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Techno-economic assessment of an off-grid PV system for developing regions to provide electricity for basic domestic needs: A 2020–2040 scenario

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HIGHLIGHTS

- Off-grid PV has a huge potential to provide effective solutions for energy poverty.
- Its implementation barrier is economic, but paths to effectively tackle this exist.
- The implementation barriers will be reduced by a favourable technological evolution.
- Cost reductions to the level of grid-connected power will be eventually achieved.

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ABSTRACT

While in the developed countries electrification is paving the way for progress and prosperity, nowadays electricity is still not accessible for about 18% of the world's population. Lack of power grids is the main reason that prevents millions in remote areas in developing countries from using electricity for the daily basic needs. PV systems provide an effective solution for these regions, but affordability remains an issue. This barrier can be widely overcome on the short term by limiting PV power supply to very high added value applications and by properly exploiting innovations, especially in energy efficiency and cost reductions. Additional to that, the long-term perspectives of off-grid PV are very favourable based on its ongoing technological improvements and cost reductions. This paper studies four off-grid PV cases of which each could cover a combination of basic energy needs regarding light, cooking, food conservation and electronic appliances. Case I considers a system that supplies power for LED lamps and electronic devices. Accordingly, Case II adds a fridge and Case III an electric rice cooker to Case I, while Case IV adds both. The paper elaborates on available technologies and future developments regarding all components in order to assess the long term evolution and potential of these applications, most specifically how their affordability would evolve over time. The modelling and optimization of the four cases are performed using the software iHOGA, which is an efficient tool to provide the lowest cost solution for off-grid PV systems. The use of iHOGA for the four cases and the installation years 2020, 2030 and 2040, taking thereby into account different developing regions, provide an evolutionary techno-economic assessment of these applications and a clear picture about the developments to be expected from off-grid PV in general.

1. Introduction

Close to 1.3 billion people around the world do not have access to electricity, most of them living in rural areas in South Asia, Southeast Asia, and Sub-Saharan Africa. No access to electricity implies exhausting work for covering basic needs and hampers economic and social development.

Abbreviations: AC, Alternating Current; AGM, Absorbed Glass Mat; CdTe, Cadmium-Telluride; CIGS, Copper Indium Gallium Selenide; C-Si, Crystalline Silicon; DC, Direct Current; DoD, Depth of Discharge; GHG, Green House Gas; HDI, Human Development Index; iHOGA, improved Hybrid Optimization by Genetic Algorithms; LCoE, levelized cost of electricity; LED, light emitting diodes; Li-ion, Lithium-ion; MPPT, Maximum Power Point Tracking; NPC, Net Present Cost; O&M, Operation and Maintenance; RoHS, Restriction of Hazardous Substances; VAT, Value Added Tax; VRLA, Valve Regulated Lead Acid.

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A concern on the global level is to boost the growth of the Human Development Index (HDI) of developing countries [1–3]. The HDI is a country development indicator that takes into account health (life expectancy), education (years of schooling) and standards of living (per capita gross income). Access to electricity can improve all these factors and with that boost the HDI significantly. Availability of electricity opens new business opportunities, while reducing the work in many domestic tasks, leaving time to more profitable labour activities. This is especially important in regions where people rely on biomass for cooking and spend many hours daily collecting it. Life expectancy can be increased significantly by the availability of sufficient potable water, which can be produced easily if electricity is available onsite. LED lamps can substitute combustion based lighting and with that avoid the health damage associated with indoor fire [4]. Also education can profit much from the availability of electricity as children can have access to computers and can study after sunset.

This urgent need for global access to electricity should bring a transformation which gives priority to sustainable growth and minimal environmental impact; among others the reliance on low-carbon energy technologies is vital. This matches with regional and global sustainability efforts [5–16]. PV is especially an interesting option here as most of the global population that don't have access to electricity live in regions with high solar radiation. Table 1 lists the world countries where most people without access to electricity live. As to be expected, the HDI in these countries is medium to low. The table provides also rough details on the solar conditions of the most affected countries, showing that these are very favourable sites for PV applications.

Dealing with developing regions implies that severe economic restrains are in place, while energy supply costs in terms of €/kWh are often higher than in developed regions. Affordability remains an implementation barrier for off-grid PV in developing regions. Nevertheless, affordability could be widely improved by focusing on basic needs and exploiting the potentials of energy efficiency. This approach is followed in this paper. The focus thereby is on basic domestic needs, most specifically lighting, cooking, food conservation and recharge of portable electronic devices (mobile phone and similar). The appliances used to satisfy these basic needs imply a wide range of technologies. For an off-grid PV system for developing regions it's highly relevant to rely on the most energy efficient technologies, for instance LED lamps instead of other lighting technologies (incandescent, halogen and fluorescent). This approach allows to achieve applications with highest added value and lowest energy demand, which translates into improved affordability. Furthermore, as off-grid PV has an ever growing competitivity, based on ongoing technological improvements and cost reductions, it is highly important to assess the long-term tendency of this aspect for the purpose of understanding the real potential behind it.

There is a big number of scientific publications on stand-alone PV systems, both pure solar and hybrid systems in combination with other renewables [18–26]. These focus on the application, simulation, engineering, monitoring and performance of PV systems in different countries and locations. For instance, Ma et al. provide a detailed assessment and performance analysis of a monitored off-grid PV system in Hong Kong, elaborating thereby on all relevant system operating data for an entire year such as the power flow between the generator, the battery and the consumer and the state of charge of the battery. On the other hand, this paper highlights the solutions to reduce the affordability barrier for off-grid PV systems for domestic users in developing regions and captures the evolutionary techno-economic aspects of these solutions on the short and long term and with that their exploitable potential in the energy poverty affected areas. This provides also a clear picture about the developments to be expected from off-grid PV in general.

2. Method

The purpose of this paper was to define off-grid PV solutions for developing regions and provide a clear understanding of their evolutionary techno-economic aspects. The focus is on single family installations. As reference coordinates locations in India, Pakistan, Bangladesh and Indonesia are used. This is based on the fact that there is high implementation need in these countries (see Table 1). Taking into account the reference years 2020, 2030 and 2040, provides the evolutionary techno-economic assessment of these solutions and a clear picture about the developments to be expected from off-grid PV in general. While this paper tackles extensively the cost reduction path and with that the affordability barrier of the emphasized solutions, it's not within the scope of this paper to tackle other implementation barriers, such as the availability of capital and policy requirements. This would be the topic of future publications by the authors. The following method is followed to achieve the mentioned objectives:

1. Define the basic domestic energy needs in developing regions and build based on these case studies.

Table 1
Global situation on access to electricity [3,12,17].

	Population (million)	No access to electricity (%)	No access to electricity (million)	HDI[a] 2014 (global rank)	Solar irradiation (kWh/m^{2}y)
World	7240	17.8	1285	0.702	–
India	1270	24	305	0.586 (135)	1600–1900
Bangladesh	158	39.2	62	0.558 (142)	1600–1700
Indonesia	255	23.5	60	0.684 (108)	1700–1900
Pakistan	190	29.5	56	0.537 (146)	1800–2000
Burma	51	70.6	36	0.524 (150)	1500–1800
Rest Asia	–	–	102	–	–
Nigeria	184	50.5	93	0.504 (152)	1900–2000
Ethiopia	90	44.4	70	0.435 (173)	2000–2300
DR Congo	71	84.5	60	0.338 (186)	1800–2200
Tanzania	47	76.6	36	0.488 (159)	1700–2400
Kenya	47	74.5	35	0.535 (147)	1700–2400
Rest Subsaharan Africa			328		
Rest World			43		

[a] HDI index rough classification: Low (<0.55), medium (0.55–0.7), high (0.7–0.8) and very high (>0.8).

2. Provide justified modelling inputs, i.e. based on a detailed assessment, for the system components (PV generator, battery, and electric appliances) in the considered time scope (2020–2040).
3. Perform the PV system modelling and optimization for the different case studies, reference years and locations using the software iHOGA.
4. Analyse and structure the iHOGA results into an evolutionary techno-economic assessment of the case studies and into useful conclusions about the potential of off-grid PV in developing regions in general.

The basic domestic energy needs in developing regions are lighting, battery recharge for electronic appliances and energy for cooking and food conservation. Of course, the list is not exhaustive, but these are the priority appliances to significantly improve life-quality in developing regions. To tackle the affordability issue of off-grid PV we consider the highest efficiency appliances, such as LED lamps and an electric rice cooker. This approach results eventually in best added value to power demand relation, which translates into a reduced affordability barrier. The added value of the LED lamps is the availability of lighting for all nocturnal activities, including the possibility for children to study and do their homework without having to rely on indoor fire, which is harmful for their health. A fridge allows to conserve food, which is basic for healthy alimentation. The electric rice cooker has a huge added value as it saves many hours in biomass collection. It also allows for indoor cooking without fire having with that very positive effect on health and life quality. The added value of portable electronics can differ widely; for instance it's very high for a mobile phone, but not necessarily for a digital camera. Nevertheless, a debate about the added value of each appliance is not so relevant here, especially considering the relatively low energy demand the battery recharge of electronic devices implies.

In this paper we consider lighting and electronic appliances (mobile phone and similar) as the most basic need. The off-grid PV system to cover this basic demand is Case I. To these, an energy efficient fridge or a rice cooker or both could be added, which gives the other 3 Cases:

– Case I: LED lamps and electronic devices.
– Case II: LED lamps, electronic devices and a fridge.
– Case III: LED lamps, electronic devices and an electric rice cooker.
– Case IV: LED lamps, electronic devices, a fridge and an electric rice cooker.

Due to the considered time scope until 2040, it's elementary that the technology assumptions to be used in the PV system modelling are justified based on a deep understanding of these in terms of their state of the art, transitions and potentials. Accordingly Sections 3,4 and 5 provide a brief techno-economic assessment for the PV generator, battery and electric appliances respectively.

In the next step of our method we perform the modelling and optimization of the off-grid PV systems using the software iHOGA, a tool developed by one of the authors [27–29]. iHOGA uses the following inputs to model and optimize the installation:

– Latitude and longitude of the installation's site.
– Monthly average of daily solar radiation [30]; from that iHOGA generates hourly solar radiation values for an entire year using the method of Graham and Hollands [31] and uses them in the system simulation.
– Monthly average temperature.
– Power demand curve of the used electric appliances.
– PV generator technology and characteristics including panel nominal power, nominal voltage, short circuit current, open circuit voltage, lifetime, efficiency degradation, temperature coefficient, specific CO_2 emissions, purchase price and performance ratio.
– Battery technology and characteristics including specific costs, nominal capacity, nominal voltage, roundtrip efficiency, maximum DoD (Depth of Discharge), self discharge, maximum charge and discharge currents, float life and cycles to failure vs DoD.
– Battery regulator technology and characteristics including type, nominal voltage and voltage range, maximum current, specific cost and MPPT (Maximum Power Point Tracking).
– Financial data including interest rate and inflation.

The iHOGA modelling provides the following outputs:

– Size of the PV generator in Wp and its ideal tilt.
– Battery capacity in kWh and battery lifetime in years.
– Initial investment and NPC (Net Present Cost) with breakdown to the component level in Euros.
– The LCoE in c€/kWh.
– The specific life cycle GHG (Green House Gas) emissions of the PV installation in gCO_2/kWh.

These iHOGA outputs are for the optimal solution; taking into account a wide range of PV generator nominal power and battery bank capacities, iHOGA performs the simulation for all the possible combinations, calculates the NPC and provides the lowest cost solution. The simulation is done in hourly steps for the entire installation's lifetime of 25 years.

It should be highlighted that iHOGA can use different models for calculating the battery voltage and the state of charge: Simple Ah model [32], Kinetic model [33], Copetti et al's model [34] or advanced weighted Ah-throughput model proposed by Schiffer in 2007 [35]. For the battery ageing iHOGA can use the equivalent full cycles to failure model, "Rainflow" cycles counting model based on Downing's algorithm [36] or Schiffer weighted Ah-throughput model [35]. The Schiffer et al's model is considered the most accurate as the cycles are weighted by factors that consider the operating conditions. It takes into account that the operating conditions are typically more severe than those used in standard tests for cycling and floattime. The model considers battery replacement when its capacity drops to 80% of its initial value or after a lifetime of 13.5 years, whatever comes first. The limit of 13.5 years is the floatlife at the average temperature of the location, obtained from taking into account 20 years lifetime at 20 °C and applying Arrhenius law. Finally it's assumed in this paper that replaced batteries are of the same battery technology at the moment of installation. Thereby, also the specific price is considered equal based on the rough assumption that the lower purchase price of the new battery compensates for the replacement costs. Further details on iHOGA can be obtained in [27].

As we are covering 4 cases and 3 installation years (2020, 2030 and 2040), we have 12 calculations for each single geographic location. As the main reference location we take Central India (24°N, 79°E), present all its results, and complement these with qualitative conclusions for the modelling performed for other locations in India, Pakistan, Bangladesh and Indonesia. The use of iHOGA for the four cases, the reference years 2020, 2030 and 2040 and the different considered locations provides the targeted evolutionary techno-economic assessment, covering thereby the wide geographic area where the implementation need is concentrated. Beyond this main objective of the paper, the authors consider it vital to provide within the discussion an explanation and justification of the results with special focus on amplifying the contrasts that result between the different cases and the different installation years.

3. PV generator

Photovoltaics includes already a wide range of commercially used and emerging materials, including Crystalline Silicon (C-Si), amorphous silicon, micromorphous silicon, Cadmium-Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), III–V elements (gallium, arsenic, etc.), organic, dye-sensitized and perovskite materials [37,38]. These different technologies confront diverse technological challenges including improvement of efficiency and long-term performance, cost reductions, material bottlenecks (such as tellurium, gallium and indium) and large-scale manufacturability. Also, subject to debate, is that some technologies rely on hazardous and restricted substances such as cadmium in the case of CdTe modules, which is restricted in the RoHS (Restriction of Hazardous Substances) directive of the European Commission [39].

The PV market is strongly dominated by C-Si with a market share historically above 80%, in exception of few occasions when emerging thin-film PV technologies, concretely amorphous and CdTe, made the commercial breakthrough. Nevertheless, in recent years the market share of thin-film PV has been around 15%. Although thin-film PV technologies may keep a manufacturing cost advantage over C-Si, roughly 10%, this difference is reduced when it comes to pricing, and the cost advantage is eventually inexistent or results even in a negative balance on the system level. This is due to the area related costs resulting from the lower efficiency of thin-film PV modules. This cost relation between C-Si and thin-film PV is likely to persist and maintain the current market order between both. In this paper the reference PV technology is C-Si.

The current record efficiency for C-Si is 25% for the mono-crystalline cell and 20.8% for the multi-crystalline cell. The silicon heterostructure cell achieved recently a record of 25.6% [38]. The 25% mono-crystalline silicon record has been achieved with wafer-made cell, but significant advances have been also achieved on the deposition of mono-crystalline silicon with a record cell achieving 21.2%. Films well below 50 μm can be produced allowing to minimize the Auger Recombination, and therefore this technology has the potential for high efficiency and low-cost. The maximum theoretical cell efficiency for C-Si is 29%. On the practical level roughly 26% could be achieved, which is slightly above the current record cell. This could eventually lead to a commercial module efficiency of up to 24% to be achieved with a mono-crystalline thin-film material, advanced cell design and ideal use of module area. Most current commercial C-Si modules are in the efficiency range of 14–17% [40]. On the long run a shift to the 17–24% range can be expected.

The global annual installed PV capacity in recent years was 30.1 GW in 2011, 30.0 GW in 2012, 38.4 GW in 2013 and 40.1 GW in 2014 [41]. The cumulative capacity achieved 178.4 GW at the end of 2014. The installed capacity for 2015 is estimated at 55 GW. In the recent years the European market has cooled down, but this was compensated by faster growth in China, Japan, USA, Australia and South Korea. Much of the growth within the next years will depend on these markets with legislative and financial support implying high impact. This transition to a truly global PV market is healthy, although it may imply slower growth on the short term. The annual global market growth averaged 26% along the last 5 years. A cautious estimate of 10% annual growth until 2020 is considered here. Still, this implies that the 500 GW cumulative capacity line will be crossed in 2020. Taking into account a learning rate for PV of 20%, an average annual cost reduction of 6% would result within the next 5 years.

Table 2
PV generator assumptions.

	2020	2030	2040
Technology	C-Si	C-Si	Thin film C-Si
Efficiency (%)	16	20	23
Nominal DC voltage[a] (V)	12/24	12/24	12/24
Lifetime[b] (year)	25	25	25
Performance after 25 years	80%	85%	90%
Manufacturing cost (€/W)	0.4	0.3	0.25
Average consumer price (€/W)	0.86	0.7	0.62
Price up to 200 Wp (€/W)	1	0.8	0.7
Price for 200–500 Wp (€/W)	0.95	0.76	0.67
Price above 500–1000 Wp (€/W)	0.9	0.72	0.63
CO_2 emissions (kg/kWp)	560	340	230

[a] There is a wide offer on the market for PV panels specifically designed for off-grid applications. The standard nominal voltage of the panel is 12 V and 24 V.

[b] PV panels exceed significantly the lifetime of 25 years. This implies here that there is still a residual value for the PV generator after 25 years. Furthermore, PV panels include valuable materials that are recovered in their recycle. This value is not accounted here, but considered as an argument for zero costs at the end of the lifetime of the installation.

Table 2 summarizes the modelling inputs in iHOGA for the PV generator. For 2020 we assume a module manufacturing cost of €0.4/W. Considering 10% overhead and 25% benefit margin, a factory gate price of €0.55/W would result. Assuming shipping and trade costs of €0.2/W and 15% VAT (Value Added Tax), then a consumer price of €0.86/W would result. For 2030 a module manufacturing cost of €0.3/W is assumed, and the same reasoning results in a consumer price of €0.7/W. For 2040 a module manufacturing cost of €0.25/W is assumed, and the same reasoning results in a consumer price of €0.62/W. These values are understood as an average, and for small installations the specific price is higher.

Warranty conditions for C-Si PV modules typically guarantee at least 90% of the nominal output after 10 years and at least 80% after 25 years. Some manufacturers are already providing guarantee for at least 84% after 25 years. These are significant improvements compared to few years ago, where rather a guarantee of 80% after 20 years was standard. This tendency is expected to continue with ongoing research and not yet fully exploited potential on reducing efficiency degradation in PV modules. In this paper we cautiously assume the PV modules installed in 2020 will eventually perform at 80% of their initial power after 25 years of operation. For modules installed in 2030 a better value of 85% is assumed, and for module installed in 2040 we assume 90%. For all cases a lifetime of 25 years is assumed in line with the installation lifetime. At this point PV modules have still a minor residual value, which is not considered here. Manufacturers also provide initial efficiency conditions as PV modules don't meet accurately nominal data. Few years ago a tolerance of −5% to +5% was typical. Currently many suppliers provide only positive tolerance within a tighter range, for instance 0–3%. Therefore in this paper we don't consider the power tolerance range. Finally, 17% of annual performance losses are taken into account for the PV panels due to factors such as temperature, dirt and dust. Operation and Maintenance (O&M) for PV panels implies cleaning every few months, which would be carried out by the installation owner. Further information on Photovoltaics is available in [9,17,37,38,40–45].

4. Battery

In previous work many authors considered the different battery technologies and concluded that the lead–acid battery will maintain for PV applications its advantage over other technologies on the short term, while on the medium and long term the Lithium-ion (Li-ion) battery will emerge as a very competitive technology [46–48], especially with the cost reductions resulting

Table 3
Battery assumptions.

	2020	2030	2040
Technology	Lead–acid, VRLA	Li-ion	Next generation
Lifetime (cycles)[a]	500–1000	1500–2500	2000–3000
Price (€/kWh)[b]	120–140	280–320	180–220
Energy density (Wh/kg)	40	250	300
Power density (W/kg)	30	600	900
Maximum power (W/Wh)	0.75	2.4	3
Roundtrip efficiency (%)	90	95	95
Maximum DoD (%)	80	90	90
Self-discharge (%/M)	3	2	2
Operating temperature (°C)	0–50	−20 to 60	No practical restrictions
CO_2 emissions (kg/kWh)	55	40	20

[a] Small battery packs have simple electronics to protect the battery and optimize its operation, while bigger ones are much better in this aspect. Bigger batteries have also better thermal management. For instance several electric car manufacturers are developing active battery cooling systems. Bigger battery packs also allow for better maintenance through display of information, user alerts and similar. All these aspects result in higher cycling for bigger batteries. For the battery lifetime, the lowest value in the indicated range is used for Case I and the highest value for case IV. The middle value is used for cases II and III, except for Case III for the installation year 2020 the higher value is used.

[b] The battery price varies in relation to its size. In the price range provided, the upper value applies for the relatively small batteries (Case I), while the lower value applies for the bigger batteries (Case IV). For Cases II and III, the middle value is used, except for Case III for the installation year 2020 the lower value is used.

from large-scale use in the mobility sector. Considering the intensive ongoing research in batteries, on the longer run other competitive battery technologies are very likely to emerge. The battery assumptions for the iHOGA modelling are summarized in Table 3. For 2020 we opt for a lead–acid battery and for 2030 for a Li-ion one. No battery technology can be specified for 2040, but we assume improved characteristics compared to 2030.

The basic design of the lead–acid battery, in which the plates are dipped in liquid sulphuric acid is often called "flooded" or "wet" cell. These are the cheapest batteries on the market, but they have a number of setbacks, which basically affect maintenance requirements and life-expectancy. This includes dehydration, which is in this context water electrolysis caused through overcharging and the consequent venting of the produced gas. Periodic refill with distilled water is required to restore the electrolyte level. Another issue is electrolyte stratification to dense acid in the bottom and water in the top. Stratification reduces battery capacity and performance and accelerates plates wear out. These problems are widely overcome in the AGM (Absorbed Glass Mat) and Gel batteries. In the AGM layout fibre mats are located between the lead plates; there is only enough electrolyte in the cell to keep the mats soaked so that the electrolyte is practically trapped. In the Gel battery a silica gelling agent is mixed into the liquid electrolyte converting it into a semi-stiff paste. This provides the same advantages of the AGM battery. Gel and AGM are collectively called VRLA (Valve Regulated Lead-Acid) batteries; the name is due to the fact that these batteries do dehydrate under extreme operating conditions and therefore integrate a pressure valve for gas release.

VRLA batteries are notably more costly than flooded cells, but they pay off in applications where professional maintenance would result costly, or is even not possible at all. In terms of lifetime in cycles, VRLA batteries are more durable than poorly maintained flooded cells, while they are less durable than properly maintained ones. Due to their advantage of being practically maintenance free, VRLA batteries are often opted for in small remote off-grid PV systems. In this paper we assume the use of a maintenance-free VRLA battery for 2020 installations. Thereby, we assume a price around €130/kWh. A lifetime roughly in the range of 500–1000 full cycles is realistic for such batteries. Also the other assumptions in Table 3 including a maximum power of 0.75 W/Wh with a maximum DoD of 80%, a roundtrip efficiency of 90% and a self-discharge of 3% per month are representative of VRLA batteries.

Li-ion batteries are widely used for portable devices, power tools, electric vehicles, telecommunication systems and aerospace applications. In particular considering the projections within the mobility sector, an accelerated market growth is expected within the next decades. This will not only bring cost reductions, but also improvements in durability, safety, energy density, specific power, charging time, etc. Recently, novel architecture using nanotechnology is being used to improve these characteristics [49].

Current prices for Li-ion batteries are roughly around €800/kWh. Intensive use of these batteries in hybrid and electric vehicles will bring significant cost reductions. The electrification of road transport counts with strong policy support worldwide as it implies big potential to reduce carbon emissions if complemented with emission reductions in power generation. Assuming an annual cost reduction of 7%, Li-ion battery prices would drop to around €570/kWh in 2020, €410/kWh in 2025 and €290/kWh in 2030. Table 3 assumes the cost of the Li-ion battery for 2030 in the range of 280–320 €/kWh. This assumption includes advanced packaging and electronics to maximize the cell lifetime. It is assumed that the battery does not require professional maintenance.

Battery manufacturers provide often conservative warranty conditions to assure that those are fulfilled even for batteries that are used under demanding circumstances. Small Li-ion batteries such as the ones used in mobile phones and laptops have typically a life-expectancy of 500–1000 full cycles, which is sufficient for the typical use-time of few years for these innovation intensive devices. For large batteries, such as the ones used in electric vehicles, the range of 1000–2000 cycles is more common. Some battery developers claim innovations that imply a life-expectancy up to 3000 cycles and beyond, nevertheless, such claims have not been supported so far with warranty conditions. The lifetime of 1500–2500 full cycles assumed in Table 3 is realistic for 2030.

Li-ion batteries are characterized through high roundtrip efficiency (roughly 95%) and minor self-discharge (typically below 2% per month). Furthermore, they can provide relatively high power; for some cathode materials a 1 kWh battery can provide a power of 2–3 kW. Also when it comes to the voltage, these are powerful batteries; a battery with a capacity of 100 Wh could easily provide 24 V. Many current generation cells can be recharged in a fast mode of less than 1 h if required. Further information on batteries is available in [50–84].

5. Electric appliances

This section provides details on the considered electric appliances in the aspects relevant to the layout, modelling, and optimization of the off-grid PV system, such as the power demand profile and operation voltage, and also emphasizes the cost aspects. The chosen technologies are justified in terms of their added value and energy efficiency.

LED lamps are likely to become the mainstream lighting technology within the next decade as they bring together significant advantages over existing technologies including higher efficiency and very long lifespan. In a rough description the following relation between bulb power and use is valid: 3 W for a reading lamp, 6 W for a small sleeping room, 9 W for a big sleeping room and 12 W for a living room. LEDs work with DC (Direct Current); AC (Alternating Current) LED lamps integrate a rectifier in their driver circuit. Suppliers often provide a warranty of 3–5 years. The lamps have an excellent light quality and a consistent performance. Towards the end of its lifespan the lamp shows a significant drop in brightness and substitution is required. The LED bulb technology has shown an impressive cost reduction record along the last decade and the cost cutting potential is not fully exploited. While market prices around €8/W have been conventional few years ago, today's prices are roughly around €1/W. In this paper we assume a price of 0.8, 0.6 and 0.4 €/W for 2020, 2030 and 2040 respectively. We consider a total of 60 W of DC LED bulbs installed for a household. We assume that complete substitution of the bulbs will take place after 10 years, which implies roughly 13,000 operation hours. DC LED bulbs are available as 12 V and 24 V.

Portable electronics are devices such as mobile phone, tablet and digital camera. The standard battery in such equipment is currently Li-ion. Recent developments have shortened the recharge time of such devices notably. For instance, a new generation smart phone could have a battery with a capacity of 20 Wh, and it could be fully charged within less than 2 h. Charging is initially fast and slows down once the battery has roughly achieved 75% of its capacity. So the power in this case peaks initially to roughly 15 W. For a tablet, the battery capacity is typically around 40 Wh, with the recharge power initially peaking to roughly 30 W. As a battery charger for small devices a power-pole to USB converter could be used (input voltage 10–32 V DC, output voltage 5 V DC), which could be complemented with a USB cable with several plugin options to allow to connect different devices. The efficiency of such voltage conversion devices is roughly around 90%.

A refrigerator is a basic appliance for food conservation and as such covers basic needs. Nevertheless, in a household the refrigerator is one of the electric appliances with the highest energy consumption. For instance an appliance with roughly 150 L refrigerator volume and 50 L freezer volume with EU energy label A++ consumes around 270 kWh/year. Thereby, commercial devices have improved notably along the last decade in terms of efficiency. Refrigerator designs developed for off-grid PV systems compromise on many aspects to minimize this energy consumption to reduce the affordability barrier. For instance the volume is adjusted to the basic need. No freezer is included; a refrigerator temperature slightly above 0 °C is considered sufficient. On the other hand, the design invests more on the insulation. For instance a 10 cm polyurethane insulation could be used. To reduce cold air losses when the fridge is opened, a roof door design is often preferred. Many of such fridges are already designed to consume DC power. The energy demand of a fridge is basically that of its gas compressor. Current fridges have an intermittent energy demand; without opening the fridge, roughly every 30–40 min the compressor runs for few minutes. The more the fridge is used the shorter the standby time and the longer the compressor operation are. Summing up this time, the fridge operates for several hours daily. The assumptions for the Refrigerator are summarized in Table 4.

The NPC of the fridge for a time frame of 25 years is included in Table 4. This is based on the fact the fridge complements an off-grid PV system with a lifetime of 25 years and it has to be substituted once within this period. The fridge is a critical component both in terms of its purchase cost and NPC, which elevates the affordability barriers for Cases II and IV. This is party compensated by the cost reductions it experiences overtime.

Table 4
Fridge assumptions.

	2020	2030	2040
Capacity (L)	100	100	100
Minimum temperature (°C)	+2	+2	+2
Energy consumption (kWh/y)	80	77	75
Nominal power (W)	55	55	50
Average daily operation (h)	4	3.8	4.1
Voltage, DC (V)	24/48	24/48	24/48
Lifetime (year)	13	13	13
Price (€)	800	720	650
NPC, 25 years time frame (€)	1241	1117	1008

For the energy consumption an average annual ambient temperature of 30 °C is assumed. This would be the temperature of the surrounding of the heat exchanger. This is realistic assuming that the fridge is stored in a relatively cool, dark spot with sufficient natural ventilation for the heat exchanger.

An electric rice cooker is a cooking appliance with relatively low energy demand. The required heat for cooking is generated internally, while the device is very well insulated so that heat losses through conduction are negligible. The top of the cooker integrates a steam outlet, so that the pressure inside the cooker would remain moderate. This implies heat losses, but these remain relatively low as long as the device is not opened during cooking. The cooking process is automatic. The functions of rice cookers have multiplied in recent years; integrated food steaming options allow for cooking vegetables, meat, fish, etc. There are a large number of energy efficient rice cookers on the market. The most commercially common devices are those for five meals. A nominal power around 500–600 W and a cooking time of 20–30 min are typical today. A realistic estimate for the electric demand for the currently most efficient rice cookers on the market is 50 Wh per meal, and there is still an unexploited energy efficiency potential of roughly 20–30% for these devices, especially through a design that allows pressure cooking, which would significantly reduce heat losses through the steam outlet. This does not only reduce the energy demand, but also the nominal power of the device and with that the requirements on the energy supply system, especially the battery. An electric rice cooker is conventionally an AC device. Recently some DC devices appeared on the market. As the energy consumption here is mainly the electric resistance that generates the heat, building DC devices does not require much transformation. In this paper we assume a DC device with a voltage of 48 V. A lifetime of 5 years is realistic for such device. This implies less than 2500 operation hours before substitution. Table 5 summarizes the assumptions for the electric rice cooker. In this paper we assume that the rice cooker is used twice daily: at midday and after sunset.

Table 6 summarizes the resulting daily energy demand for the different cases and the different reference years and provides a note on how the demand profile is composed. The demand profile

Table 5
Electric rice cooker assumptions.

	2020	2030	2040
Electric demand (Wh/Meal)	50	40	40
Nominal power (W)	500	400	400
Cooking time (min)	30	30	30
Voltage, DC (V)	48	48	48
Lifetime (years)	5	5	5
Price (€)	70	100	80
NPC, 25 years time frame (€)	246	351	271

Price assumptions: For 2020 it is assumed that a currently standard rice cooker is converted to DC. For 2030 and 2040 the design integrates pressure cooking. Thereby, the 2040 price is lower based on the learning rate.

Table 6
Daily electricity demand (Wh/day).

	2020	2030	2040
C I (LED + electronics)	245	245	245
C II (LED + electronics + fridge)	465	455	450
C III (LED + electronics + cooker)	745	645	645
C IV (LED + electronics + fridge + cooker)	965	855	850

LED lamps demand profile: 40 W along the 5 h after sunset.
Electronic devices: Smartphone recharge (20 Wh battery) during 2 h with 75% capacity achieved after 1 h, plus recharge of other smaller batteries along 5 h with a power of 5 W. The recharge time is directly after sunset.
Fridge: the compressor operates at nominal power every 25 min for 5 min.
Electric rice cooker: 30 min cooking time at nominal power, one time at midday and a second time after sunset.

is used in the iHOGA modelling. Due to the efficiency improvements taken into account for the fridge and rice cooker over time, the daily electricity demands decrease from 2020 to 2030 and 2040 for Cases II, III and IV.

6. Results

The iHOGA modelling results presented next have been obtained for the installation site Central India (24°N, 79°E). For this location the optimal PV generator tilt is 15° facing true south. The years 2020, 2030 and 2040 refer to the installation year. For all cases a DC installation is considered. All economic values use 2015 Euros. All calculations use an annual interest rate of 4% and 2% inflation. No costs are accounted for O&M; it is assumed that the periodic inspection of the battery bank and the occasional PV panel cleaning can be carried out by the user. The smallest PV panel size is 90 Wp. The system electronics include an MPPT for the installation years 2030 and 2040.

Table 7 provides the iHOGA modelling results for the PV generator. Comparing the PV generator size of the different cases for the same installation year, a relatively proportional relation to the energy demand can be observed. This implies that the demand profile has relatively low impact on the PV generator size. This is especially the case as the energy storage technology considered here has a relatively high roundtrip efficiency of 90% and above. The dimensioning of the PV generator does not get notably affected by the fact if more energy is consumed during night or day or if the used appliances are low power ones with long operation time (case of the fridge) or appliances with high power and short operation time (case of the electric cooker). It is eventually the battery that has to cope with the demand profile.

The iHOGA optimization calculates for Case I a PV generator of 145 Wp for the installation year 2020. This value drops to just 90 Wp for the 2040 installation although in this case the demand profile remains the same. This results due to improved efficiency on the power supply side thanks to the lower PV panel efficiency degradation, higher battery roundtrip efficiency and the inclusion of an MPPT in the battery regulator for the 2030 and 2040 installations. These three factors play the same role also in Cases II, III and IV, while additional to that there is also a drop in the energy demand in these cases due to efficiency improvements in the rice cooker and fridge on the longer run. In all cases, the required PV generator is substantially smaller for 2040 compared to 2020; for instance in Case III it is half the nominal power.

The specific cost of the PV generator changes only slightly between one case and the other as all cases imply relatively small installations with a daily demand below 1 kWh. On the other hand substantial reductions in the specific cost, roughly 30%, result through the learning curve between 2020 and 2040. As on top of that the PV generator is shrinking, the resulting cost reductions are very high: roughly 50–60%. The PV generator is not substituted and does not require professional maintenance along the installation lifetime of 25 years, so its NPC is equal to its initial cost.

Table 8 provides the iHOGA modelling results for the battery. A minimum autonomy of two days is taken into account in the calculation of the battery. This already considers the maximum DoD. There are also voltage requirements on the battery pack; several cells are connected in series to achieve the required voltage, which implies that the battery capacity is a multiple of the capacity of a row of cells. After complying with the criteria of minimum autonomy and voltage, iHOGA calculates the installation's NPC for a wide range and combinations of battery capacity and PV generator size and choses the solution with the lowest NPC.

In all cases the battery capacity results smaller for 2030 and 2040 than for 2020, which is the result of a reduced energy demand (except for Case I), the higher DoD for later battery technologies and their ability to cope with voltage requirements without much oversizing. Relatively high voltage requirements result when the system voltage to daily demand relation is high. This results for example in Case III, with a daily demand around 0.7 kWh, while requiring 48 V for the battery pack to be able to cope with the power peak of the rice cooker without excessive current. For the mentioned reasons, the battery capacity resulting for Case III, installation year 2020 (lead–acid), is relatively high.

The resulting initial investment for the battery increases in 2030 compared to 2020 due to the shift from the lead–acid to the Li-ion battery. After that, substantial cost reductions following the learning curve occur between 2030 and 2040. Thereby, 2040 values are not far from the 2020 ones. It should be reminded here

Table 7
iHOGA results for the PV generator.

	2020	2030	2040
PV generator size (Wp)			
C I	145	120	90
C II	260	180	180
C III	480	240	240
C IV	540	300	300
PV generator initial investment (€) (equal to NPC)			
C I	145	96	63
C II	247	137	126
C III	360	182	161
C IV	486	216	189

Table 8
iHOGA results for the battery.

	2020	2030	2040
Battery bank capacity (kWh)			
C I	0.96	0.72	0.72
C II	1.56	1.20	1.20
C III	3.15	1.56	1.56
C IV	3.15	2.40	1.92
Battery bank initial investment (€)			
C I	134	230	158
C II	203	360	240
C III	374	468	312
C IV	374	672	346
Battery lifetime (year)			
C I	3.0	10.9	13.5
C II	3.4	8.1	13.5
C III	3.1	13.5	13.5
C IV	3.3	13.5	13.5
Battery bank NPC (€)			
C I	939	364	267
C II	1244	607	405
C III	2104	789	526
C IV	2366	1133	583

that the battery specific cost is roughly 15% cheaper for Case IV compared to Case I which is due to the capacity difference.

A much more relevant economic indicator than the initial investment for the battery is its NPC which drops by a factor of 3–4 between 2020 and 2040. This is the result of the much longer battery lifetime in cycles for Li-ion compared with lead–acid; for 2020 installations, the battery would have to be substituted every 3–3.4 years, while for later installations this range is 8.1–13.5 years. This massive drop in the NPC shows how much all cases calculated here, and off-grid PV in general, will profit from advances in battery technology, especially the cost reductions expected for Li-ion batteries. There is also a substantial cost reduction factor related to the battery capacity. For instance for 2020 the energy demand for Case IV is factor 3.9 than that of Case I, but the battery NPC is only factor 2.5. This is in the first place the result of the better electronics for larger battery packs, which improve the cell operating conditions notably allowing to extend its lifetime.

To a minor extent, the battery profits from the improved energy efficiency for the rice cooker and fridge; the resulting lower energy demand on the longer run results in longer life in years for the same battery capacity, which reduces the battery NPC. Also the demand profile has an impact on the battery life. Electric appliances that consume all or part of their energy during the day, for instance the fridge, have a substantial direct consumption from the PV generator, while those operating only at night, for instance the LED bulbs, rely totally on the battery and with that consume from its cycles.

Table 9 summarizes the economic results of the iHOGA modelling for the off-grid PV system. These results refer to the power supply side of the system (PV generator, battery, system electronics, cables and connectors), i.e. they don't consider the purchase of the electric appliances. As can be observed, the initial investment for all cases and installation years is below €1100. All cases show a drop in the initial investment between 2020 and 2040, which are due to the already highlighted cost reductions on the component level and the overall improved energy efficiency. Comparing cases I and IV a rough rule of thumb can be observed; doubling the investment cost allows to provide 4 times the amount of energy. This speaks in principle for bigger installations; nevertheless, the full picture has also to be considered here; additional electric appliances also bring additional costs for their purchase. This makes the electric rice cooker and with that Case III very favourable from the economic perspective; the rice cooker is relatively cheap and provides a high added value, while the fact that it consumes 400–500 Wh/day is not drastic.

Summarizing the NPC evolution in Table 9, there is a substantial drop from 2020 to 2040 on the power supply side of the installation due to the improved life cycles to cost relation for the battery bank, its improved round trip efficiency, the inclusion of an MPPT in the battery regulator, the lower efficiency degradation of the PV generator and its lower specific cost, and finally the improved energy efficiency on the demand side (rice cooker and fridge). For instance, for Case IV, the NPC of the power supply side for the 2040 installation is just one third of that for 2020.

The LCoE has been calculated here to provide a comparison to what grid connected household consumers pay (conventionally between 10 and 20 c€/kWh depending on the country). For the 2020 installations the LCoE is much higher than the conventional grid-connected one. On the long run the calculated LCoE is roughly comparable to the grid-connected one. The effect of the installation's size as already explained (a bigger installation implies lower specific cost of the PV generator and battery bank and more cycles for the last) can be clearly perceived in the drop of electricity cost from Case I to Case IV. For instance for 2020, the LCoE is c€60/kWh for case I, while it is just c€35/kWh for Case IV.

Also a relevant economic indicator is the equivalent electricity bill which is the equivalent monthly payment for the installation. This indicator is used here to provide easy comparison with grid-connected consumers. Already on the short term, for an equivalent monthly €10.4, a family could cover its energy need for electronic devices, lighting, cooking and food conservation. On the longer run, this cost drops to only €3.5 per month. The excellent added value to cost becomes very evident here, alone by considering the hours saved in biomass collection for cooking. Also the advantages in health and life quality resulting from avoiding indoor fire for cooking and lighting and allowing proper food conservation are huge.

Table 10 summarizes the iHOGA modelling results for the life cycle GHG emissions. In renewable energy terms, the installation has relatively high specific life cycle GHG emissions on the short run, but these are reduced drastically over time. For instance for Case I the emissions for the 2020 installation reach 225 gCO_2/kWh, while this value is as low as 15.7 gCO_2/kWh for 2040. This reduction has to do with the improved energy efficiency of the installation over time, requiring smaller battery and PV generator, as well as with the significantly less energy needed to produce PV panels and batteries, the lower specific GHG emissions of this energy and the much longer battery lifetime. Considering the high GHG emissions related to traditional cooking and lighting in developing regions, the environmental benefits resulting here are huge.

The results presented here have been obtained for the installation site Central India (24°N, 79°E). The same calculation has been performed for South India (12°N, 77°E), a high mountain location in the far North of India (32°N, 77°E), North Pakistan (32°N, 72°E), South Pakistan (22°N, 66°E), Bangladesh (23°N, 90°E), Kalimantan (1°S, 114°E) and Java (8°S, 111°E). Similar results have

Table 9
iHOGA economic results for the off-grid PV system.

	2020	2030	2040
Initial in investment, power supply (€)			
C I	479	526	421
C II	650	697	566
C III	934	850	673
C IV	1060	1088	735
NPC, power supply side (€)			
C I	1352	728	598
C II	1759	1012	799
C III	2732	1239	955
C IV	3120	1617	1040
LCoE (c€/kWh)			
C I	60	32	27
C II	42	24	20
C III	41	21	16
C IV	35	21	13
Equivalent electricity bill (€/month)			
C I	4.5	2.4	2.0
C II	5.9	3.4	2.7
C III	9.1	4.1	3.2
C IV	10.4	5.4	3.5

The initial investment includes a cost of €200 for the following: battery controller, cables, connectors, basic system electronics and installation. The NPC considers the replacement of some components after 10 years of operation at a cost of roughly €100. After that no replacements are required until the end of the lifetime of the installation.

Table 10
iHOGA results for the life cycle GHG emissions (gCO_2/kWh).

	2020	2030	2040
C I	225	44	15.7
C II	176	49.4	15.9
C III	243	24.4	14.7
C IV	172	25.4	13.8

Table 11
Costs over the installation's lifetime on example of Case III installation year 2030.

	PV system	Appliances	Total	Details
Initial	€850	€136	€986	1.56 kWh Li-ion battery bank + 240 Wp PV generator + installation, cables, connectors, etc. + 60 W LED lamps + rice cooker
Year 6		€80	€80	Rice cooker
Year 11	€100	€104	€204	Replacement of basic components + Rice cooker + LED lamps
Year 14	€468		€468	1.56 kWh Li-ion battery bank + its installation cost
Year 16		€80	€80	Rice cooker
Year 21		€80	€80	Rice cooker

been obtained with eventually a difference of ±5% in the NPC. This has to do with the fact that the minimum battery autonomy taken into account in the iHOGA modelling is 2 days. For all the considered locations the iHOGA optimization calculates the resulting minimum battery capacity as the ideal solution. In other words, making the battery bigger would just result in a higher NPC, even if a bigger battery would allow for a smaller PV generator. These higher NPC solutions are of course discarded by iHOGA, which eventually gives the lowest NPC solution. This implies that for a specific case and installation year, the battery has the same size for all the mentioned locations. Furthermore, as the modelling considers cautiously severe operating conditions of the battery in all the considered locations (detailed in Section 2), the lifetime of the battery results also similar. What differs significantly between the different locations is the size of the PV generator and its tilt. Nevertheless, due to the fact that the NPC of the PV generator is roughly just 15–20% of the installation's NPC, a bigger or smaller PV generator does not make eventually a difference in the total NPC beyond the ±5%.

7. Discussion

This discussion will focus, within the context of this paper, on the technological, economical and environmental aspects of off-grid PV as a real solution for energy poverty in developing regions.

From the point of view of resources, solar energy is globally available, while solar radiation values are precisely high in the developing world. PV is size flexible: starting from the small PV cell integrated in consumer products up to central power plants. As sustainable technologies, PV and batteries profit continuously from technological improvements and cost reductions following the learning curve. Also electric and electronic appliances are on a fast improvement track in terms of their added value and energy efficiency. This crystallizes into off-grid PV solutions that become better and cheaper over time, as has been extensively shown along this paper. Independently of it if such solutions are implemented to tackle energy poverty in developing regions or not, and the scale of that, this favourable tendency will carry on; the main PV market today is the grid-connected one, and much of the current research in batteries targets the mobility sector, while the market for electric and electronic appliances is truly global. In this sense, this paper does not create a tendency; it actually highlights an existing one, and emphasizes that off-grid PV is a real solution for energy poverty.

Within the above mentioned context, the economic potential is best highlighted though the results obtained for the LCoE in Table 9; in a rough description it could be said that the kWh cost of off-grid PV for 2020 is 2–3 times the price of electricity a simple grid-connected consumer pays, while it is similar for 2040. It should be reminded here that grid-connected consumers pay typically 2–3 times the cost of the central power generation as they have to compensate also for the power transmission and distribution costs. The overall picture is that on the long run for the considered geographic areas it will not make much difference for the energy consumer in economic terms if electricity is provided through connection to the national grid or through local off-grid PV systems.

On the other hand, it remains a fact that off-grid PV is still a relatively expensive energy source today with a kWh cost twice of three times the grid connected one. This point, however, can be tackled through the approach followed in this paper in which the energy demand is limited to energy-efficient high added value appliances. A daily 1 kWh per household could for instance cover several basic needs, while it implies an equivalent monthly electricity bill around €10. In economic terms this pays off alone through the costs and time the off-grid PV system saves for purchasing or collecting conventional fuels.

While, as highlighted, the LCoE of off-grid PV is not really a limiting factor for its implementation in areas affected by energy poverty, the availability of capital for the initial investment could be. Table 11 shows on example of Case III for the installation year 2030 how the costs are distributed over the lifetime of the installation. In this case an initial investment close to €1000 is needed, while a cost close to €500 results from the battery replacement. For Case IV, these same costs practically double due to the high purchase cost of the fridge. It is relative if these costs imply a serious implementation barrier or not, but if they do, solutions could be provided in the form of micro-credits.

Beyond the highlighted socio-economic benefits, the environmental benefits for off-grid PV, especially in terms of GHG emissions, are fundamental. In renewable energy terms, off-grid PV has currently a relatively big carbon footprint, but the long-term tendency is very positive as has been highlighted in Table 10. As the economic restrains relax over time and the implementation barriers become lower, an accelerated market growth in developing regions will take place, which will go hand in hand with ongoing substantial reductions in the specific GHG emissions of off-grid PV. This is added to the local environmental benefits of PV systems replacing big amounts of inefficiently burnt fossil fuels and biomass to provide energy for lighting and cooking.

8. Conclusions

The conclusions of the paper are summarized as follows:

- Off-grid PV can provide effective solutions for energy poverty in developing regions practically without any resource restrains and with very positive socio-economic and environmental impacts.
- The long-term perspectives of the technology are very favourable which are based on the ongoing technological improvements and cost reductions in PV technology, batteries and electric appliances.
- On the long term, off-grid PV systems in developing regions will provide domestic electricity at a LCoE comparable to the electricity price grid-connected consumers pay.

– On the short-term the LCoE from off-grid PV is roughly 2–3 times than that of the electricity price grid-connected consumers pay.
– This current high energy cost is the main implementation barrier for off-grid PV in developing regions.
– This barrier could be notably reduced by limiting PV energy to high added value appliances (LED lamps, electronic devices, rice cooker, etc.) and by properly exploiting innovations, especially in energy efficiency.
– A second economic barrier is the availability of capital for the purchase of such systems, which could, however, be tackled by solutions such as the availability of micro-credits.

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