Direct current microgrids based on solar power systems and storage optimization, as a tool for cost-effective rural electrification

Original
Direct current microgrids based on solar power systems and storage optimization, as a tool for cost-effective rural electrification / Gandini, Dario; de Almeida, Anibal T.. - In: RENEWABLE ENERGY. - ISSN 0960-1481. - 111:(2017), pp. 275-283. [10.1016/j.renene.2017.04.009]

Publisher:
Elsevier Ltd

Published
DOI:10.1016/j.renene.2017.04.009

Direct current microgrids based on solar power systems and storage optimization, as a tool for cost-effective rural electrification

Dario Gandini
Politecnico di Torino,
Dep. Electronics and Telecommunication, Italy

Anibal T. de Almeida
ISR, University of Coimbra,
Dep. Electrical Engineering, Portugal

Abstract

Around 20 % of world population lives without electricity access, most of them are concentrated in Sub-Saharan rural areas. Traditional approaches to electrify rural areas imply capital intensive infrastructures and large investments, while DC microgrids, based on renewable sources and storage systems, can be easily implementable and lead to cost effective solutions. The use of super efficient appliances can dramatically reduce the households electricity consumption, leading to smaller and cheaper systems. In this study an analysis of the use of efficient DC appliances is performed starting by essential energy services. Solar home system design optimization can be achieved by the evaluation of irradiation variation and the load requirements, finding the most cost-effective solution. Rural electrification can have a major impact to drastically improve the quality of life of millions of people through the sustainable use of solar energy.

Preprint submitted to Renewable Energy *March 21, 2017*

Keywords:

DC microgrid, solar home system, SHS, energy storage, rural electrification

1. Introduction - Electricity poverty

Worldwide 1.3 billion people, equivalent to 18 % of the global population, live without access to electricity [IEA World (2014)]. Sub-Saharan Africa has more people living without access to electricity than any other World region, more than 620 million people, about half of the global total. It is also the only region in the World where the number of people living without electricity is increasing. Since 2000, the number of people without electricity rose by around 100 million. Nearly 80 % of those lacking access to electricity are in poor rural areas. [IEA Africa (2014)]

A lack of access to such energy services often re-sults in relying on expensive, inefficient and hazardous alternatives. For example, households can typically spend 20-25 % of their income on kerosene, although the potential cost of useful lighting can be very small. Each year 4.3 million premature deaths, of which nearly 600 thousands are in Africa, can be attributed to household air pollution resulting from the traditional use of solid fuels, such as fuel wood and charcoal. [WHO (2014)]

Often, the traditional approach to serve these communities is to extend the conventional electric power grid. This approach may often be technically and financially inefficient due to a combination of capital scarcity, reduced grid reliability, extended building times and construction challenges to connect remote areas. In principle, sustainably financed and operated microgrids based on renewable energies can overcome many of the challenges faced by traditional rural electrification strategies. [Schnitzer et al. (2014)]

The International Energy Agency (IEA) estimates that more than 50 % of those without electricity access could be served by off-grid alternatives [IEA Africa (2014)]. New decentralized models based on renewable generation and innovative payment schemes are gaining ground as a viable alternative. These initiatives are frequently rely on government and international donor funds for start-up, scale-up activities, research or development.

2. Traditional approach: costs and losses

About 8.5 % of the global power production was lost in transmission and distribution networks in 2011, of which roughly 87 % was estimated to be due to technical losses. [Waide & Scholand (2014)] After the losses in power lines and cables, transformers are the second largest source of losses in electricity networks. Line losses in conductors and cables will typically account for about half of system technical losses whereas those in transformers will typically account for 45-50 %. Although they can be quite efficient, distribution transformers are costly and are estimated to account for 36 % of all global technical losses. [De Almeida et al. (2016)] Figure 1 shows the transformer efficiency and the different losses, as a function of the load, for a small 75 kVA oil-immersed distribution transformer.

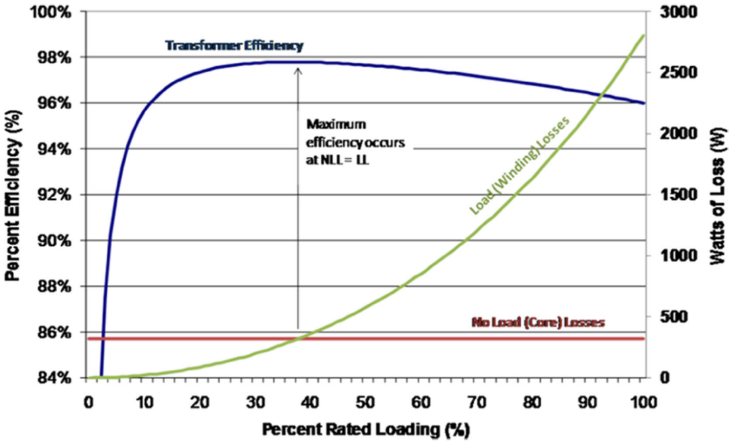

Figure 1: Efficiency and losses combination for a 75 KVA oil-immersed transformer [Eide et al. (2010)]

The transformer losses have two main components: core losses and copper losses. Maximum efficiency is reached when the two losses are equal, or rather at particular value of load. Due to variable consumption, particularly for residential case, a power transformer may undergo a considerable load variation during a 24 hours period. There may be intervals during which transformer carries a substantially rated load and others during which transformer carries only a small part of its rating. At very low loads (below 10 %), a situation likely to happen in most of the time in rural electrification, the efficiency dramatically drops, as the core losses are almost constant.

To electrify a rural area with a few users, a system composed by solar photovoltaic (PV) and storage, can have a system efficiency similar to a conventional grid-connected system and an impressive investment cost reduction. In Table 1 the typical distribution system hardware costs are sum-

Equipment	Cost example
Lines	30.000 $/km: 46 kV
Feeders	88.000 880.000 $/km
Rural Substation	23 $/kW (e.g. 1 MW = 23.000 $)
Mainline, conduit	300 $/m
Lateral, conduit	200 $/m
Installation of transformer	2.700 $
Installation of - 3 switches	20.800 $
Connections	60 $/kW
1-phase transformer	50 kVA: 3.000 $
2-phase transformer	75 kVA: 7.800 $

Table 1: Example of distribution system hardware cost in US$, [Knap et al. (2000)]

marized [Knap et al. (2000)] and in the next section the solar PV and lithium batteries cost trends are presented.

3. Solar PV and lithium storage cost trends

Combined use of renewable energy sources (RES) and storage is becoming a more and more an interesting solution to increase electricity access in rural areas. In the last ten years, both the prices of solar photovoltaic (PV) and of storage are coming down fast. In a high solar radiation region, as is most of Africa, solar PV electricity is the most interesting and cost-effective option. Figure 2 presents the collection of some PV module costs focused on different markets [Mehta (2013), Fraunhofer (2016), Bloomberg NEF (2015), NREL (2016)]. PV module cost was near 2 USD per watt in 2010, nowa-

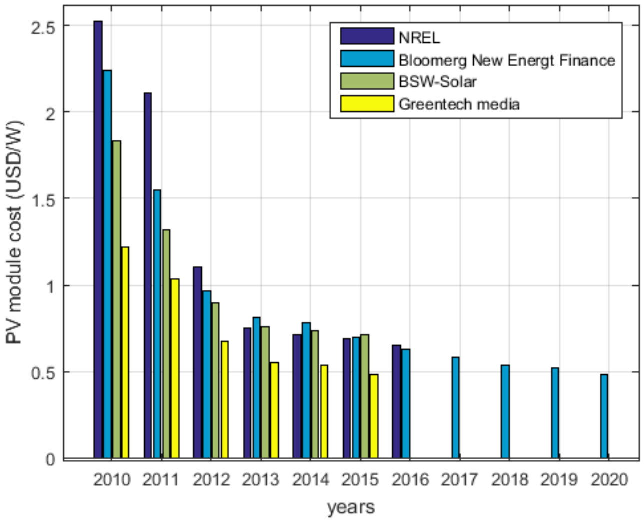

Figure 2: Solar PV module cost outlook 2010-2020. Greentech Media reports modules cost realized by Chinese companies [Mehta (2013)], BSW Solar are cost of German market [Fraunhofer (2016)], Bloomberg New Energy finance includes a modules cost forecast up to 2020 [Bloomberg NEF (2015)], NREL presents the costs of US market [NREL (2016)]

days is around 0.5 USD and cost estimation, in 2020, is down to 0.4 USD per watt. Modules costs are only a slice of total costs: power electronics equipment coupled to module can double total cost [Fraunhofer (2016)]; the sum of hardware equipments and soft costs, in 2009, were 64 % of total cost and nowadays they are 78 % [NREL (2016)].

With recent technology and mass-market developments (namely due to electric vehicles) lithium-based batteries are the most cost-effective storage option and, in the same way as PV modules, lithium-based batteries cost is also coming down, [Boucar& Ramchandra (2015)]. Figure 3 shows cost trends of Li-ion batteries. In recent surveys [Nykvist & Nilsson (2015)] a

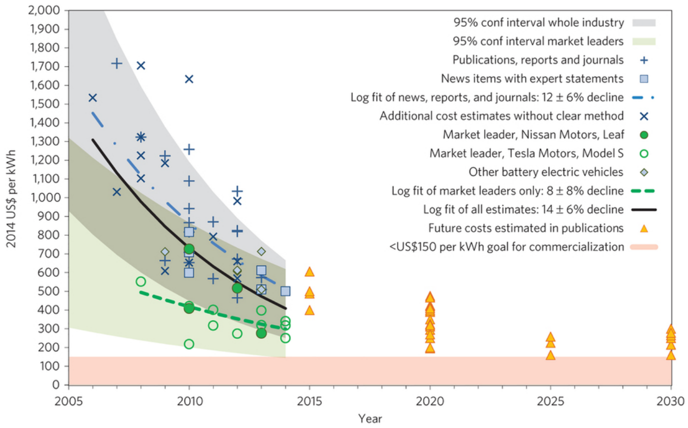

Figure 3: Cost of Li-ion battery packs in BEV. Source: [Nykvist & Nilsson (2015)]

value under 150 US$/kWh is considered the goal for commercialization by 2020. Lithium batteries, as well as PV modules, need electronics equipment, as power electronics converters and a battery management system; the total cost for consumers includes also commercialization and installation costs that, with the electronics equipment, can be responsible for 50-80 % of the total cost [Morris (2014), IRENA (2015)]. These values will be used in the following analysis to compute the economic sustainability of direct current (DC) microgrids based on the combination of PV modules and lithium batteries for storage.

4. Direct current: benefits on supply system and appliances

Direct current (DC) networks have the potential to increase the affordability of rural electrification in developing countries by reducing complexity, costs and by increasing total system efficiency. With DC networks, the parallelization of generators is easier, avoiding complex synchronization algorithms, inverter final stage is not necessary, avoiding the associated investment and its losses. Furthermore output filters, that in alternate current (AC) network are designed for 50 or 60 Hz, become smaller (necessary to remove only the high switching frequency) with additional increase of system efficiency and decrease of power system costs (Figure 4).

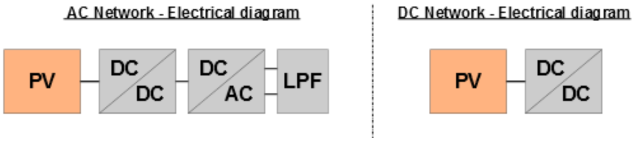

Figure 4: Block diagram of grid connected photovoltaic generator in case of AC or DC network. Where LPF is the inverter output filter, useless in case of DC network

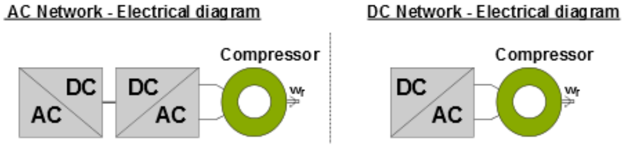

Figure 5: Block diagram of efficient loads (e.g. refrigerators, or air conditioners) in case of AC or DC networks

Considering the load side, most of the efficient appliances (e.g. LED lighting, TVs, Laptops) are already DC loads. Additionally, the most efficient existing AC loads, as refrigerators, fans or air conditioner systems, are driven by inverters with a AC/DC converter first stage. In AC networks, there is a need for this first stage, whereas in DC networks, this conversion is not required, as shown in Figure 5.

4.1. Super efficient appliances

Highly efficiency DC appliances have the potential to increase dramatically the affordability of DC networks used for rural electrification in developing countries by reducing the size of the required power systems. Considering an equal level of services, the use of highly efficient DC appliances can have, a remarkable impact on system cost reduction [Phadke et al. (2015)]. The estimated solar home system (SHS) costs using super-efficient or standard appliances are reported in Table (2).

Energy Service	SHS09s	SHS14s	SHS14se
	[USD]	[USD]	[USD]
Light	5	5	15
Battery	275	245	55
PV	500	185	40
Balance of System	100	100	65
Appliances	110	110	180
Total cost	990	645	350

Table 2: Estimated costs of a solar home system (SHS) with efficient or standard appliances in USD (SHS09s: 2009 SHS with standard appliances, SHS14s: 2014 SHS with standard appliances, SHS14se: 2014 SHS with super-efficient appliances) [Phadke et al. (2015)]

The U.S. ENERGY STAR [1] program collects the most efficient appliances of the U.S. market. The first television of the list is a LED 16 inches

---

[1] ENERGY STAR is a U.S. Environmental Protection Agency (EPA) voluntary program that helps businesses and individuals save money and protect our climate through superior energy efficiency. http://www.energystar.gov/about

screen, with a declared annual consumption of 19 kWh (value related to an use of 5 hours per day). A super-efficient DC solution has four times lower consumption. Below some of the Global competition LEAP Awards 2014 winners are shown: the products featured in the Global LEAP Awards are among the best off-grid LED room lighting appliances, Table 3, and TVs, Table tab:tvleap, in the World. TVs of the list have consume from 5 W to 10 W and LED lights of the list have consumption in the range 3 ÷ 5 W.

Model	LED-DC12V	SLL-L1903D	T5 Tube
Power	5 W	3 W	5 W
Category	LED Bulb	LED Indoor Fixture	LED Indoor Fixture
Rated Luminance	425 lm	310 lm	400 lm
Color Rendering Index (CRI)	82	70	82
Operating Voltage	12 V	8-18 V	12 V

Table 3: Winners of Global LEAP Awards outstanding off-grid LED room lighting appliance competitions 2014. Global LEAP Award is a Clean Energy Ministerial initiative.

Thermal comfort is one of the most important services that electricity access can improve. In rural areas, particularly in hot-humid climates, the thermal comfort can be improved by the use of ceiling fans, as presented in [Hwang et al. (2009)] . Nevertheless, ceiling fans contribute significantly to residential electricity consumption. For example, in India, ceiling fans alone accounted for approximately 6 % of residential energy use in 2000: this figure is expected to grow to 9 % in 2020 [Rue du Can et al. (2009)].

Model	SO16M	SO19M	UA23HG 4060AR
Power	6 W	8 W	10 W
Category	Small TV	Medium TV	Large TV
Screen Size	671 cm^2	995 cm^2	1458 cm^2
Functional Voltage Range (Rated)	12-18 V	12-20 V	10.5-14.6 V

Table 4: Winners of Global LEAP Awards outstanding off-grid televisions competitions 2014. Global LEAP Award is a Clean Energy Ministerial initiative.

In [Shah et al. (2013)] an analysis of the potential for improvement of ceiling fan components to reduce global energy consumption and greenhouse gas (GHG) emissions, is presented. Improved blade design, the increased use of brushless DC (BLDC) motors are identified as cost effective options to improve the efficiency of ceiling fans, with a potential power consumption saving of more than 50 %.

In [Desroches & Garbesi (2011)] the most efficient appliances are listed, divided by category, specifying the best at the research stage and of the market. Considering the best ceiling fan available on the market, it consumes 2 W to achieve 19.3 $m^3/min/W$. The fan, with a diameter of 1.3 m, has different operating speeds: minimum 49 rpm consuming 1.49 W, up to a maximum of 178 rpm consuming 14.81 W.

Another essential household service is the possibility to conserve food.

Among all refrigerators, available on market, it is possible to find super-efficient DC solutions. These appliances use variable speed drive (VSD) to drive a high efficiency BLDC motor, leading to an annual consumption less than 100 kWh. Obviously, the refrigerator consumption is related to the external ambient temperature and its usage (number of times that the door is open and duration of opening, amount of food). Below different typical energy consumption at different ambient temperatures are shown.

Ambient Temperature	Daily Cunsumption
21 ^{o}C	168 Wh
32 ^{o}C	276 Wh
43 ^{o}C	432 Wh

Table 5: Example of a high efficient DC refrigerator daily consumption related to ambient temperature. Refrigerator capacity: 28l.

By using these data, annual consumption at 21 ^{o}C is 61 kWh, while it is 158 kWh with an ambient temperature of 43 ^{o}C; the mean value between these two scenarios is 110 kWh/year. Analysing these values, it can be seen that the refrigerator works between 13 % of the time, at the lower ambient temperature, and 33 % of the total working time, at the higher ambient temperature.

In rural environment pumps for agricultural irrigation can also be a major end-use; their cost is highly variable on pump characteristics (e.g. flow, head) that are higly variable on geographic location and crop type as it can be seen in [Kelley et al. (2010)].

4.2. High efficiency semiconductor technologies

High efficiency appliances use power switching converters whose technology can significantly reduce the power losses. In [20] three different inverters are compared: two three-level three-phase Silicon inverter topologies are compared with a standard two-level three-phase topology employing new Silicon Carbide (SiC) power transistors. The use of SiC power MOSFET can decrease inverter losses by 60 %, Figure 6.

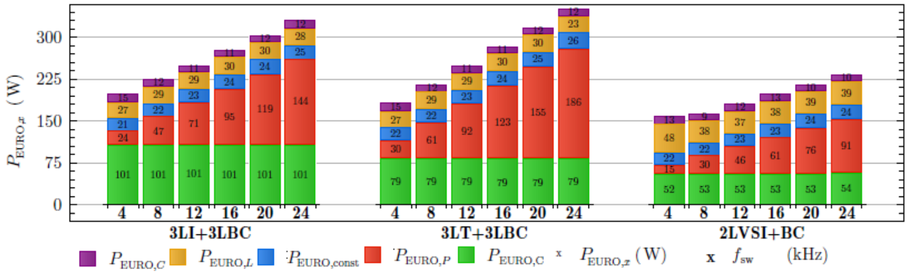

Figure 6: Breakdown of the inverter losses for different switching frequencies. Colour code: violet capacitor losses, yellow inductor losses, blue. cooling system losses, red transistor conduction losses, green switching losses. Sources: [Burkart (2013)]

In [Liu et al. (2013)] the performance of an interleaved DC-DC converter with new generation SiC transistors is evaluated and the reached efficiency at different operating powers is shown in Figure 7. The use of new semiconductor technologies, converter structures and control systems are therefore an essential element to achieve energy consumption reduction in systems using renewable energy sources, namely solar PV.

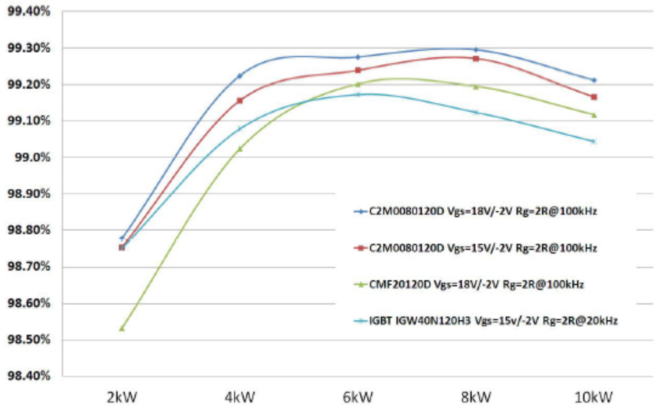

Figure 7: Interleaved converter of 10 kW, efficiency comparison at different frequencies with Gen1 & Gen 2 SiC MOSFET and Si IGBT. Source: [Liu et al. (2013)]

4.3. Eco-Design regulation

In the majority of motor drive system applications, the largest energy saving originates from the adjustment of the motor speed and torque to the optimal values required for the process. The use of a variable speed drive (VSD) for saving energy according to system demands is con-sidered an established concept. In a way similar to the regulations for industrial motors based on the Eco-Design Directive [Directive 2009/125/EC (2009)] efficiency classes for general purpose drives (GPD) are introduced in the standards EN 50598-2 [Tsoumas et al. (2014)]. Using the Complete Drive Module (CDM) with IE2 classification, the highest, can be targeted coupled with super-efficient motors and pumps.

5. Electricity consumption in poor rural areas

In [IEA Africa (2014)] is reported that, for those that have electricity access in sub-Saharan Africa, the average residential electricity consumption per capita per year is 317 kWh, or 225 kWh excluding South Africa. Consumption per capita is significantly lower in rural areas, typically in the range of 50 to 100 kWh per year.

There is no single internationally accepted and adopted definition of household minimum electricity level of electricity. In [IEA Africa (2014)] an initial threshold level of electricity consumption for rural households of 250 kWh is considered, whereas a different value is the threshold of [Sanchez (2010)] that assumes 120 kWh per person (600 kWh per household, assuming five people per household). The Energy Sector Management Assistance Program (ESMAP) has led the development of a framework that categorizes household electricity access into six tiers based on supply levels (tier 0 being no electricity, tiers 4 and 5 being greater than 3 kW of maximum power demand) and different attributes of supply. [ESMAP (2015)]

In the following analysis, first of all, a set of energy services supplied by high efficient appliances is given and, then the household electricity consumption is obtained. According to [Global LEAP (2015)] the most important appliances in rural areas are lights, mobile chargers, televisions, refrigerators and fans. In Table 6 the used essential energy services, daily use and consumption are summarized; assuming load profiles similar to European consumption behavior, the consumption profiles shapes are extracted from [De Almeida et al. (2011)]. Figure 8 shows the load diagram of a village

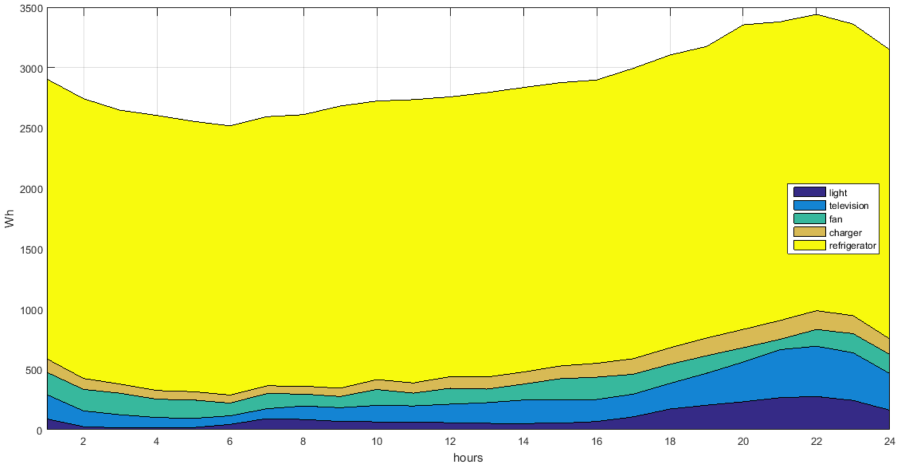

Figure 8: Consumption breakdown of a village with a limited set of appliances, 200 users. Elaboration from [De Almeida et al. (2011)]. Dark blue: lights, Light blue: Television, Green: Ceiling fan, Orange: Mobile charger, Yellow: Refrigerator.

with 200 households. Aggregated data of residential consumption are assumed to be country independent. Since there are no reliable references from rural Africa regions, European load profiles were used: this also give the opportunities to show single appliances profiles.

Daily consumption, for a single house, is 340 Wh, of which 270 Wh is due to the refrigerator. Annual total consumption is 124 kWh and the refrigerator, alone, consumes 100 kWh: thus 80 % of consumption is caused by the refrigerator. These values will be used in the next sections as parameters to optimize the solar power system and associated storage.

Energy Service	General Info	Daily Use	Daily consumption
Lighting	2 x 300 lm	4 hours	12 Wh
Refrigerator	38.7 liters	24 hours	270 Wh
Television	15.6″	4 hours	22 Wh
Ceiling Fan	19.3 m3/min/W	8 hours	16 Wh
Mobile phone charger	2600 mAh	One charge per day	12 Wh

Table 6: User's energy services. First column shows energy services of the house, second column appliances general information, third column time of utilization and finally daily consumption of each appliances.

6. Design: environment analysis and system optimization for a cost effective solution

The use of renewable energy sources to increase electricity access requires an evaluation based on the available natural resources. Solar resource needs to be taken into account in the precise location of the new microgrid. Some of the available solar radiation database are NASA SSE, HelioClim-1, NCEP/NCAR, World Radiation Data Centre, NREL/USA, SWERA, SOLEMI, Meteonorm, SolarGIS, SRRI, PVGIS, Climate-SAF PVGIS. There are some software tools, ususally not free, that could perform generation analysis starting from one of these database. In the follow system design is performed in a similar way to other tools and add particular attention to the treade-off between PV solar power and storage capacity, with the target of solar home system cost reduction, starting from dataset of solar radiation.

In particular, the NREL dataset is made up of hourly data of all days of the year. For a limited number of locations, radiation data are related to ambient temperature. Figure 9 shows a post-processing of the dataset: daily irradiance values are shown. Johannesburg was the selected location of the analysis. Daily irradiance has wide variations, also in months where it seems constant are present falls. Usually, to design PV systems nominal power, it is used the average irradiance on the year, but other choices can bring to a better solution.

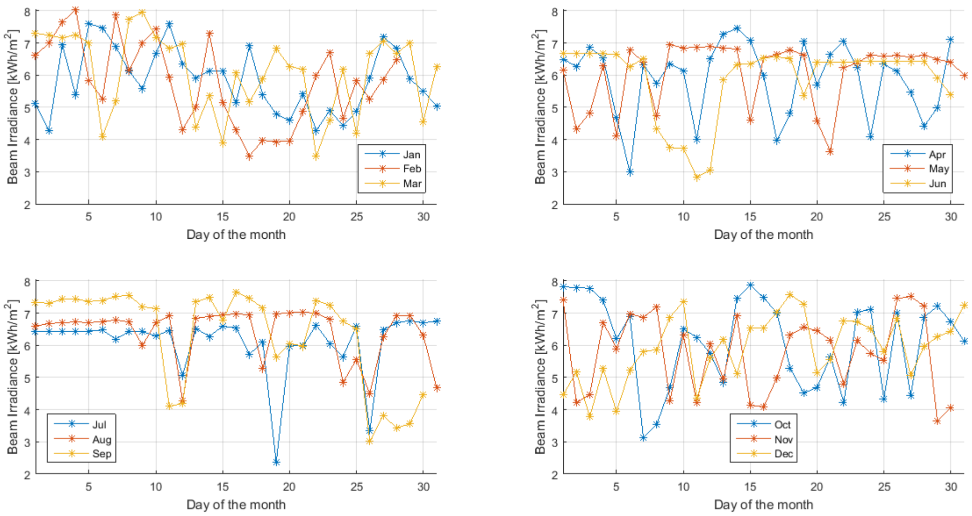

Figure 9: Johannesburg, daily irradiance, all days of the year clustered in months (elaboration from NREL database).

In Figure 10 maximum, minimum, median and average values calculated based on monthly data, for each month, are shown. The daily absolute minimum irradiance is in July, 2.3 kWh/m^2, while the absolute maximum is in February, 8 kWh/m^2. The average irradiance is around 6 $kWh/m^2/day$.

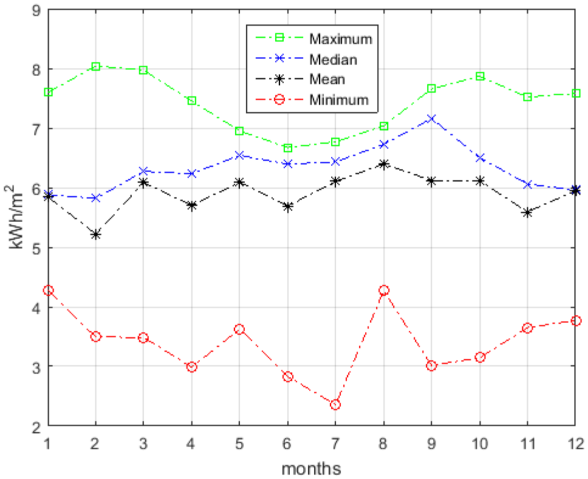

Figure 10: Johannesburg, daily irradiance. For each month maximum, median, average and minimum values are calculated.

In order to design the solar home system (1) must be verified: energy generated from PV panel considering system efficiency must equal or higher than consumed energy.

$$E_{PV} \cdot \mu \geq E_C \tag{1}$$

Produced energy can be directly consumed or stored in batteries and used later, during night-time or bad weather: in order to correctly design a solar home system, the production/consumption mismatch must be taken into consideration. With poor design blackout events can occur. Figure 11 shows the suggest power system block diagram.

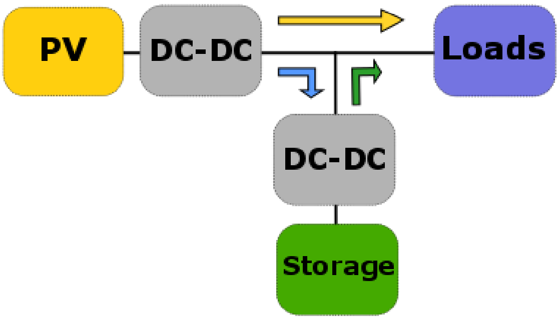

Figure 11: Power system block diagram.

The equation (2) defines solar plant nominal power [Z. Sen (2008)] and in (3) variable μ_{tot} is defined, that is the total daily efficiency, as function of simultaneous production and consumption percentage 'd'. During period d consumed energy is directly taken from PV panels, while during $(1-d)$ energy is taken from batteries earlier charged [Gandini (2016)].

$$P_N \geq \frac{E_{consumption}}{\mu_{tot}} \cdot \frac{P_{STC}}{G} \tag{2}$$

$$\mu_{tot} = d \cdot \mu_{drt} + (1-d) \cdot \mu_{drt} \cdot \mu_{stg} \tag{3}$$

Where 'G' is the irradiance, 'P_{STC}' is the power in standard test condition equal to 1 kW/m^2 and '$E_{consumption}$' is the daily energy consumption. 'μ_{drt}' is the system efficiency in case of simultaneous production and consumption and 'μ_{stg}' is the storage round-trip efficiency, including its own power converter. Due to system design, daily total efficiency is a combination of these two efficiencies.

In Table 7 assumed efficiencies are reported. Temperature efficiency, that models the reduction of generated power introduced by high ambient temperature, is an average value calculated from temperature profiles of NREL database. Converters' efficiencies are derived from the use of newest power semiconductor technologies.

Efficiencies	
Temperature	0.98
MPPT	0.99
PV converter	0.97
Wire & Connections	0.95
Storage	0.95
Storage Round trip	0.90
Storage converter	0.96

Table 7: Estimated system's efficiencies

Table 8 shows the variation of daily total efficiency, when changing simultaneous production/consumption percentage according to equation (3) and data of Table 7. This percentage changes with users consumption behavior.

Table 9 shows solar PV nominal power, calculated according to (2), changing daily irradiance and simultaneous production/consumption percentage. Using as irradiance the absolute daily minimum, in column two, the largest nominal power is obtained: this approach is the most conservative, leading to an oversizing of the solar power plant. On almost all days of the year, there

d	μ_{tot}
10%	0.7939
20%	0.8050
30%	0.8161
40%	0.8273
50%	0.8384

Table 8: Equivalent total efficiency variation with different direct consumption percentage

$P_N(d, G)$	Abs max G 8 kWh/m^2	Abs min G 2.4 kWh/m^2	Avg G 6.3 kWh/m^2
d = 10%	53 W	178 W	67 W
d = 20%	52 W	176 W	66 W
d = 30%	51 W	174 W	65 W
d = 40%	51 W	171 W	64 W
d = 50%	50 W	169 W	63 W

Table 9: Minimum nominal power of solar PV changing percentage of direct consumption and daily irradiance.

is an energy over production, which is in excess of household consumption.

Because of during period $(1 - d)$ consumed energy is taken from battery equation (4) is used to find the minimum energy storage capacity necessary to always supply loads; where DOD is the depth of discharge, which is necessary to avoid safety problems and to increase battery lifetime, around 30%.

$$E_{storage} \geq E_{consumption} \cdot (1-d) \cdot [1 + min(DOD)] \tag{4}$$

In order to increase reliability an analysis over a whole year was performed. Figure 12 shows the daily overproduction (total production minus household consumption considering system's efficiencies) for each month and day of a year. System's parameters are 95 W of PV nominal power, a storage capacity of 300 Wh, calculated by (4) and the energy consumption obtained in section (5). Values under zero are black out events.

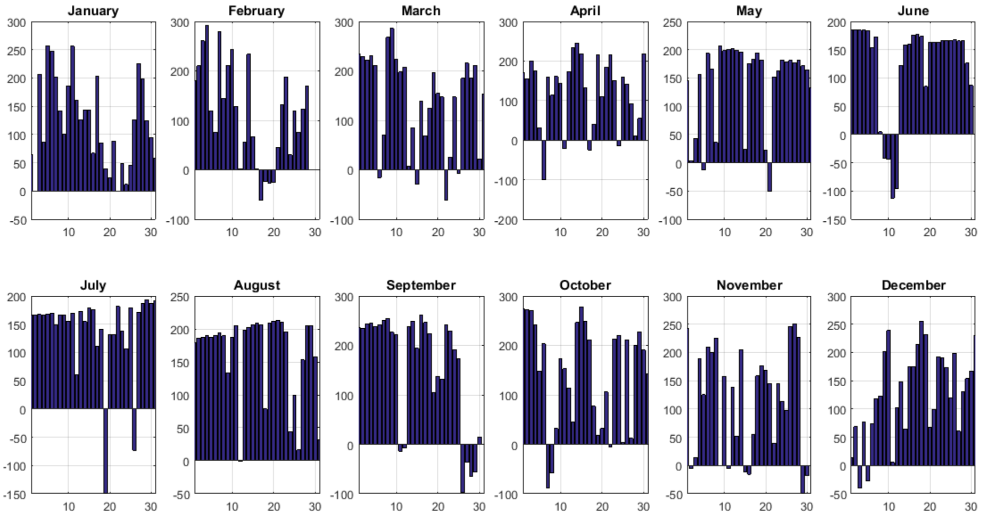

Figure 12: Energy overproduction (Wh), in Johannesburg. PV nominal power: 95 W. Storage capacity: 300 Wh. X axis are days. Y axis are energies [Wh].

Black-out events occurs because equation (4) is true only in case of PV nominal power calculated using the absolute minimum irradiance, column two of Table 9. In order to design a storage system with other PV nominal powers and avoid black-out events it is necessary to add a correction factor, equation (5) is the generalized formula to design storage capacity with different PV nominal powers to ensure energy continuity. '$E_{blackout}$' is the daily missing energy. Over the year the maximum missing energy of consecutive days is taken. For each PV nominal power it is simulated the over/under production using a storage sized with (4), then consecutive black-out events are identify and it is considered the maximum missing energy. In this particular simulation, the worst case is in June, as shown in Figure 13.

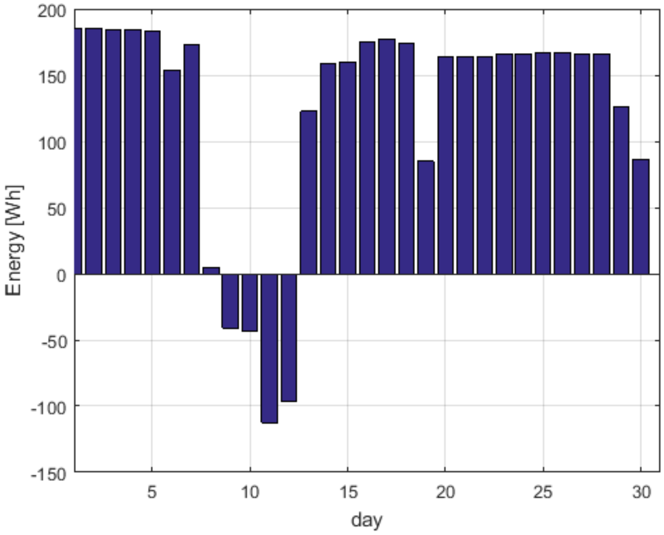

Figure 13: Energy overproduction (PV nominal power 95 W, storage capacity 300 Wh), in June. Each bar represents a day. Greatest event of consecutive blackouts of the year.

$$E_{storage} \geq E_{consumption} \cdot (1-d) \cdot [1+min(DOD)] + max\left(\sum_{i} E_{blackout,i}\right) \quad (5)$$

The sum of consecutive missing energy daily values, in June, is 350 Wh.

Therefore with a PV nominal power of 95 W and a storage of 650 Wh, considering daily irradiance data from NREL and consumption of Table 6, black out events are avoided. With an adequately designed battery, it is possible to store energy over produced in days before the critical period, and then use it in low irradiance days. In case of the storage being completely charged, it is possible to use the energy excess to supply ancillary services as water pumps and water purification systems.

Figure 14 shows the relation between solar PV nominal power, storage size and monthly cost of energy. Energy cost is based on the amortization of system considering life time. Included costs are PV module [Bloomberg NEF (2015)], storage [Nykvist & Nilsson (2015)] and power electronics equipment (converters, balancer, installation) as a percentage of module and storage costs. The estimated lifetime of all system is conservatively assumed to be 10 years. Because of NREL dataset has an uncertainty of 10 %, it is still possible the occurrence of electricity interruptions, but one day of interruption means 99.7 % of guaranteed service. Designing solar power systems in such a way to minimize storage size, as the use of minimum irradiance over the year to calculate PV nominal power, is the most cost effective solution. Monthly cost of energy is in all design options less than 8 USD. Values under 5 USD can be an affordable cost also for households in poor areas.

7. Conclusions and recommendations

Electricity access is still a dream for around 20 % of world population and Sub-Saharan Africa has more people living without access to electricity than

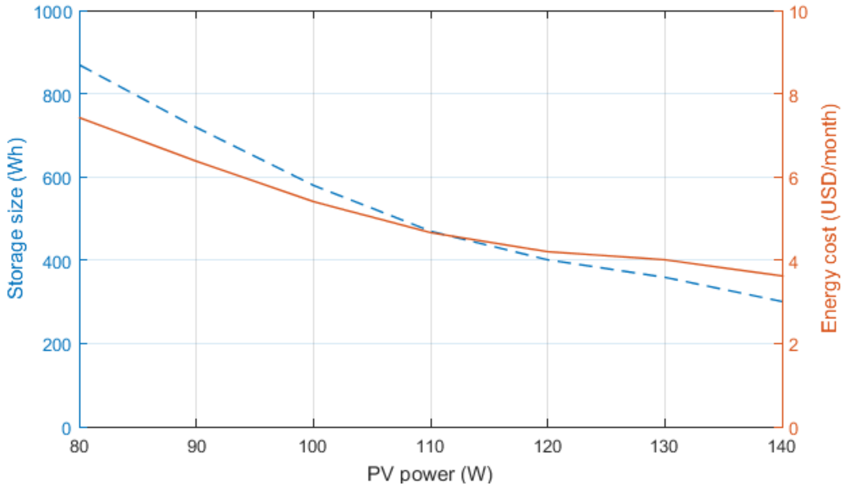

Figure 14: On left axis storage sizing function of PV nominal power in order to avoid black out, on right axis energy cost per month. Estimated system life-time 10 years. Cost of energy is function of PV nominal power and storage size.

any other World region. Traditional approaches to electrify rural areas imply capital intensive infrastructures and large investments. DC microgrids, based on renewable sources and storage systems, can be easily implementable and lead to cost effective solutions.

The use of super efficient appliances can dramatically reduce the households electricity consumption, leading to smaller and cheaper systems. An analysis of the use of efficient DC appliances performed by simulation of household consumption with an approach oriented to give basic energy services, was carried out. The design of a solar home system can be achieved by analysis of irradiation variation during a complete year, and the required load, finding the most cost effective solution. Rural electrification can be a win-win challenge: improve quality of life of millions of people in a sustainable way. Moreover, it can be a future important market as shown by new companies, active in this field, leading also to local employment in the installation and maintenance of these distributed clean energy systems.

References

IEA, *World Energy Outlook*, 2014

IEA, *Africa Energy Outlook*, 2014

World Health Organization (WHO), *World Helth statics*, 2014

D. Schnitzer, D. S. Lounsbury, J. P. Carvallo, R. Deshmukh, J. Apt and D. M. Kammen, *Microgrids for rural electrification*, United Nations Foundation, February 2014.

P. Waide and M. Scholand, *The potential for global energy savings from high efficiency distribution transformers*, Waide Strategic Efficiency Limited and N14 Energy Limited, 2014.

A. Eide, N. Borg and E. Toulouse, "Comments on Eup Study: Lot 2 Distribution and Power Transformers," CLASP Europe, 2010

K. E. Knapp, J. Martin, S. Price and F. M. Gordon, *Costing methodology for electric distribution system planning*, The Energy Foundation, November 9, 2000.

S. Mehta, *PV Technology, Production and Cost Outlook*, GMT, 2013.

Fraunhofer Istitute for Solar Energy System, *PHOTOVOLTAICS REPORT*, Freiburg, 2016.

Bloomberg New Energy Finance, *New Energy Outlook 2015*, 2015.

Ran Fu, Donald Chung, Travis Lowder, David Feldman, Kristen Ardani, and Robert Margolis *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016*, NREL, 2016.

D. Boucar and P. Ramchandra, *Potential of lithium-ion batteries in renewable energy*, Renewable Energy, vol. 76, pp. 375-380, April 2015.

B. Nykvist and M. Nilsson, *Rapidly falling costs of battery packs for electric vehicles*, Nature climate change, vol. 5, no. 4, pp. 329-332, 2015.

J. Morris, *Helping Battery Cost Declines Keep Going and Going*, Rocky Mountain Institute, 2014.

IRENA, *Battery storage for renewables: market status and technology outlook*, 2015.

A. Phadke, A. Jacobson, W. Y. Park, G. R. Lee, P. Alstone and A. Khare, *Powering a home with just 25 Watts of solar PV*, Berkeley Lab, April 2015.

R. L. Hwang, M. J. Cheng, T. P. Lin and M. C. Ho, *Thermal perceptions, general adaptation methods and occupant's idea about the trade-off between thermal confort and enegy saving in hot-humid regions*, Build and Environment, 2009

S. de la Rue du Can, V. E. Letschert, M. A. McNeil, N. Zhou and J. A. Sathaye, *Residential and Transport Energy Use in India: Past Trend and*

Future Outlook, Berkeley CA: Lawrence Berkeley National Laboratory, 2009

N. Shah, N. Sathaye, A. Phadke and V. Letschert, *Cost and benefits of efficiency improvement in ceiling fans*, EEDAL, 2013

L. Desroches and K. Garbesi, *Max Tech and Beyond: Maximizing appliance and equipment efficiency by design*, LBNL, 2011

J. R.Burkart, *Comparative Evaluation of SiC and Si PV Inverter Systems Based on Power Density and Efficiency as Indicators of Initial Cost and Operating Revenue*, COMPEL, 2013

J. Liu, K. L. Wong, S. Allen and J. Mookken, *Performance Evaluations of Hard-Switching Interleaved DC/DC Boost Converter with New Generation Silicon Carbide MOSFETs*,Cree Inc, 2013

EU, *Directive 2009/125/EC*, European Parliament and of the Council, 21 October 2009.

I. P. Tsoumas, H. Tischmacher and P. Kollensperger, *The European Standard EN 50598-2: Efficiency classes of converters and drive systems* , Electrical Machines (ICEM), 2014

T. Sanchez, *The Hidden Energy Crisis: How policies are failing the worlds poor*, London: Practical Action Publishing, 2010

ESMAP, *Beyond connections - Energy Access redefined*, The world bank group, Washington DC, 2015

Global LEAP, *Off-Grid appliance market survey*, 2015

A. de Almeida, P. Fonseca, N. Feiberg and B. Schlomann, *Characterization of the household electricity consumption in the EU, potential energy savings and specific policy recommendations*, Energy and Building, vol. 43, no. 8, pp. 1884-1894, August 2011

L.C. Kelley, E. Gilbertson, A. Sheich, S.D. Eppinger, S. Dubowsky, *On the feasibility of solar-powered irrigation*, Renewable and Sustainable Energy Reviews 14, pp. 2669-2682, 2010

Zekai Sen, *Solar Energy Fundamentals and Modeling Techniques* London: Springer-Verlag, 2008, pp. 102-103.

De Almeida, A., Santos, B., Martins, F., 2016. Energy-efficient distribution transformers in europe: impact of ecodesign regulation. Energy Efficiency 9 (2), 401–424.

Gandini, D., 2016. Energy storage as enabling technology for smart grid. Ph.D. thesis, Politecnico di Torino.