs per characteristic unit of each equipment.

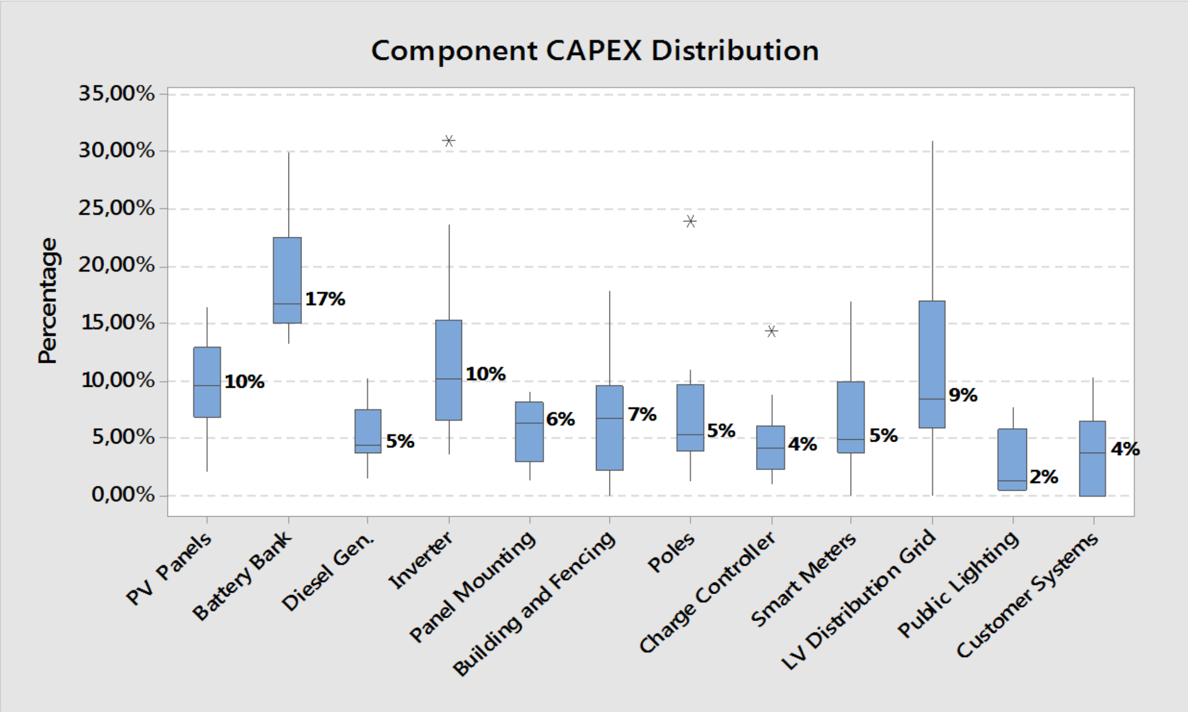


Figure 14. Selection of PV minigrid equipment cost weight

Table 6. Sizing parameters per Subcomponent (sample size: 16 minigrids)

Mini grid project	Customers	Distribution lines km	PV size kWp	Batteries kWh	Inverter KVA	Genset KVA	Powerhouse area m2
Palestine	39	5,0	19	168	29	0	75,0
Tanzania	63	4,4	16	61	30	13	15,0
Bihar, India	95	2,0	34	86	18	25	N/A
Dubung, Tanahun, Nepal	112	3,0	18	115	25,5	0	35,4
Talek, Narok, Kenya	120	3,0	40	154	24	13	50,0
Laithway, Myanmar	130	4,5	9	87	7	6	N/A
Mombou, Chad	133	3,5	40	430	36	50	56,0
Kakpin, Ivory Coast	150	3,5	39	360	45	45	240,0
Lengbamah, Lofa, Liberia	156	0,8	23	181	24	33	52,0
Segbwema, Kailahun, Sierra Leone	156	5,5	128	488	144	0	28,8
Volta lake, Ghana	157	2,7	54	407	48	33	60,0
Tunga Jika, Nigeria	290	8,8	100	350	54	0	35,7
Kutubdia, Bangladesh	360	4,0	100	517	90	60	280,0
Samfya, Luapula, Zambia	480	12,0	60	936	60	0	N/A
Manikgonj, Bangladesh	1099	14,0	228	887	144	150	394,0
Bambadinca, Guinea Bissau	1421	13,3	312	1987	135	240	75,0

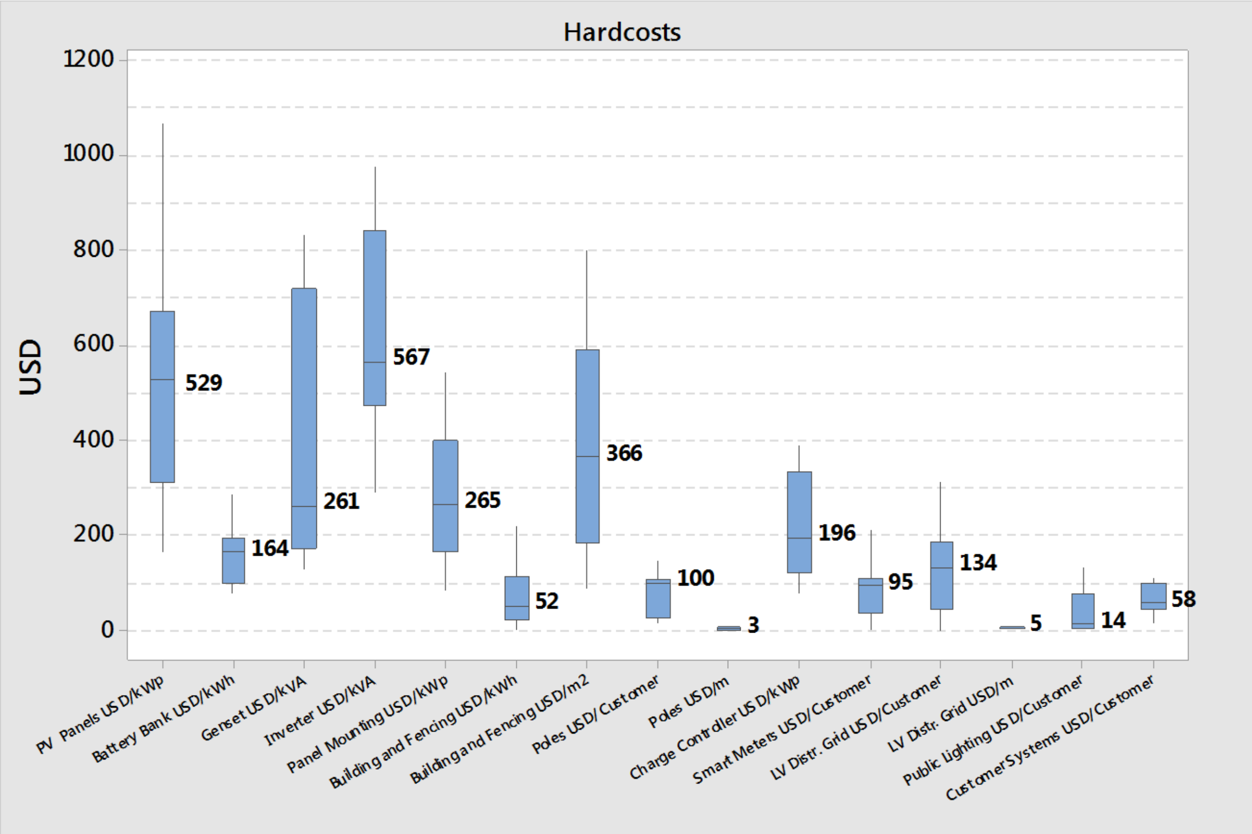


Figure 15. Selection of PV minigrid equipment benchmark costs

Regarding the main equipment in PV hybrid minigrids, Figure 15 shows that there is a wide range in the Costs of PV panels (from 180 to 1060 USD/kWp) and Inverters (from 300 to 990 USD/KVA), as well as in Powehouse building or Fencing (from 100 to 800 USD/m2) and Gensets (130 to 850 USD/KVA). Hence, a first observation can be that there is scope for minigrid projects to reduce these component costs and reach similar values to the best benchmarks found in this study, which are the minigrids developed in areas or countries with higher maturity and that are promoting multi-minigrid development to seek scalability.

The cost of batteries is less variable from case to case, with a range of Cost between 100 to 300 USD/kWh. It must be noted that the majority of minigrids assessed have installed Lead-acid battery banks, with only one reported case of Lithium ion.

These figures can be compared to published references on equipment cost trends and projections; however, the source and potential interests of such references (whether it is manufacturing industry, pro or against renewable energy or fossil fuel think tanks, etc.) shall be observed.

7 | COST PER CUSTOMER (TIERED APPROACH)

The demand segmentation per tiers reveals the wide variety of customer patterns found within the PV minigrid cases analysed; from minigrids with an identical (flat) basic level of service per customer (cases in Myanmar and Zambia, where all customers consume below 8kWh/month), to minigrids where most customers consume in the high end tiers (large residential and commercial or productive customers, like the cases of Palestine and Bangladesh). In the majority of cases (11 out of 16), customers are distributed within 3 or 4 different tiers.

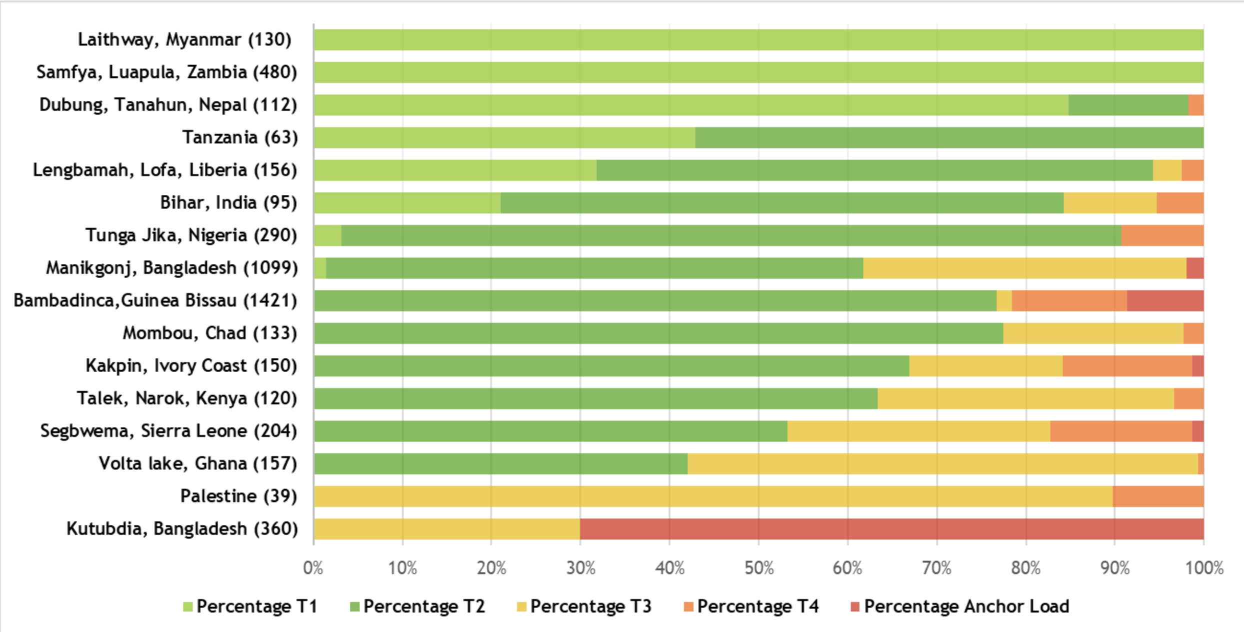


Figure 16. Customer distribution per tiers; n. of customers in brackets (sample size: 16 minigrids)

The CAPEX per customer Tier levels found are shown in the table below and in Figures 17-18, following the methodology presented in Table 3.

	USD Per Customer T1	USD Per Customer T2	USD Per Customer T3	USD Per Customer T4	USD Per Customer Anchor
MIN	$288	$484	$559	$2.597	$1.215
MEDIAN	$742	$1.273	$2.516	$5.277	$5.492
MAX	$1.892	$3.080	$4.845	$8.279	$38.427

CAPEX per Tier 1 or Tier 2 can be compared to Solar Home Systems (SHS) costs, since these residential systems typically provide up to 20kWh/month of electricity per unit; however, SHS normally provide DC service, and therefore a proper comparison with the above cost references shall consider SHS providing AC service (i.e., including a small inverter).

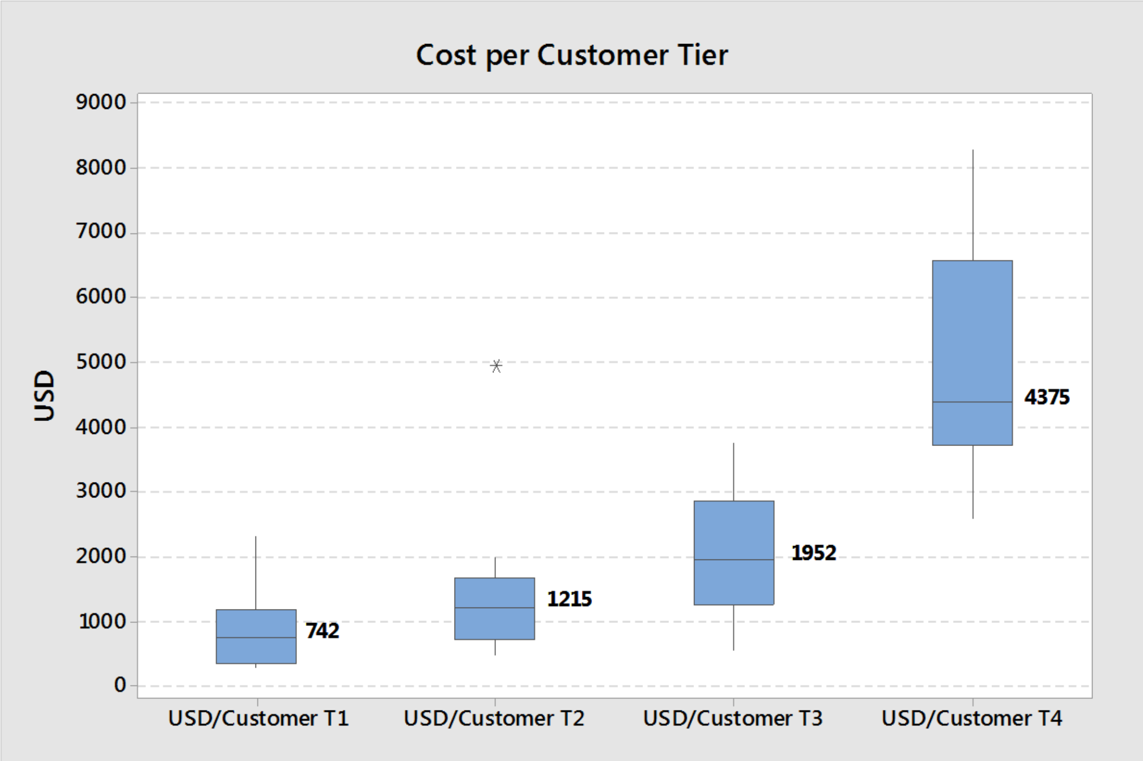


Figure 17. PV minigrid CAPEX per customer (sample size: 16 PV minigrids)

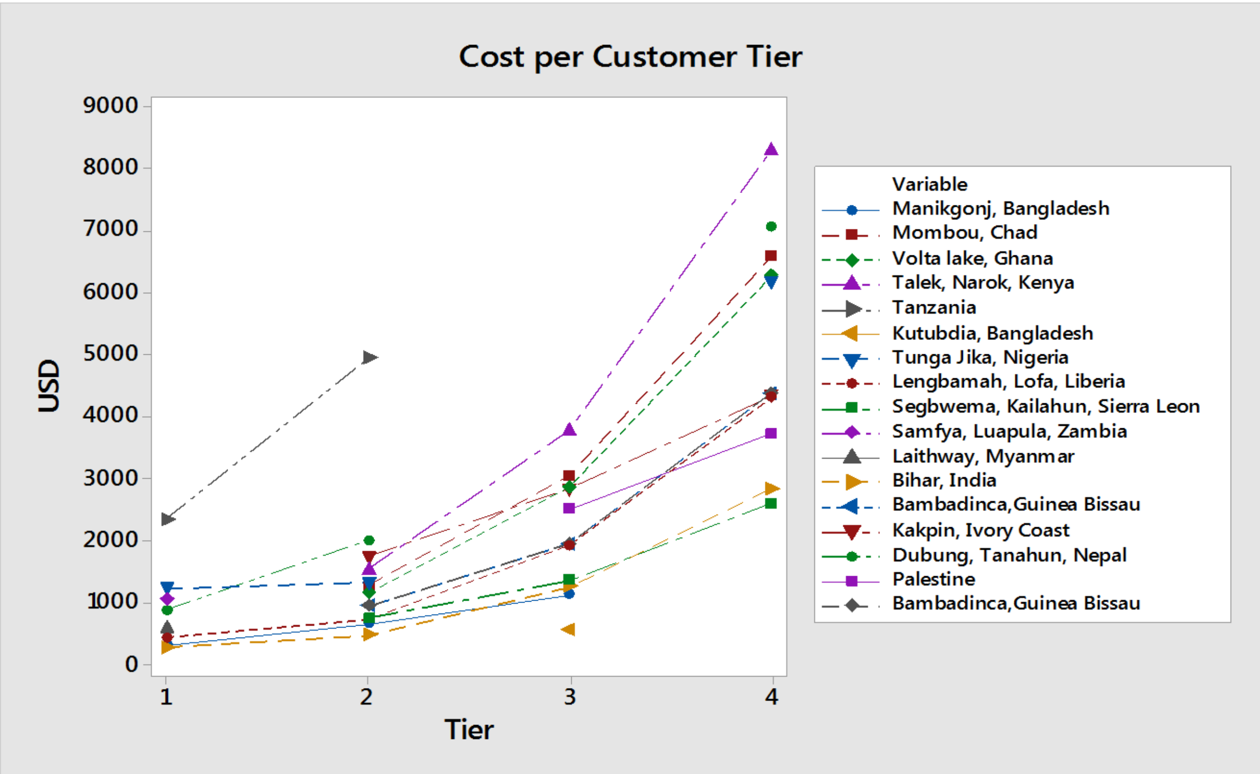
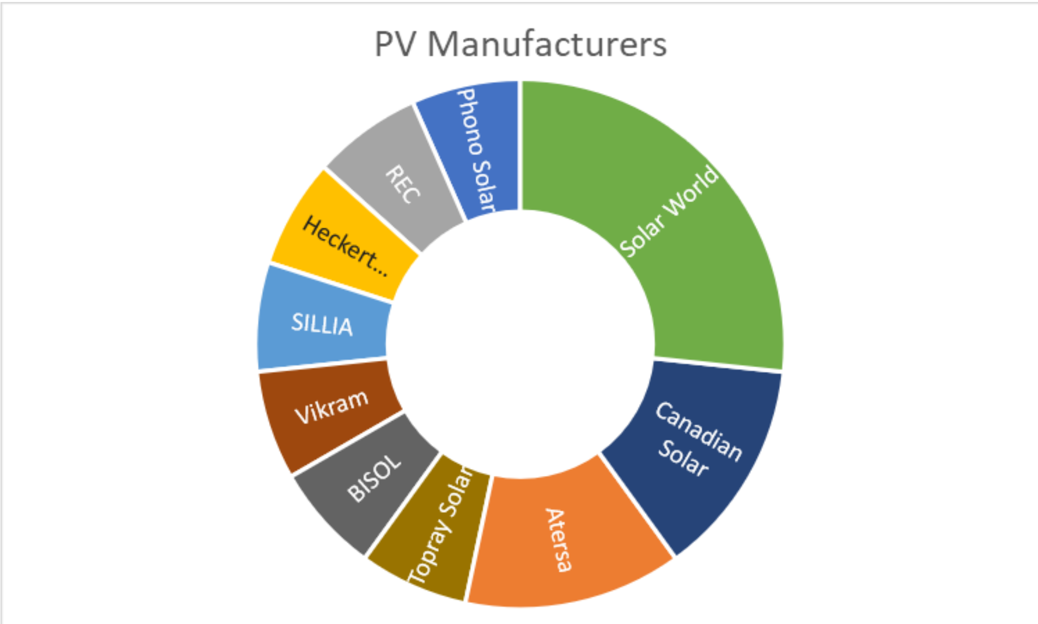


Figure 18. PV minigrid CAPEX per customer in each case study (sample size: 16 PV minigrids)

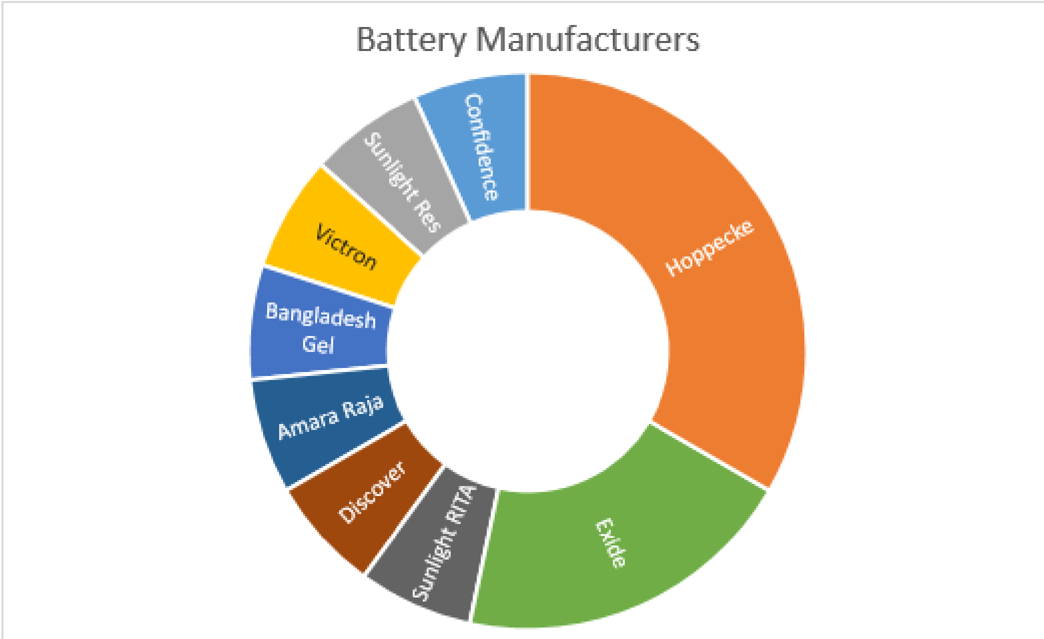
8 | EQUIPMENT SUPPLIERS

The following graphs show the occurrence of equipment manufacturers found in the 16 PV minigrid cases assessed.

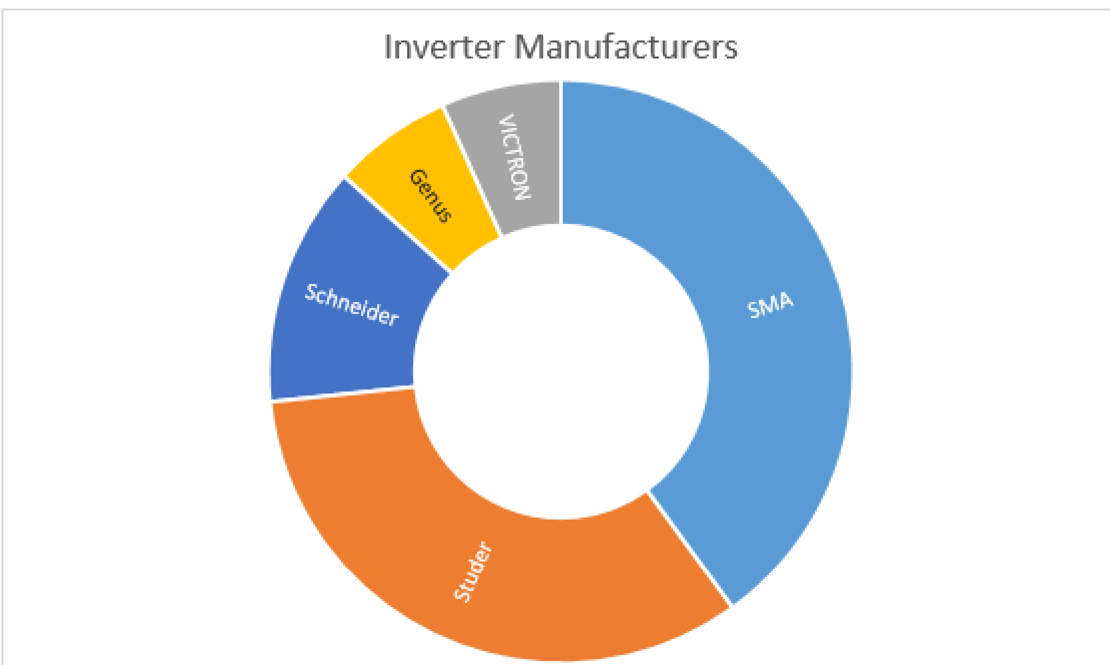
Starting with the PV modules, there is wide variety of brands found (10 different ones), with only Solar World and Canadian Solar being cited more than once. A similar situation is found with batteries, with 9 different brands mentioned, where only Hoppecke, Exide and Sunlight are cited



more than once.



Regarding Conversion and Smart metering, there are specific manufacturers that are more popular within the cases assessed: SMA and STUDER for the conversion equipment, and CIRCUTOR and SPARKMETER for the smart meter supplies.



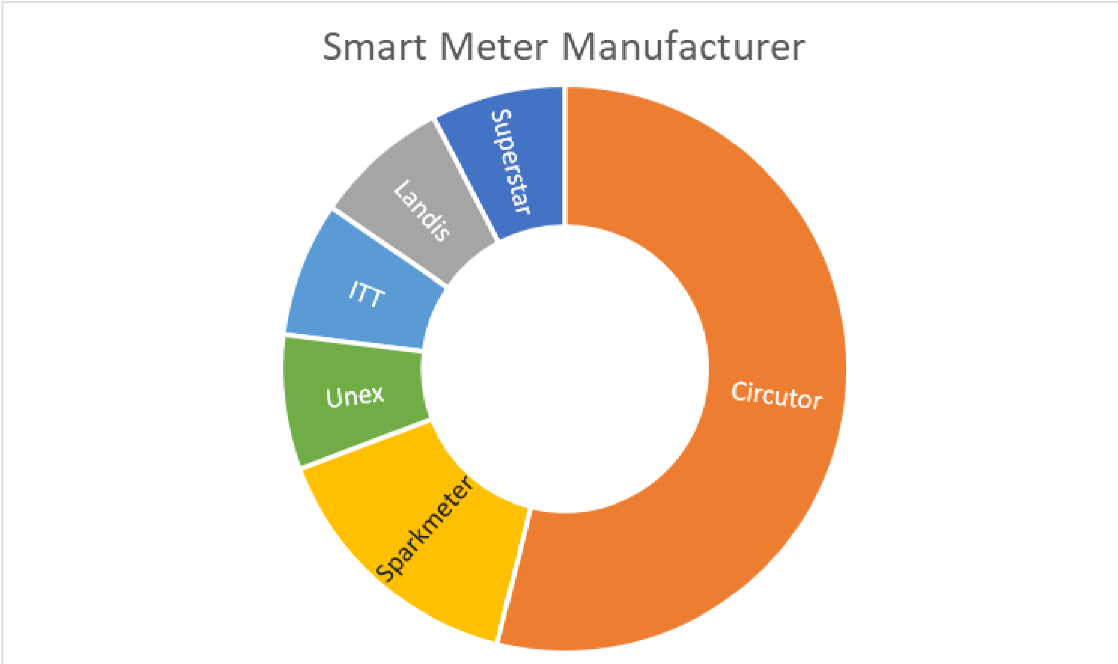


Figure 19. PV minigrid main equipment manufacturers occurrence (sample size: 16 minigrids).